SEISMIC INTERACTION EFFECTS FOR STEAM GENERATORS IN CANDU 600 MWe NUCLEAR POWER PLANTS

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SUMMARY

Typical CANDU-PHW 600MWe Nuclear Power Plants (NPP) contain four identical Steam Generators (SG). Because of space limitations around the Fuelling Machine area, each one of these SG's is supported by a single column of approximately 45ft long which is anchored to the base slab at the bottom. The SG itself is housed in an internal box concrete structure. Seismic restraints and/or snubbers are used to support the SG laterally from this internal box structure. Conventionally, these SG's are designed by the use of an envelope floor response spectrum for the internal structure; as an upper bound on the seismic response of light secondary systems. Nevertheless, mass coupling effects between the SG and the internal structure may be important since the SG has a considerable mass and is supported almost the full height of the internal structure. An obvious solution to account for the coupling effects is to utilize an elaborate dynamic model which incorporates the different SG's, the reactor, and the reactor building in one dynamic model. Recent theoretical work by the authors (1), (2) in this area drew attention to some of the fallacies of using elaborate coupled models which involve small modal mass ratios for the secondary systems. Thus, a practical solution to account for the beneficial seismic interaction effects for secondary systems like SG's is lacking. The paper presents a substructuring technique to overcome the difficulties associated with using a coupled model with small modal mass ratios. The technique accounts for interaction effects as well as multiple input motions and provides a clear understanding of the beneficial coupling effects. Typical results using this substructuring technique combined with spectrum analysis for a typical CANDU NPP on a soil site are presented and discussed. Guidance on the validity of the approach to other similar secondary systems applications is given.

(1) Aziz, T.S., Duff, C.G., 'Mass Coupling Effects in the Dynamic Analysis of Nuclear Power Plants', ASME Paper 78-PVP-28, ASME Pressure Vessels & Piping Conference, Montreal, Canada, June 25-29, 1978.

(2) Aziz, T.S., Duff, C.G., 'Decoupling Criteria for Seismic Analysis of Nuclear Power Plant Systems', ASME Paper 78-PVP-29, ASME Pressure Vessels & Piping Conference, Montreal, Canada, June 25-29, 1978.

Introduction

Typical CANDU-PHW 600MWe Nuclear Power Plants (NPP) contain four identical Steam Generators (SG). Because of space limitations around the Fuelling Machine area, each one of these SG's is supported by a single column of approximately 45ft long which is anchored to the base slab at the bottom. The SG is housed in an internal box concrete structure. Seismic restraints and/or snubbers are used to support the SG laterally from the internal box structure. Conventionally, these SG's are designed by the use of an envelope floor Response Spectrum (FRS) for the internal structure, as an upper bound on the seismic response of light secondary systems. Nevertheless, mass coupling effects between the SG and the internal structure may be important since the SG has a considerable mass and is supported almost the full height of the internal structure (Figure 1). An obvious solution to account for the coupling effects for the primary system (Reactor Building) and the secondary system (SG) is to utilize an elaborate dynamic model which incorporates the different steam generators, the reactor, and the Reactor Building (RB) in one dynamic model (6). This approach may have some drawbacks as discussed in Reference 1 and 2 by the authors.

The objective of this paper is to develop a substructuring approach to quantify the seismic interaction effects for steam generators as those found in a CANDU 600MWe without resorting to a fully coupled dynamic model. By definition, a substructuring approach as used herein would involve analyzing the SG in isolation from the RB and vice versa without neglecting the true nature of the seismic interaction effects present.

Nature of the Seismic Interaction

The nature of the seismic interaction between the SG and the RB is a somewhat unique problem. To define the nature of this seismic interaction a lumped mass dynamic model for the Reactor Building (i.e. containment, internal structure, vault, reactor, and soil) as shown in Figure 2 was analyzed. Modal quantities such as frequencies, mode shapes, participation factors, modal masses, modal damping and modal stiffnesses were obtained. In this model, the weight of the four SG's was lumped as mass allocated to node 5 which is close to their center of gravity. Subsequently, a lumped mass dynamic model for a single SG in isolation was analyzed to obtain similar modal quantities as described before. In this model, flexibilities of the upper and the lower seismic restraints supporting the SG were taken into consideration; while the internal structure was assumed rigid. Another coupled model which includes the RB and the SG was analyzed and similar modal quantities were obtained.

