ABSTRACT

The spectral analysis is still a valuable method to the seismic structure design, especially when one focalizes the topics of secondary systems in large industrial installations, as nuclear power plants. Two aspects of this situation add their arguments to recommend the use of this kind of analysis: the random character of the excitation and the multiplicity and the variability of the secondary systems. The first aspect can be managed if one assumes the site seismicity represented by a power spectrum density function of the ground acceleration, and then, by the systematic resolution of a first passage problem, to develop a uniformly probable response spectrum. The second one suggests also a probabilistic approach to the response spectrum in order to be representative all over the extensive group of systems with different characteristics, which can be enrolled in a plant.

The present paper proposes a computational tool to achieve in-structure floor response spectra for secondary system design, 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.

In this work, the ExeSASSI program is created to manage SASSI2000 several modules and a set of auxiliary programas created to perform the probabilistic analyses.

1. INTRODUCTION

In 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 of the secondary systems.

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 modal analysis is used, each modal damping coefficients are 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 behavior. Then, the soil high damping characteristics can be considered. But the structural element loss of energy is represented by the Rayleigh damping, which is defined for the whole structure considering the complete frequency range, leading to most 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.

To execute this proposed procedure different computational programs are used many time, So, to enhanced the communication between the developed programs and to facilitate the use of them is created the manage program ExeSASSI. The ExeSSASSI coordinates the joint execution of the soil-structure interaction dynamic analysis system, SASSI, and the other programs which perform the coupling and probabilistic analyses.

2. 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 $PSDF_o = \Phi_o(\omega)$, instead of the control point acceleration time history. In sequence, the power spectral density function of the primary structural joint response, $PSDF_s = \Phi_s(\omega)$, is obtained through well known transmissibility function.

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

\[
\begin{bmatrix}
C_{ss} & C_{su} \\
C_{su} & C_{ss} - C_{ff} + X_{ff}
\end{bmatrix}
\begin{bmatrix}
U_s \\
U_f
\end{bmatrix} =
\begin{bmatrix}
0 \\
X_{ff} \cdot U_f'
\end{bmatrix}
\]

\[C(\omega) = K - \omega^2 M\]

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 $\omega$ 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):

\[U(\omega) = H(\omega) \cdot F(\omega)\]
If the seismic movement is represented by the base acceleration one-sided power spectra density function \( \Phi_b(\omega) \), the PSD of the structural nodal response is given by equation (4):

\[
\Phi_{us}(\omega) = (H(\omega))^2 \Phi_b(\omega)
\]  

(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):

\[
\ddot{U}_{sx}(\omega) = H_{xx}(\omega)F_{bx}(\omega) + H_{yx}(\omega)F_{by}(\omega) + H_{zx}(\omega)F_{bz}(\omega)
\]

(5)

\[
\ddot{U}_{sy}(\omega) = H_{xy}(\omega)F_{bx}(\omega) + H_{yy}(\omega)F_{by}(\omega) + H_{zy}(\omega)F_{bz}(\omega)
\]

(6)

\[
\ddot{U}_{sz}(\omega) = H_{xz}(\omega)F_{bx}(\omega) + H_{yz}(\omega)F_{by}(\omega) + H_{zz}(\omega)F_{bz}(\omega)
\]

(7)

Each of the seismic input excitation direction is associated to the same PSDF \( \Phi_b(\omega) \), and 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).

\[
\overline{H}_x(\omega) = \sqrt{(H_{xx}(\omega))^2 + (H_{yx}(\omega))^2 + (H_{zx}(\omega))^2}
\]

(8)

\[
\overline{H}_y(\omega) = \sqrt{(H_{xy}(\omega))^2 + (H_{yy}(\omega))^2 + (H_{zy}(\omega))^2}
\]

(9)

\[
\overline{H}_z(\omega) = \sqrt{(H_{xz}(\omega))^2 + (H_{yz}(\omega))^2 + (H_{zz}(\omega))^2}
\]

(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, \( \Phi_{suj}(\omega) \), 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. Specified 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:
\[ L\left(t^*\right) = 1 - \left(1 - e^{-\frac{a^2}{2\lambda_0}}\right) \exp\left(-\frac{e^{-\frac{a^2}{2\lambda_0}}}{1 - e^{-\frac{a^2}{2\lambda_0}}} t^*\right) \]  

where \( \lambda_i = \frac{\omega_i^2}{\omega_i} \cdot \Phi_{u_i}(\omega) d\omega \) for \( i = 1, 2, 3 \)  \hfill (12)

### 2.1. 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 \( \omega_{ni} \), is used to represent the secondary system with mass \( m_i \), connected to the primary system at their support points. Then, for each \( \omega_{ni} \) the PSDF \( s^i \) are computed, representing the coupled SS response at this frequency. So, the probabilistic methodology described above produces a uniform probable coupled response spectrum UPCR.

