

BUILDING-SOIL-BUILDING INTERACTION IN SEISMIC ANALYSIS OF NUCLEAR POWER PLANTS

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Abstract

Since a nuclear power plant is normally composed by several buildings of different dynamic characteristics clustered in a fairly small area, the mutual interaction effect can be significant for the total response evaluation, when a seismic excitation is of concern.

Although relevant work has been done in the field of the single-building-soil interaction, both by numerical methods and theoretical approaches, the problem above has not been completely investigated. Furthermore, in the majority of the cases, the studies carried out for the building-to-building interaction problems assume a plane geometry, with the two buildings aligned according to the direction of the seismic motion.

In the present paper, a truly three-dimensional representation of the problem is taken into account and a parametric study is presented, in order to obtain an appropriate description of the phenomenon.

In particular, this treatment has the peculiar advantage of allowing the detection of those components of the motion, such as transverse displacement, rolling and twisting, that are necessarily hidden by a plane idealization.

To the above mentioned purpose, two different computer codes were implemented. The first one derives from a semi-analytical procedure based on a solution of the wave propagation problem in terms of a Fourier expansion of the space variables. A computer program associated with this solution was already written by GAZETAS, for two-dimensional situations, for a single foundation. The second one is a finite element program which uses a cylindrical coordinates extension of the LYSMER-WAAS consistent boundary. This method was developed and utilized by KAUSEL for the case of a single foundation.

Both programs make the assumptions of linearly elastic, horizontally layered soil with hysteretic damping. The buildings are idealized as 4-degrees of freedom systems with respect to an underlying rigid foundation mat.

The dynamic response of the bases of the buildings is shown in form of plots of the amplification functions. A comparison is established with the results obtained by the program FLUSH.

1. Formulation of the problem

Any soil-structure interaction problem, under linear hypotheses, can be alternatively treated by the approaches commonly denoted "one-step" and "three-step" solutions.

The three-step approach is developed in the following three distinct phases :

- a) determination of the motion of the soil, generally simulated by a stratified half-space or half-plane, at the foundation level considering rigid but massless foundations.
- b) computation of the dynamic stiffness (frequency dependent) of the foundation system.
- c) dynamic analysis in the frequency domain of the structures supported by springs, the properties of which are derived from the stiffness given by the second step.

It should be noticed that step a) is coincident with the one-dimensional site amplification problem in the case of surface foundations and vertically propagating S-waves.

Step b) can be accomplished by means of several procedures.

For the case of two structures, extending the procedure described in [1] , [2] , a net of equally spaced points is individuated on the soil surface, exactly including the foundations and the intermediate area. Then, a double Fourier transform with respect to the space variables describing the surface of a unit stress pulse, combined with an analytic solution of the wave propagation problem, allows the construction of the flexibility coefficients for a larger set of points, including the ones mentioned above.

From these coefficients the flexibility matrix [C] of the system composed by the two foundations can be made up.

Upon inversion of [C] , the stiffness matrix [K] can be obtained; this can be accomplished and the order of the matrix itself can be reduced by condensation of the degrees of freedom of each foundation into rigid body motion components. Both operations are summarized by the following congruent transformation :

$$[K] = [L]^T [C]^{-1} [L] \quad (1)$$

where :

$$[L] = \begin{bmatrix} [L_1] & [0] \\ [0] & [L_2] \end{bmatrix} \quad (2)$$

and $[L_i]$ ($i=1,2$) is a matrix relating the displacement components of the interface nodes to the six rigid body components of the i -th foundation.

In other words, the procedure is a straightforward extension of the one already presented by the Authors for the 2-D case [3] .

Alternatively, always keeping unmodified the condensation process given by Eq. (1), the flexibility matrix [C] can be determined by a finite element solution of the wave propagation problem for unit stress pulses [4] . This latter approach allows the study of a more general class of foundation geometries and is more simple than the previous one because, if

the soil is horizontally stratified, the problem is characterized by an axial symmetry.

It should be observed that the two methods lead to a different degree of approximation as, in general, the first one overestimates the result while the second one gives an underestimate of it. In particular, relatively large differences can be found in off-diagonal terms, while the evaluation of the diagonal coefficients is usually of the same order of approximation.

