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Evaluation of Radiation Damping Using 3-D Finite Element Models

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Summary

Current experimental techniques which evaluate the damping characteristics of large nuclear power plant structures in-situ produce estimates of damping for the complete soil-structure system for each response mode that has been excited. These coefficients of total system damping include material and radiation damping contributions, as well as structural damping. Quantifying the correct partition of these damping coefficients into their structural, radiation and material damping components is of interest in order to improve analytic models of structural response.

This paper presents an analytic approach which is being used to quantify the contribution of radiation damping to overall system damping. The approach uses three-dimensional finite element techniques and can easily include details of site geology, foundation shape, and embedment depth. The approach involves performing free vibration response analyses for each soil-structure interaction (SSI) mode of interest. The structural model is specified without damping and, consequently, amplitude decay of the structure's free vibration response is a measure of the radiation damping characteristics of the soil-structure system for the particular deformational mode being investigated.

The computational approach developed is highly efficient in order to minimize the impact of including three-dimensional geometry within the model. A new finite element code, FLEX, has been developed to represent the soil continuum. FLEX uses a highly optimized explicit time integration algorithm which takes advantage of parallel processing on vector machines, such as the CRAY 1 computer. A modal representation of the superstructure is used in combination with a substructuring approach to solve for the coupled response of the soil-structure system. This requires solving for numerical Green's functions for each degree-of-freedom of the foundation (assumed rigid). Once computed for a particular site and foundation, these Green's functions may be used within a convolution integral to represent the continuum forces on the foundation for any free vibration SSI response computation of any superstructure model.

This analytic approach is applied to an investigation of the radiation damping coefficients for the first two fundamental SSI modes of the HDR containment structure.

1. Introduction

An improved understanding of damping and better estimates of damping coefficients are of interest in the design and validation of nuclear power plant structures to withstand seismic hazards. Current experimental techniques which evaluate the damping characteristics of large structures in-situ produce estimates of damping for the complete soil-structure system for each response mode that has been excited. These coefficients of total system damping include material and radiation damping contributions as well as structural damping. Quantifying the correct partition of these damping coefficients into their structural, radiation and material damping components is of interest in order to improve analytic models of structural response.

This paper outlines a numerical approach based on the finite element method which is being used to quantify the contribution of radiation damping to overall system damping. This is done by numerically simulating the free vibration response of the soil-structure interaction (SSI) modes of interest. In these analyses, only radiation damping effects are included within the model. The rate at which structural amplitude diminishes during free vibration response is a measure of the radiation damping of the soil-structure system for the particular deformational mode being investigated. The calculated radiation damping component may be subtracted from the total system damping measured in field tests, leaving a residue composed of other possible damping influences, including structural and material damping. Further study is needed to determine if the remaining damping component can be considered to be purely structural damping (i.e., effectively linearly elastic response of the local site material; therefore, no material damping). This finding may depend strongly on the level of excitation occurring in the field tests.

The finite element procedure illustrated in Fig. 1 is general and can include general site geology, foundation shape and embedment effects. Linear and nonlinear models may be used for both the site and structure. Assuming linear site and structural models allows the substructuring approach shown as one option in Fig. 1. This assumption greatly reduces the cost of large three-dimensional analyses and is the subject of the remaining discussion. In order to minimize the cost of solving such problems, a new computer code, FLEX, has been developed with highly optimized solution algorithms. FLEX has been designed to utilize the increased computing capability of new generation computers, such as the CRAY 1. This paper describes the analytical method and results from a preliminary investigation of radiation damping for the first two SSI modes of the Heissdampfreaktor (HDR) containment structure.

2. Analytic Method

The analytic method makes use of a substructuring approach to the problem of SSI analyses and is applicable for linear models of the site and structure. The continuum is represented by an assemblage of three-dimensional continuum finite elements, while the normal modes of a lumped mass, beam finite element model are used to represent the structure. The foundation of the structure is assumed to be inflexible and is composed of rigid elements.

2.1 Continuum Model

The three-dimensional finite element code, FLEX, has been developed to solve for the dynamic response of the soil continuum. The code uses a highly optimized explicit time integration algorithm and can process 100,000 3-D element time steps per second of CRAY 1 time.

FLEX is used to solve for numerical Green's functions, $[G(t)]$, which represent continuum resistance forces on the rigid foundation in response to a step function in velocity for each foundation degree-of-freedom of interest. Once computed for a particular site and foundation configuration, these Green's functions can be used to represent the continuum forces on the foundation for any free vibration SSI response computation for any superstructure model.

These Green's functions include radiation damping effects. In order to account for radiation damping, adequate absorbing boundaries must be used on subsurface boundaries of the grid in order to avoid trapping radiated energy within the finite element model. FLEX uses the viscous boundary condition of Lysmer and Kuhlemeyer [1].