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 \( \omega_{ni} \) are used and displacement transfer functions, DTF, are obtained for unitary load acting on these points. The inverse of the DTF obtained for direction \( j \) at support point \( n \) is used to compute the local stiffness of the PS at this point \( ksp_{n,j}(\omega_{ni}) \), according to equation (13):

\[ ksp_{n,j}(\omega_{ni}) = \frac{1}{\left| DTF_{n,j}(\omega_{ni}) \right|} \]  \hfill (13)

Then, the local stiffness corresponding to each support point \( n \), acting at the direction \( j \), for each frequency of analysis \( \omega_{ni} \) is given by the equation (14):
\[
    k_{n,j}(\omega_{ni}) = \omega_{ni}^2 m_i \cdot \frac{\sum_{n=1}^{\infty} kp_{nj}(\omega_{ni})}{\omega_{ni}^2 m_i}
\]

(14)

With a conveniently choice of the frequency values \(\omega_{ni}\), 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.

### 2.2. Transposition Factors and Inelastic Floor Response Spectra

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

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

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

\[
    C = \frac{\sigma_y}{\sigma_0} \leq 1 \quad N1 = \frac{K2}{Ka} \quad N2 = \frac{E2}{E1}
\]

(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.

![Figure 1: Nonlinearity relations](image-url)
2.3. Developed Programs

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. 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 is written to obtain the equivalent transfer functions \( H(\omega) \), from the results computed by SASSI2000. Two others programs, GFiBase and ExConf, 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.

3. Overview on the Calculation Procedure

The computational methodology considers the concept of superposition effects and all the involved analyses must be linear. Then, the nonlinear soil properties that are strain dependent should be evaluated in free-field analyses in advance, using programs like SHAKE. Besides the soil properties, SHAKE evaluates the seismic excitations acting at the control point for the three orthogonal directions where the control point is chosen.

For the seismic environment it is suggested body waves propagating in vertical directions. The soil particle movement at the vertical direction can be associated to P-wave whereas for the horizontal directions the SH and SV wave types are used. Then, in module SITE, the input data associated with the incident angle is zero.

Usually, local slabs vertical responses can introduce important effects on secondary systems, mainly for civil structures founded on rigid soil or rock. It is very important that the primary system model should be sufficiently refined to represent the seismic movements in the secondary system support points (including local effects if necessary) along frequency range. The choice of the structural nodal points where the responses are obtained, are based on the best representation of the SS support points dynamic behavior.

3.2. Input data files

All input data are the same used for conventional soil-structure interaction analysis, then, all SASSI2000 recommendations should be followed.

The input data files for SASSI2000 modules (SITE, POINT, HOUSE, ANALYS and MOTION) are prepared as they would be for a conventional soil-structure interaction analyses. The SASSI2000 responses are obtained for input excitation acting at each direction separately. Then the SomaMot program is used to combine all the responses. With the combined
responses the first passage problem analyses are performed by the programs GFibase and ExConf.

The ExeSASSI program is used to manage all modules executions of SASSI200 and all auxiliary programs. The ExeSASSI permits to generate an uncoupled and a coupled response spectra, in the last case the module ACOPLA is activated and all the iterative analyses for all selected frequencies of analyses are performed.

3.3. Choice of the frequencies of analyses

In frequency domain, the seismic response amplitudes depend on the input excitations and on the transfer functions from the control point to the SS support location. The transfer functions peak frequencies are extremely influenced by the natural frequencies of the soil and of the primary system. So, a previously evaluation of these natural frequencies is very important for a good choice of the frequencies of analyses.

<table>
<thead>
<tr>
<th><strong>1. Problem idealization</strong></th>
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<tbody>
<tr>
<td>Primary and secondary system idealization</td>
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<tr>
<td>Choice of the 3D model and of the excitation</td>
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<table>
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<tr>
<th><strong>2. Input data</strong></th>
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<tbody>
<tr>
<td>soil – Free-field analysis with SHAKE</td>
</tr>
<tr>
<td>structure – 3D FEM generation</td>
</tr>
<tr>
<td>excitation – artificial TH or PSDF</td>
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<tr>
<th><strong>3. Choice of the nodal points for the responses</strong></th>
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<tr>
<td>Choice of the nodes of the 3D model which better represent the Secondary System support points</td>
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<tr>
<th><strong>4. Input files elaboration</strong></th>
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<tbody>
<tr>
<td>Elaboration of the input data files for: SITE; POINT; HOUSE; ANALYS; MOTION; SOMAMOT; GFIBASE and EXCONF</td>
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<tr>
<th><strong>5. Choice of the frequency of analyses</strong></th>
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<tbody>
<tr>
<td>- choice of equally spaced frequencies in the range of the excitation, soil and structure natural frequencies</td>
</tr>
<tr>
<td>- iterative analyses without coupling effects (SITE; POINT; HOUSE; ANALYS; MOTION; SOMAMOT; GFIBASE)</td>
</tr>
<tr>
<td>- PosExeSASSI macros for FDEP and TF plots</td>
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<tr>
<td>- iterative frequencies choices until 5 frequencies between each two peaks are achieved</td>
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<th><strong>6. Results generation</strong></th>
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<tr>
<td>- <strong>without coupling effects:</strong></td>
</tr>
<tr>
<td>run MOTION, SOMAMOT, GFIBASE and EXCONF</td>
</tr>
<tr>
<td>plot TF, PSDF, RS and UPRS using macros PlotaTF and PlotaEsp</td>
</tr>
<tr>
<td>- <strong>including coupling effects:</strong></td>
</tr>
<tr>
<td>create coupled SS (masses, modal freq. and modal dampings)</td>
</tr>
<tr>
<td>run HOUSE/ACOPLA, ANALYS, MOTION, SOMAMOT; GFIBASE and EXCONF</td>
</tr>
<tr>
<td>plot TF, PSDF and UPCRS using macros PlotaTF and PlotaEsp</td>
</tr>
</tbody>
</table>