A decoupling criterion based on modal mass ratios and frequency ratios was derived and presented previously by the authors (2) as shown in Figure 3. When implementing these criteria one has to be careful in selecting the critical modes which contribute to the response for both the primary and the secondary systems. Mathematically, the sum of the modal masses of a system is equal to its actual mass. Thus, if only a few modes contribute to the response, the modal masses for the remainder of the modes will be small. If such modes are considered in applying any decoupling criterion, which is bound to be dependent on the mass ratio, one may reach wrong conclusions. In the example presented, a study of the value of the modal masses revealed that only the first three modes of the RB need to be considered for decoupling evaluation. (The sum of these three modal masses is 97% of the total actual mass). Had the seventh mode of the RB (modal mass happened to be zero) been considered for example, large mass ratios would have been encountered and wrong conclusions as far as coupling would have been arrived at. The different frequency and mass ratios obtained are plotted in Figure 3;

where (P_n, S_m) defines the n^{th} mode of the primary system and the m^{th} mode of the secondary system. Points outside the graph scales were not plotted. Figures 4 and 5 demonstrate the behaviour of the absolute values of ($\Gamma\phi$) for node 4 and 5 (lower and upper SG lateral supports respectively) of the RB model as obtained by a coupled RB/SG model versus a RB model. It can be observed from these two figures that the nature of the motion (both frequency content and amplitude) obtained at nodes 4 and 5 is basically the same, whether obtained by the RB model alone or the coupled RB/SG model.

Guided by Figures 4 and 5, it can be concluded that for the case under consideration (soil site), the nature of seismic interaction between the RB and the SG is not of the inertial type (feedback due to large modal mass effects). The seismic interaction present is primarily because of the differences in input motions at points of support of the SG. Thus a multiple support approach, as presented in the following section, is considered the most suitable technique to analyze the SG in isolation. While the formulation as presented later is applicable to time-history as well as spectrum solutions, only the later results will be presented because of space limitations.

SG Analysis using a Multiple Support Approach

The equation of motion of the SG itself subjected to input motions at points a, b and c (Fig. 6) are as given below:

$$\left[M_{rr}\right]\left\{\ddot{X}\right\} + \left[C_{rr}\right]\left\{\dot{X}\right\} + \left[K_{rr}\right]\left\{X\right\} = -\left[K_{rs}\right]\left\{U_s\right\} - \left[C_{rs}\right]\left\{\dot{U}_s\right\} \qquad (1)$$

where:

$\left\{X\right\}\left\{\dot{X}\right\}\left\{\ddot{X}\right\}$ = Absolute displacement, velocity, and acceleration vectors of the unsupported nodes of the system (free nodes)

$\left\{U_s\right\}\left\{\dot{U}_s\right\}\left\{\ddot{U}_s\right\}$ = Absolute displacements, velocity, and acceleration vectors of the supported nodes of the system (deriving points)

$\left[M_{rr}\right]\left[C_{rr}\right]\left[K_{rr}\right]$ = Mass, damping, and stiffness matrices when points a, b and c are fixed in space

$\left[K_{rs}\right]$ $= \left[\left\{A\right\}\left\{B\right\}\left\{C\right\}\right]$ = stiffness coupling between the supported and the unsupported nodes

Choosing a reference motion $\left\{S\right\}$, such that it represents the displacements at the unsupported nodes due to displacements of the supported nodes, the relative motion $\left\{Y\right\}$ of the unsupported nodes will be given by:

$$\left\{Y\right\} = \left\{X\right\} - \left\{S\right\} \qquad (2)$$

$$\left\{S\right\} = -\left[K_{rr}\right]^{-1}\left[K_{rs}\right]\left\{U_s\right\} \qquad (3)$$

$$\left[M_{rr}\right]\left\{\ddot{Y}\right\} + \left[C_{rr}\right]\left\{\dot{Y}\right\} + \left[K_{rr}\right]\left\{Y\right\} = -\left[M_{rr}\right]\left\{\ddot{S}\right\} = \left[M_{rr}\right]\left[K_{rr}\right]^{-1}\left[K_{rs}\right]\left\{\ddot{U}_s\right\} \qquad (4)$$