2.2 Structural Model

The structure is represented by a lumped mass, beam finite element model whose equations of equilibrium are

$$[\lceil M \rfloor]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = \{F\} \tag{1}$$

where x, $\dot{x}$ and $\ddot{x}$ are the displacements, velocities and accelerations of the model and $[\lceil M \rfloor]$, $[C]$ and $[K]$ are the mass, damping and stiffness matrices, respectively. $\{F\}$ is composed of external forces which may vary with time. The equations of equilibrium may also be expressed in terms of the structure's modal degrees-of-freedom (Bathe, Wilson [2]) as

$$\{\ddot{q}\} + [\lceil 2\xi\omega \rfloor]\{\dot{q}\} + [\lceil \omega^2 \rfloor]\{q\} = [\phi]^T\{F\} \tag{2}$$

assuming mass normalized modes, $[\phi]^T[\lceil M \rfloor][\phi] = [\lceil I \rfloor]$, and proportional damping where q, $\dot{q}$ and $\ddot{q}$ are the modal displacements, velocities and accelerations and $[\phi]$ is the matrix of mode shapes. The ξ and ω in eq. (2) are damping ratios and natural frequencies, respectively, for each mode of the system. $[\lceil I \rfloor]$ is the identity matrix.

The free vibration response of the in-situ structure can be found using eq. (2) where the SSI interaction forces are included in the righthand side of the equation. A particular SSI mode of response may be initiated by setting the initial values of $\{q\}$, $\{\dot{q}\}$ and $\{\ddot{q}\}$ equal to the desired set of initial conditions and computing the resulting free vibration response with time.

2.3 Coupling of Structure and Continuum

The coupled response of the soil-structure system requires the inclusion of the continuum forces on the foundation's degrees-of-freedom in the external force vector $\{F\}$. Consequently, $\{F\}$ is a function of time and of the complete previous history of motion of the foundation. $\{F\}$ may be determined by using a convolution integral approach. By convolving the Green's functions, $[G(t)]$, previously computed with the previous history of foundation velocity response, the continuum resistance forces may be determined as

$$\{F(t)\} = \int_0^t [G(t-\tau)]\{\ddot{x}(\tau)\}\, d\tau \tag{3}$$

Eq. (3), when substituted into the righthand side of eq. (2) provides a complete set of equilibrium equations for determining the in-situ free vibration response of the soil-structure system. Radiation damping is implicitly included within the continuum resistance forces. If the modal damping ratios, ξ, are set to zero, radiation damping is the only damping included in the model. Eqs. (2) and (3) together account for the fact that damping in the soil-structure system may be nonproportional. Therefore, the modal equations are coupled through the modal force vector defined by eq. (3). This coupling requires that the system of modal equations be integrated simultaneously to obtain the structure's response.

3. Application

The analytic approach described above has been used to determine the coefficients of radiation damping for the first two in-situ modes of the HDR containment structure (a decommissioned pressurized boiling water reactor in West Germany). The measured mode shapes are shown in Fig. 2 [3]. In the first mode, inner and outer containment structures bend in phase, in the second mode, the inner and outer structures bend out of phase. As expected from the mode shapes, the measured estimates of total damping are higher for the first mode (4.2 percent) than for the second mode (2.1 percent).

A preliminary structural model [4] is shown in Fig. 3, along with its first two fixed base modes. The elastic site model (Kot et al. [5]), derived from seismic surveys of the HDR site, is shown in Fig. 4 along with the complete model of SSI.

The Green's functions for the rigid foundation were computed and then used in the modal solution of the free vibration response of the first two HDR modes. These modes were excited through initial conditions which closely approximate the mode shape desired. The free vibration response of a point on the superstructure for each mode of response is shown in Figs. 5 and 6. Due to coupling of the structural modes through the ground interaction forces and to difficulties in defining initial conditions which excite a single in-situ mode, the responses are not simply damped harmonic motions. Log decrement methods were used to estimate radiation damping coefficients. These are 2.2 percent damping for the primary mode at a frequency of 1.25 Hz and .2 percent damping for the second mode at a frequency of 2.5 Hz. Subtracting these values from measured values of total system damping gives the results shown in Table 1 of about 2 percent critical damping in each mode of response. Further investigation is required to assess whether assuming the entire 2 percent to be structural damping (i.e., material damping is negligible) is valid or whether the structural damping component is actually less than 2 percent.

CPU time required to compute the Green's functions for 3.2 seconds of real time response was 131 CP seconds on a CRAY 1 for each degree-of-freedom of interest. For the HDR analyses, Green's functions for both the horizontal translation and base rotation cases were generated. Computation of the structural model's modes and the complete solution of its coupled free vibration response required 2 CP seconds for each analysis.