Step c) involves the determination of a model for the structural response evaluation. In the present case, in order to make easier the comparison of the different methods and to allow a parametric investigation, the two buildings are idealized as described in fig. 1. The structure of each building is considered as a rigid body, joined to its foundation by viscously damped elastic connectors, and has, with respect to the footing, four degrees of freedom: horizontal displacements u, v according to x and y axis, vertical displacement w , rotation ψ about z axis. Besides, the foundation has the six degrees of freedom of a space rigid body motion: $U, V, W, \theta, \phi, \psi$.

In the frequency domain, the motion of the two buildings is described by:

$$\left(\begin{array}{cc} [\bar{K}_{11}] & [\bar{K}_{12}] \\ [\bar{K}_{21}] & [\bar{K}_{22}] \end{array} \right) - \Omega^2 \left(\begin{array}{cc} [J_1] & [0] \\ [0] & [J_2] \end{array} \right) \left\{ \begin{array}{c} \{s_1\} \\ \{s_2\} \end{array} \right\} = \left(\begin{array}{cc} [\bar{K}_{11}] & [\bar{K}_{12}] \\ [\bar{K}_{21}] & [\bar{K}_{22}] \end{array} \right) \left\{ \begin{array}{c} \{s_0\} \\ \{s_0\} \end{array} \right\} \quad (3)$$

where $[J_i]$ is the inertia matrix, $[\bar{K}_{ij}]$ is the stiffness matrix after the assemblage of the structure and foundation stiffnesses, while:

$$\{s_i\}^T = \{U_i, V_i, W_i, \theta_i, \phi_i, \psi_i, u_i, v_i, w_i, \psi_i\} \quad (4)$$

$$\{s_0\}^T = \{U_0, 0, 0, 0, 0, 0, 0, 0, 0, 0\} \quad (5)$$

being U_0 the amplitude of the generic Fourier component of the control motion at the free surface.

Eq. (3) can be put in dimensionless form, by introducing as adimensionalizing quantities the height of the stratum H for the lengths, ρH^3 for the masses (ρ being the density of the soil), H/C_s for the times (C_s being the velocity of S-waves in the soil). The response is modified by dividing the linear accelerations by \ddot{U}_0 and the rotational accelerations by \ddot{U}_0/H . As a consequence, Eq. (3) gives the amplifications of the accelerations versus a frequency $a = \Omega H/C_s$.

The "one-step" approach consists in modelling the complete system, generally by means of the finite element technique. Of course the modelling of truly three-dimensional situations, except the axy-symmetric case, results in a prohibitive cost of the analysis.

An attractive solution is represented by the program FLUSH [5], which, although essentially two-dimensional in nature, simulates the 3-D effects by adding lateral viscous boundaries. The details of this technique can be found in [6].

It should be noticed, however, that in such models the buildings always need to be aligned.

2. Test cases

An hypothetical plant, composed by a reactor building and an auxiliary building, was analyzed.

The (undamped) natural frequencies of the two buildings are :

	f_x	f_y	f_z	f_ψ	(Hz)
reactor building :	3,5	3,5	14,0	5,5	
auxiliary building :	4,2	4,0	17,0	6,5	

A 2% damping is then added to the structural models.

With reference to fig. 2, the characteristics of the soil layer are : $H = 30,5\text{m}$ (100ft), $\rho = 1932 \text{ Kg/m}^3$ (3,75 slugs/ft³), $\nu = 0,333$, $G = 1,142 \cdot 10^8 \text{ N/m}^2$ (2385 Kp/ft²), $C_s = 244 \text{ m/sec}$ (800 ft/sec), $\beta = 8\%$.

Two sets of cases were analyzed. For aligned buildings (fig. 2) three distances D_x were considered : 1,68; 2,37; 3,76 times the size x of the foundation of the auxiliary building (hereafter referred as DIST. 1, DIST. 2 and DIST. 3)

Two cases of building misalignment were considered, as shown in fig. 3 (POS. 1 and 2) where $D_2 = 2,37$ times the size x of the foundation of the auxiliary building.