Equation 4 can be solved in the time domain or alternatively transformed into its modal coordinates utilizing conventional modal analysis and widely used conventional notations:

$$\left\{Y\right\} = \left[\phi\right]\left\{q\right\} \qquad (5)$$

$$\left\{\ddot{q}\right\} + \left[2\beta\omega\right]\left\{\dot{q}\right\} + \left[\omega^2\right]\left\{q\right\} = \left[\phi\right]^T\left[M_{rr}\right]\left[K_{rr}\right]^{-1}\left[K_{rs}\right]\left\{\ddot{U}_s\right\} \qquad (6)$$

The stiffness coupling terms $\left\{A\right\},\left\{B\right\}$ and $\left\{C\right\}$ for the case in hand (Fig. 6) with lateral support K_n and K_m at nodes 'n' and 'm' respectively are given by:

$$\{C\} = \begin{Bmatrix} 0 \\ 0 \\ 0 \\ -k_m \\ 0 \\ 0 \end{Bmatrix} \quad \{B\} = \begin{Bmatrix} 0 \\ 0 \\ -k_n \\ 0 \\ 0 \end{Bmatrix} \quad \{A\} = [K_{rr}]\{J\} - \{B\} - \{C\} \tag{7}$$

$\{J\}$ = a vector whose elements are all unity

It can be shown that

$$\{\ddot{q}\} + [2\beta\omega]\{\dot{q}\} + [\omega^2]\{q\} = [1/\omega^2][\phi]^T[K_{rs}]\{\ddot{U}_s\} \tag{8}$$

$$= \{\Gamma_a\}\ddot{U}_a + \{\Gamma_b\}\ddot{U}_b + \{\Gamma_c\}\ddot{U}_c \tag{9}$$

where:

$$\{\Gamma_a\} = \left[\frac{1}{\omega^2}\right][\phi]^T\{A\} \tag{10}$$

$$\{\Gamma_b\} = \left[\frac{1}{\omega^2}\right][\phi]^T\{B\} = \left\{\frac{-\phi_{in}}{\omega_i 2}K_n\right\} \tag{11}$$

$$\{\Gamma_c\} = \left[\frac{1}{\omega^2}\right][\phi]^T\{C\} = \left\{\frac{-\phi_{im}}{\omega_i 2}K_m\right\} \tag{12}$$

It can be shown that: $\{\Gamma_a\} + \{\Gamma_b\} + \{\Gamma_c\} = -\{\Gamma\}$ (13)

Where $\{\Gamma\}$ is the participation factor $= [\phi]^T[M_{rr}]\{J\} = \left[\frac{1}{\omega^2}\right][\phi]^T[K_{rr}]\{J\}$ (14)

and $\{S\} = \{J\}U_a - [K_{rr}]^{-1}\{B\}(U_b-U_a) - [K_{rr}]^{-1}\{C\}(U_c-U_a)$ (15)

Equation (9) is very similar to the basic equation of motion of a one degree of freedom system and can be solved utilizing the three input motion spectra at points a, b, and c (Fig.7); the only difference being the redefinition of the participation vectors $\{\Gamma_a\}$, $\{\Gamma_b\}$ and $\{\Gamma_c\}$ as given by equations 10, 11 and 12.

Example

A typical SG was analyzed utilizing the previous multiple support spectra approach. Table (1) gives the participation factors obtained for the first five modes of the SG. It can be concluded from this table that the participation factors associated with the input motion at point 'a' are small ($\Gamma_a\phi$ are even smaller than Γ_a). Utilizing these participation factors and the conventional mode shapes of the SG, the accelerations for the different nodes were calculated. The results for different modal combination rules are presented in Figure 9 for a single input approach and a multiple support input approach. In all these analyses (guided by the nature of the 2nd derivative of equation (15)) the rigid range accelerations $\{S\}$ were combined with the relative modal accelerations $\{Y\}$ utilizing the SRSS rule as demonstrated in Figure 8. Having obtained the absolute accelerations of the different nodes of the SG, an equivalent seismic mass was calculated for the SG utilizing the actual acceleration of Fig. (9). This mass was found to be 97.3% of the actual mass of the SG which confirmed the approach of lumping the SG's mass at node 5 of the RB model.