**Figure 2:** Simplified script for UPRS and UPCRS generation
Initially, equally spaced frequencies are used by the *ExeSASSI*, covering the complete range between the minimum and maximum frequencies involved in the analyses without coupled effects between primary and secondary systems. The frequencies associated to peaks of the transfer functions peaks or peak of PSD of the structural nodal response are studied. In sequence new frequencies are choice and iterative analyses are performed until there are at least five, 5, frequencies of analyses between two peaks of the responses.

Figure 2 presents the summary of the necessary items for the generation of the response spectra (RS), uniformly probable response spectra (UPRS) and coupled uniformly probable response spectra (UPCRS) for generic SS.

## 4. EXAMPLE

The methodology is illustrated with a lumped mass beam model that 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. Three beam branches 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. Figure 3 presents a schematic view and Table 1 presents the natural frequencies of the model.

![Figure 3: Beam model of the superstructure](image-url)
Table 1: Natural frequencies of the primary system model

<table>
<thead>
<tr>
<th>Mode</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
</tr>
</thead>
<tbody>
<tr>
<td>(f) (Hz)</td>
<td>5.46</td>
<td>6.36</td>
<td>7.41</td>
<td>11.77</td>
<td>13.01</td>
<td>15.42</td>
<td>15.45</td>
<td>20.62</td>
<td>22.27</td>
<td>25.47</td>
<td>25.91</td>
<td>27.9</td>
<td>29.8</td>
</tr>
</tbody>
</table>

A piping secondary system (0.55 MN), supported partially on inner and on external structure, is modeled 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 frequencies of analyses presented on Table 2 are used by the ExeSASSI. Equivalent TF from the seismic control motion at the base of the model to the nodes 155, 174 and 176 are obtained for the nodes representing the SS support points.

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

<table>
<thead>
<tr>
<th></th>
<th>0.05</th>
<th>1.02</th>
<th>2.00</th>
<th>2.78</th>
<th>3.56</th>
<th>4.35</th>
<th>5.13</th>
<th>5.37</th>
<th>5.86</th>
<th>6.35</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.59</td>
<td>6.84</td>
<td>7.18</td>
<td>7.47</td>
<td>7.81</td>
<td>8.15</td>
<td>8.50</td>
<td>8.94</td>
<td>9.38</td>
<td>9.86</td>
<td></td>
</tr>
<tr>
<td>10.35</td>
<td>11.82</td>
<td>12.79</td>
<td>13.77</td>
<td>14.75</td>
<td>15.72</td>
<td>17.68</td>
<td>19.63</td>
<td>21.58</td>
<td>24.02</td>
<td></td>
</tr>
</tbody>
</table>

For each one of the frequencies of analyses, 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.

Figure 4 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 5 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. It is to be noticed that the 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.
Figure 4: UPRS – uncoupled analysis envelope for nodes 155; 174 and 176

Figure 5: UPCRS – coupled analysis secondary system modeled by node 181
5. CONCLUSIONS

A computational tool is developed for the generation of secondary system seismic design response spectrum. The standard SASSI2000 system is used with new additional programs. Special situations are considered as the interaction of the main and the secondary system, the effect due to a multiple supported secondary system and the consideration of response spectrum in a probabilistic way, using the first passage solution and leading to a uniformly probable response spectrum.

With the proposed methodology one can achieve the following advantageous:

- Better damping effects representation, considered directly in the soil-structure interaction formulation in frequency domain, because neither the use of modal damping nor the definition of the Rayleigh coefficients is 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.
- Possibility of easy evaluation of the ductile reserve of secondary systems under inelastic behavior.

REFERENCES