3. Discussion of Results

Figures 4+7 show the amplification functions of the accelerations for the case of aligned buildings and are obtained from either the 3-D computer programs described in section 1. A comparison between the two developed programs and the program FLUSH is presented, for a single building and for the coupled system in Figs. 8,9.

Particularly meaningful are the plots of figs. 11+15. They refer to misaligned buildings and represent the motions that are effectively present in real situations and that are only discoverable by truly three-dimensional models.

The components are the transverse motion according y , the rolling about x and the twisting about z . As it can be easily seen, their amplitudes could be significant for the evaluation of the global response of the building systems.

Acknowledgements

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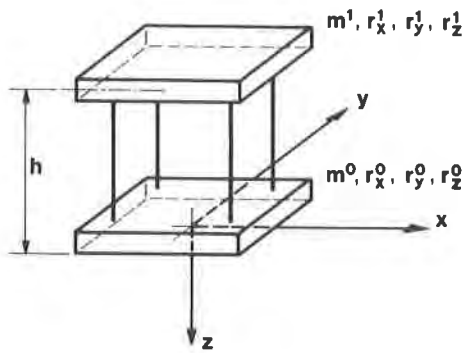


Fig. 1 - Pictorial sketch of the building idealization

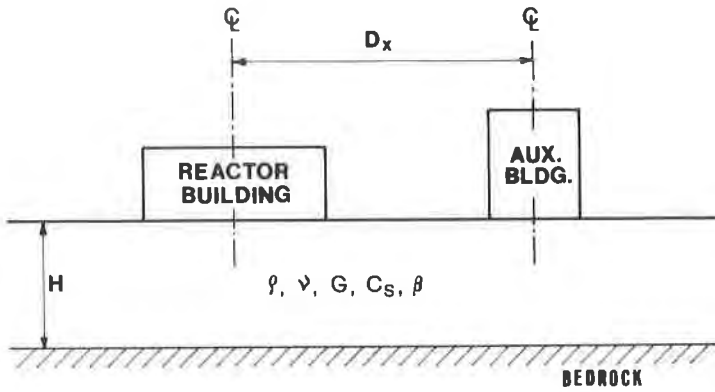


Fig. 2 - Test case : elevation

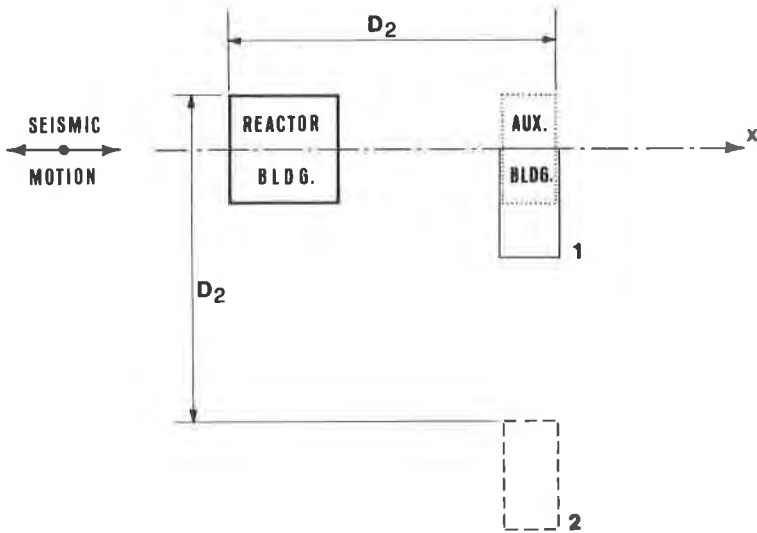


Fig. 3 - Test case : plan

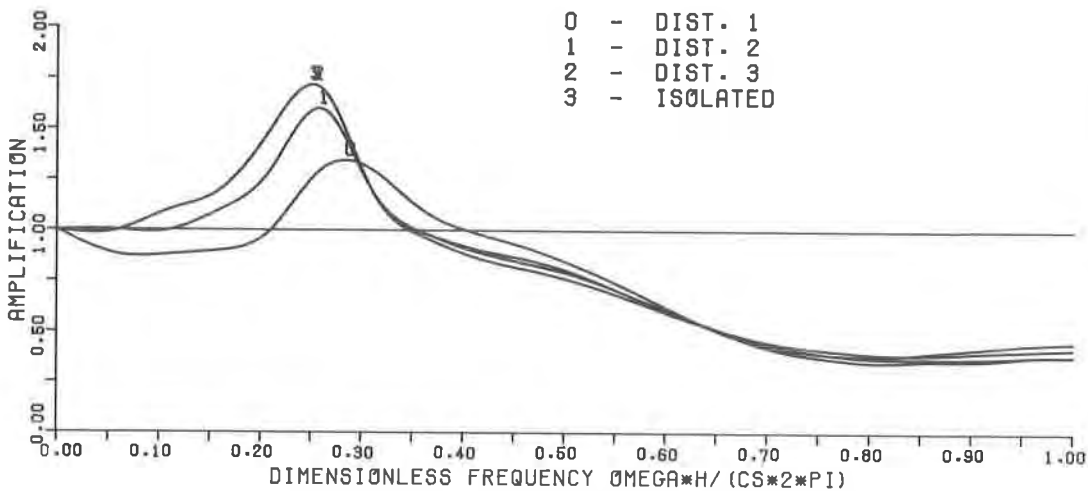