Conclusions

1. The nature of the seismic interaction between a RB and a SG for the case studied was found to be due to a difference in the motion at the SG supports, rather than due to mass ratio effects (very small modal mass ratios were encountered for the dominant modes). Thus, a multiple input approach was found more appropriate to this problem.

The motions derived for the RB were found to be basically the same, whether the SG's are modelled as a single mass or as a detailed lumped mass model. The effective mass of the SG, due to the seismic interaction, was confirmed to be very close to its actual mass for the case studied (0.1g ground acceleration and a soil site).

2. The multiple input spectrum approach, utilizing an SRSS rule for modal combination, leads to substantially lower results compared to an envelope spectrum type approach. When using SRSS of the absolute sum of the effects of the input spectra, the beneficial effects of a multiple input spectrum were found to be small. For the case studied, two of the input spectra are generated by motion of the same structure and thus are bound to be perfectly correlated at some frequencies. Thus, an algebric sum for support effects may be possible (i.e. correlation in this case is a beneficial effect). When this is the case, the reduction in the response is substantial as demonstrated in Figure 9.

4. The approach of lumping the weight of the SG's as a single mass in the RB dynamic model is justified. A simple modal test as demonstrated in Figures 4 and 5 is very useful to confirm this conclusion in design situations with different layouts and soil conditions.

TABLE 1

Participaction Factors for Multiple Inputs to the SG

Mode	f(Hz)	Γ	Γ_b	Γ_c	Γ_a
1	6.45	1.13	-1.43	.37	-.07
2	10.11	.37	.43	-.44	-.36
3	15.55	1.76	-.13	-1.64	+.01
4	28.80	-1.33	-.08	1.34	+.07
5	33.70	-.80	-.12	1.51	-.59

REFERENCES

(1) Aziz, T.S., and Duff, C.G., 'Mass Coupling Effects in the Dynamic Analysis of Nuclear Power Plants' ASME Paper 78-PVP-28, ASME Pressure Vessels & Piping Conference, Montreal, Canada, June 25-29, 1978.

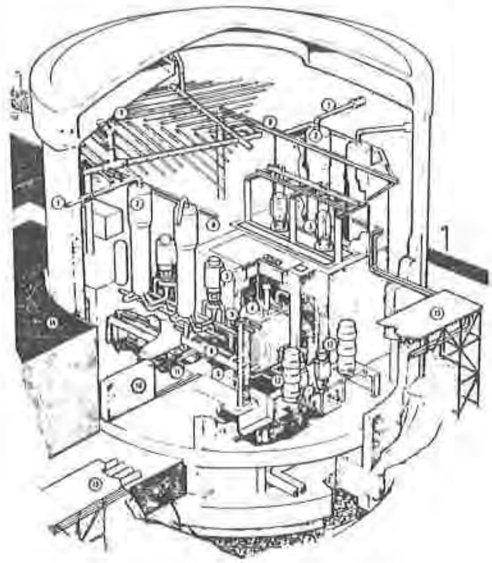
(2) Aziz, T.S., and Duff, C.G., 'Decoupling Criteria for Seismic Analysis of Nuclear Power Plant Systems', ASME Paper 78-PVP-29, ASME Pressure Vessels and Piping Conference, Montreal, Canada, June 25-29, 1978.

(3) Kasawara, R.P., and Peck, D.A., 'Dynamic Analysis of Structural Systems Excited at Multiple Support Locations', Paper presented at ASCE Specialty Conference on Structural Design of Nuclear Plant Facilities, Chicago, December 17, 1973.

(4) Vashi, K.M., 'Seismic Spectral Analysis of Structural Systems Subjected to Nonuniform Excitation at Supports', 2nd ASCE Specialty Conference on Structural Design of Nuclear Power Plant Facilities, New Orleans, Louisiana, December 1975.