Fig. 4 - Reactor building response (aligned) : base x acceleration

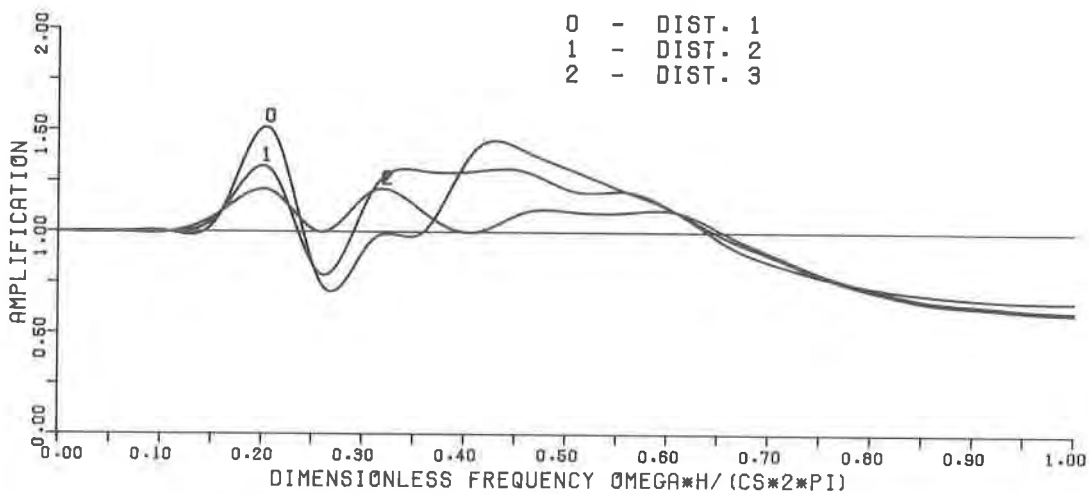


Fig. 5 - Auxiliary building response (aligned) : base x acceleration

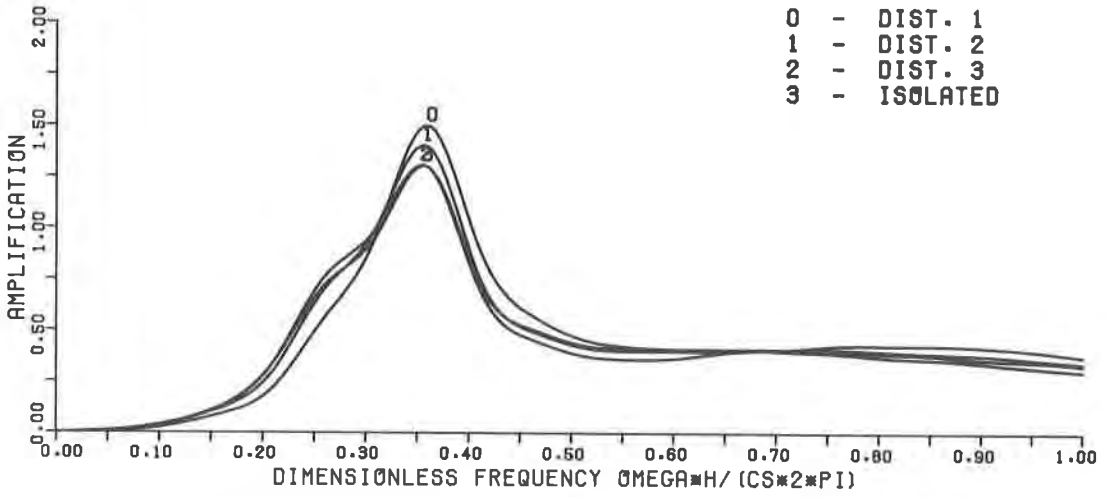


Fig. 6 - Reactor building response (aligned) : base rotational acceleration about y

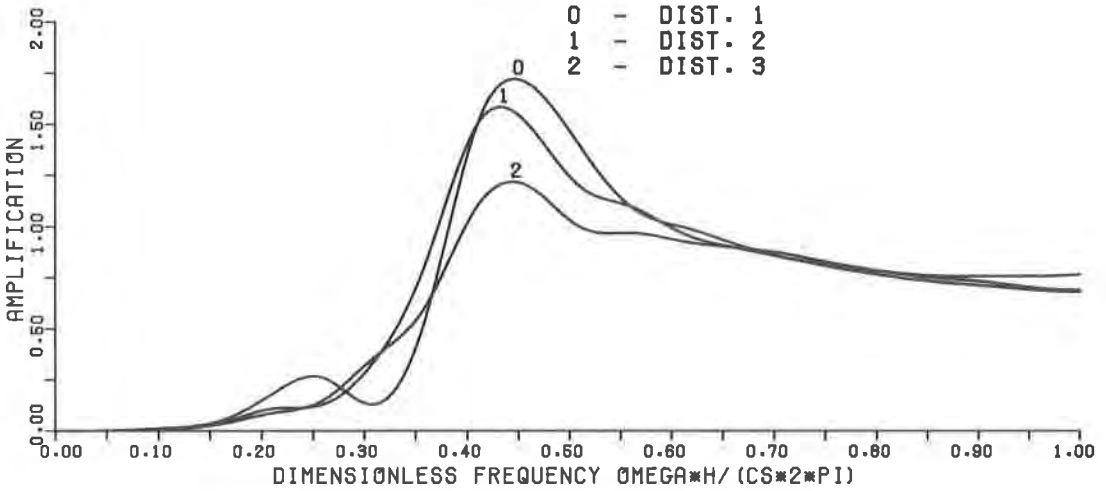


Fig. 7 - Auxiliary building response (aligned) : base rotational acceleration about y

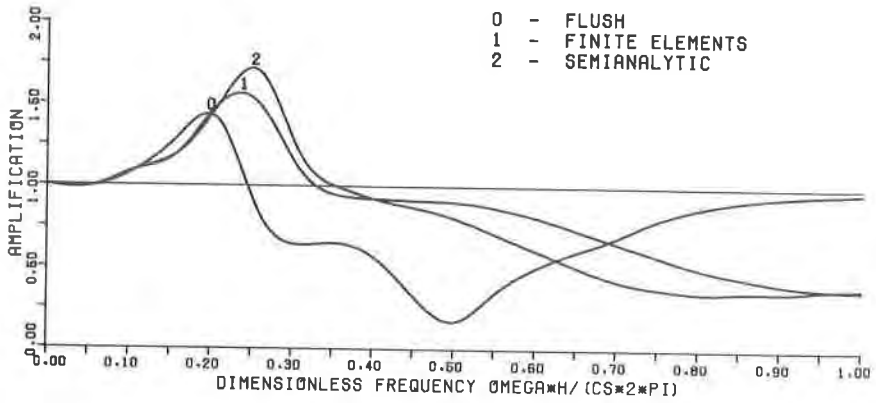


Fig. 8 - Comparison of reactor building response evaluation (isolated building) : base x acceleration