(5) Wu, R.W., Hussain, F.A., and Liu, L.K., 'Seismic Response Analysis of Structural Systems Subjected to Multiple Support Excitation', 4th SMiRT, San Francisco, August 1977.

(6) Asmis, G.J.K., Duff, C.G., 'Seismic Design of Steam Generators - A Multiple System Approach', 4th SMiRT, San Francisco, August 1977.



1 MAIN STEAM SUPPLY PIPING
2 BOILERS
3 MAIN PRIMARY SYSTEM PUMPS
4 CALANDRIA ASSEMBLY
5 FEEDERS
6 FUEL CHANNEL ASSEMBLY
7 DOUSING WATER SUPPLY
8 CRANE RAILS
9 FUELLING MACHINE
10 FUELLING MACHINE DOOR
11 CATENARY
12 MODERATOR CIRCULATION SYSTEM
13 PIPE BRIDGE
14 SERVICE BUILDING

Fig. 1 REACTOR BUILDING CUTAWAY

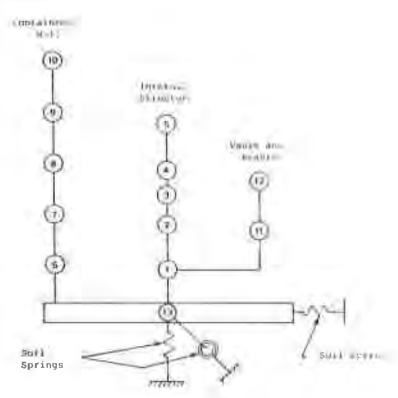


Fig. 2 CANDU 600 MWe REACTOR BUILDING