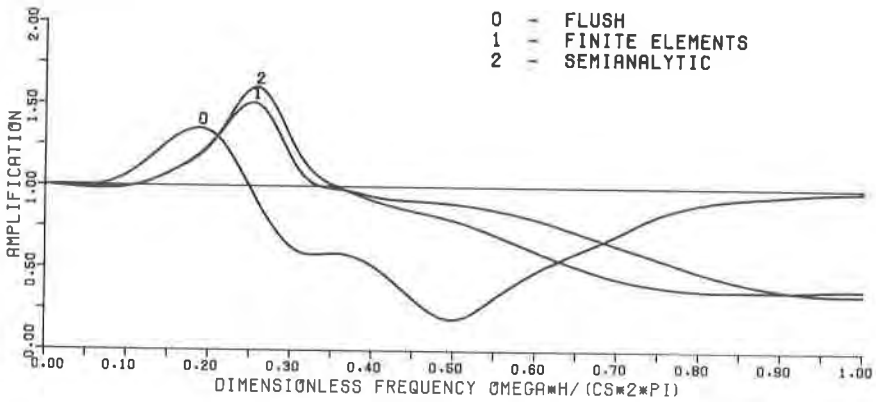


Fig. 9 - Comparison of reactor building response evaluation (auxiliary building at DIST.2): base x acceleration