DYNAMIC MODEL

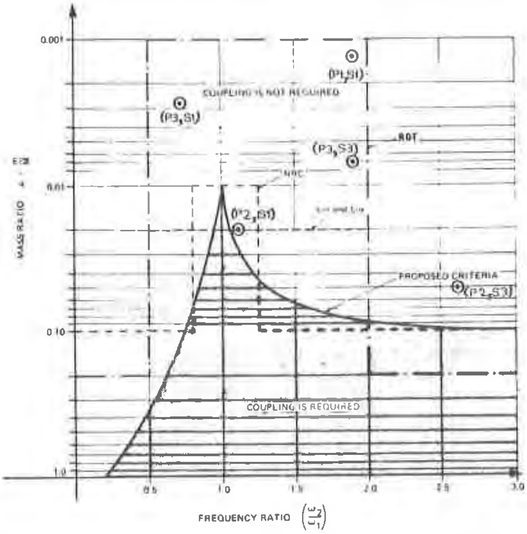


Fig. 3 IMPLEMENTATION OF DECOUPLING CRITERIA

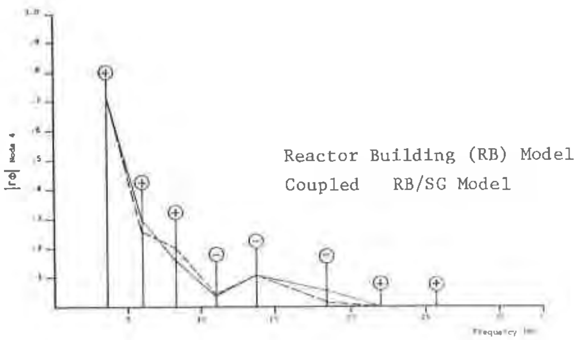


Fig. 4 BEHAVIOUR OF $|\Gamma\Phi|$ WITH FREQUENCY AT NODE 4

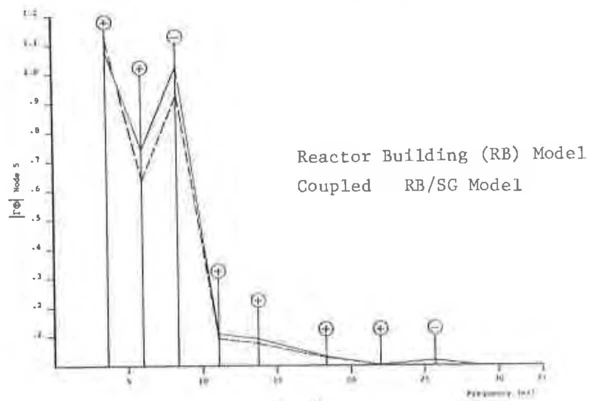


Fig. 5 BEHAVIOUR OF $|\Gamma\Phi|$ WITH FREQUENCY AT NODE 5

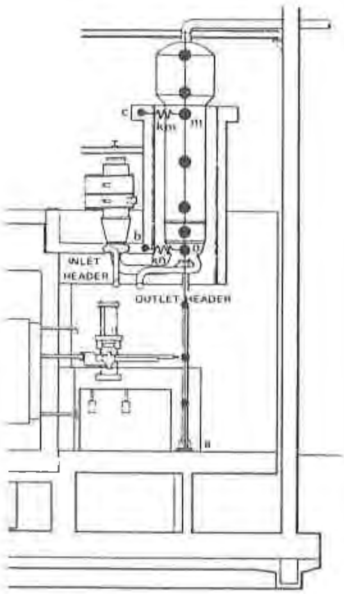


Fig. 6 SG ANALYSIS USING MULTIPLE SUPPORT INPUT

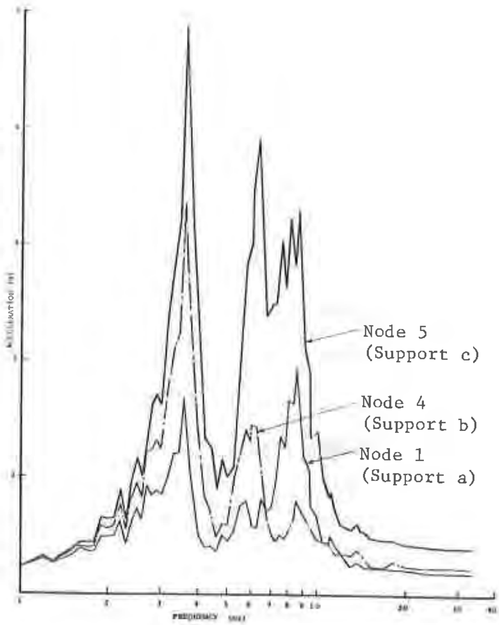


Fig. 7 FRS AT DIFFERENT POINTS OF REACTOR BUILDING

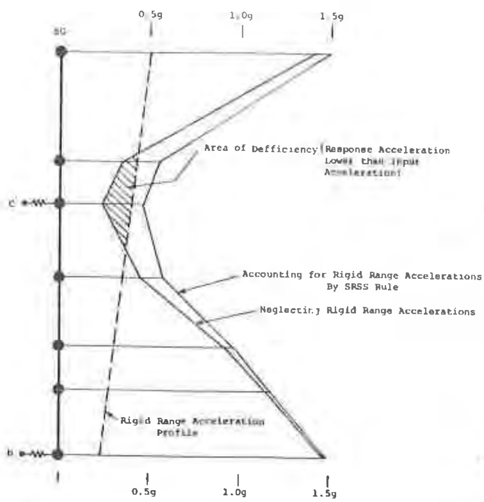


Fig. 8 CORRECTION FOR ABSOLUTE ACCELERATION BY SRSS RULE

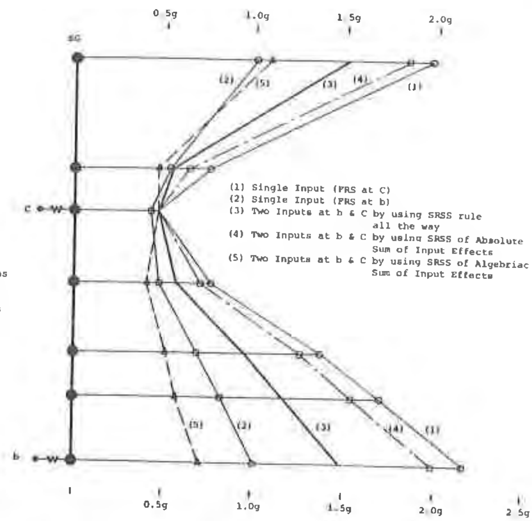


Fig. 9 ACCELERATION PROFILES USING DIFFERENT APPROACHS