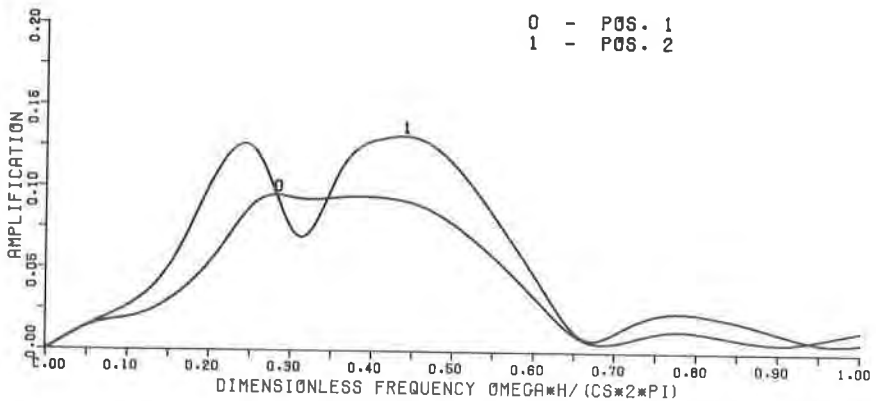


Fig.10 - Reactor building response (misaligned) : base transverse acceleration

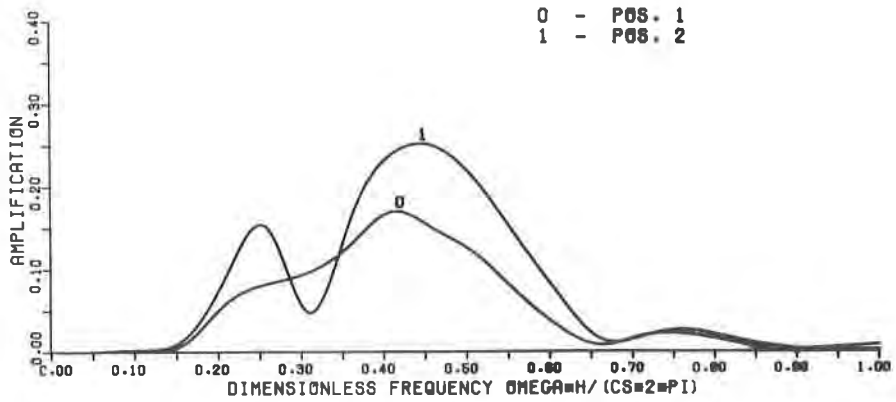


Fig.11 - Auxiliary building response (misaligned) : base transverse acceleration

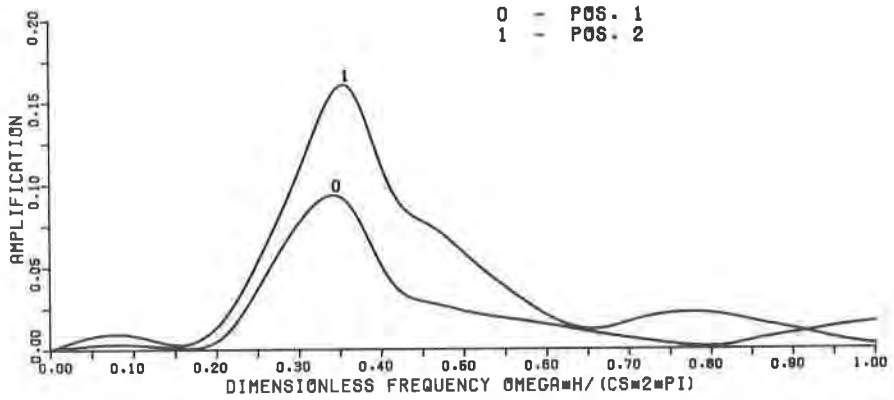


Fig.12 - Reactor building response (misaligned) : base rotational acceleration about x

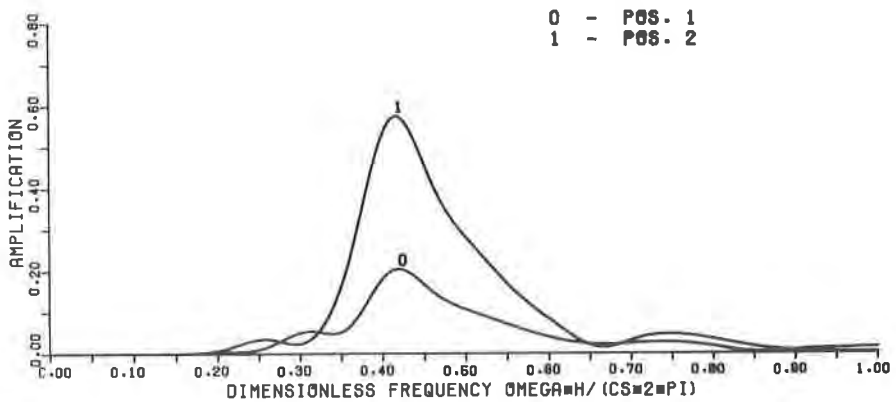


Fig.13 - Auxiliary building response (misaligned) : base rotational acceleration about x

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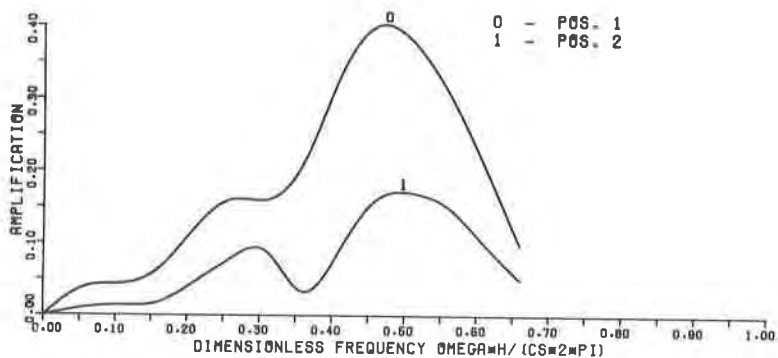


Fig.14 - Reactor building response (misaligned) : base twisting acceleration

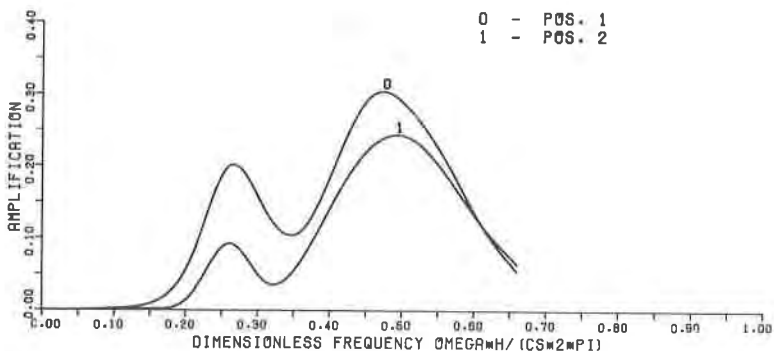


Fig.15 - Auxiliary building response (misaligned) : base twisting acceleration