Results of the analyses are only as correct as the models being used to generate them. Deficiencies in in-situ frequency response of the beam model used in the analyses have indicated the need to develop an improved beam model of the structure and to investigate any influence this revised model may have on the damping coefficients determined.

4. Summary

Efforts are being made to increase understanding and help quantify the damping characteristics for large containment structures in-situ. Three-dimensional finite element analyses are being performed using FLEX, a highly optimized explicit time integration code in conjunction with a substructuring approach to SSI analysis in order to reduce the cost of three-dimensional solutions. Preliminary results for radiation damping coefficients of the HDR reactor have been evaluated and are being studied.

5. Acknowledgment

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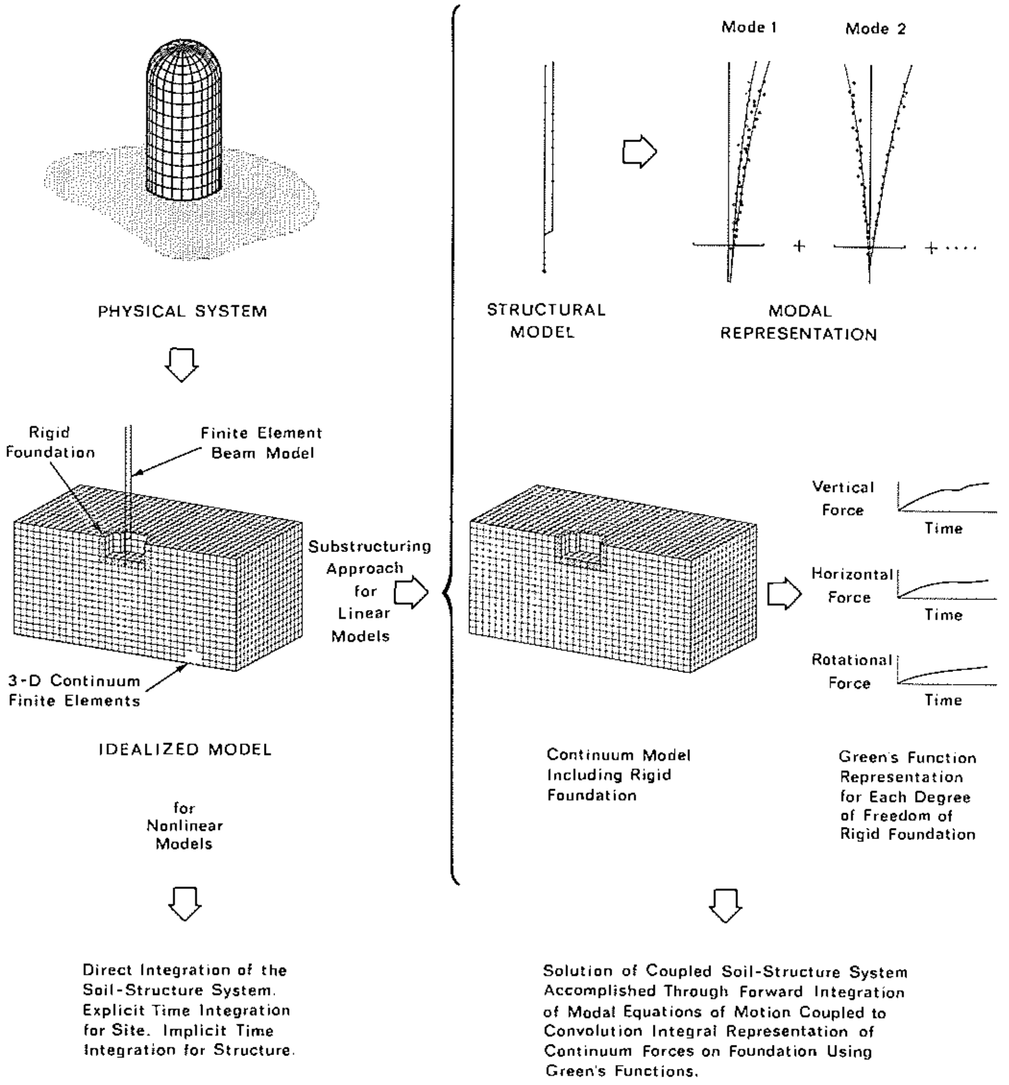
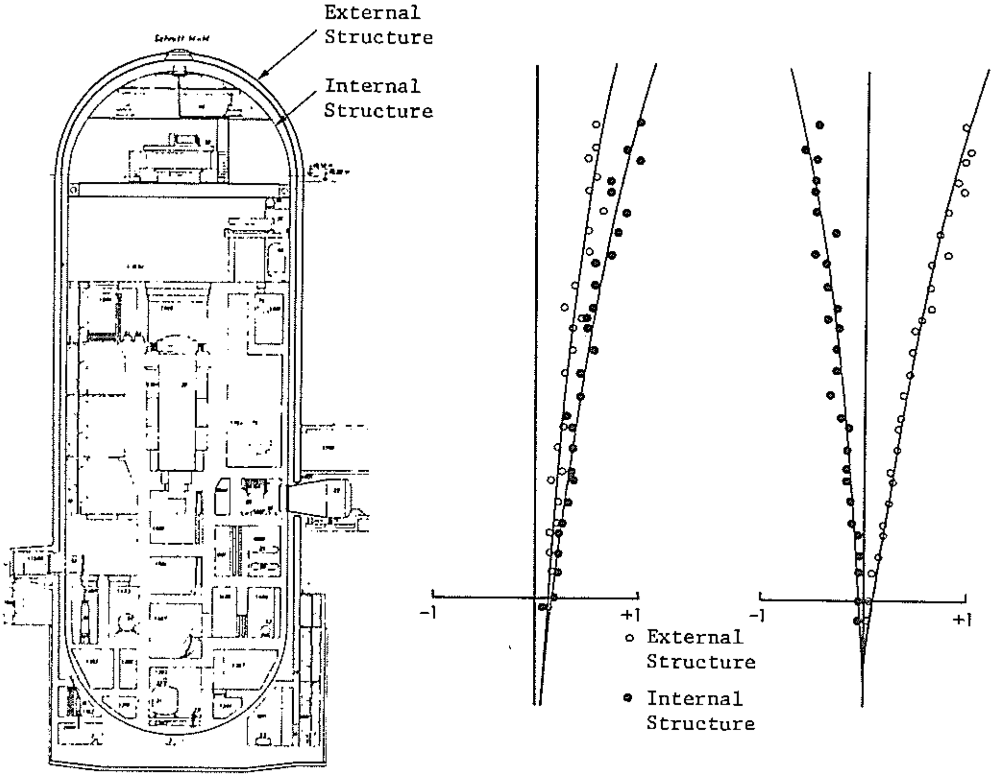
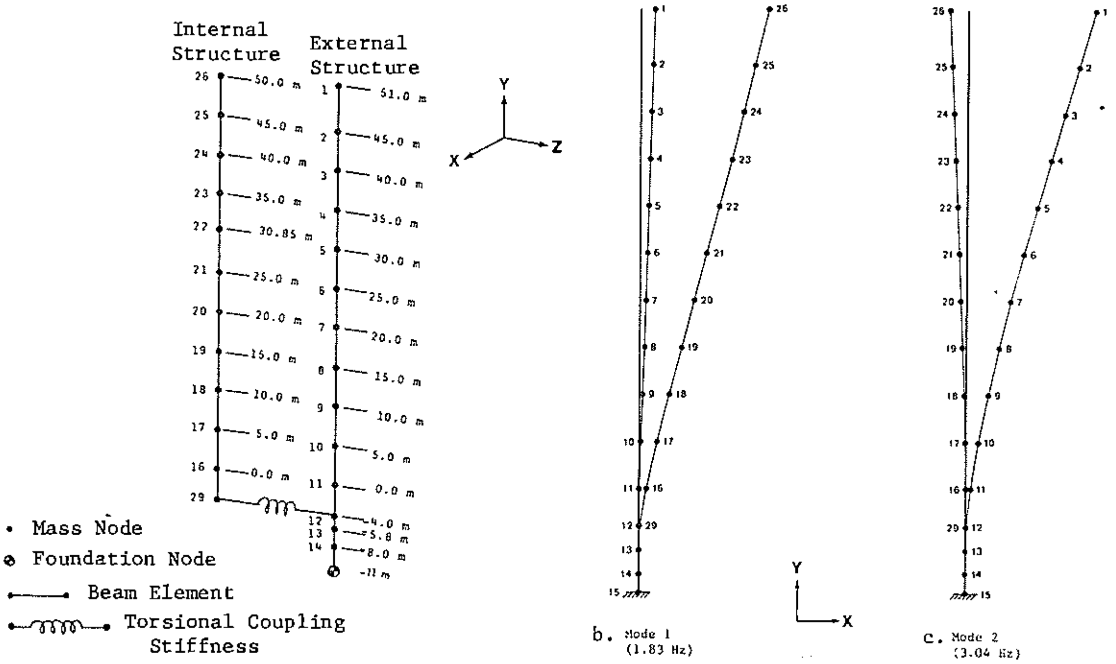


Fig. 1. Approach to solving soil-structure interaction response of nuclear containment structure using finite element models.



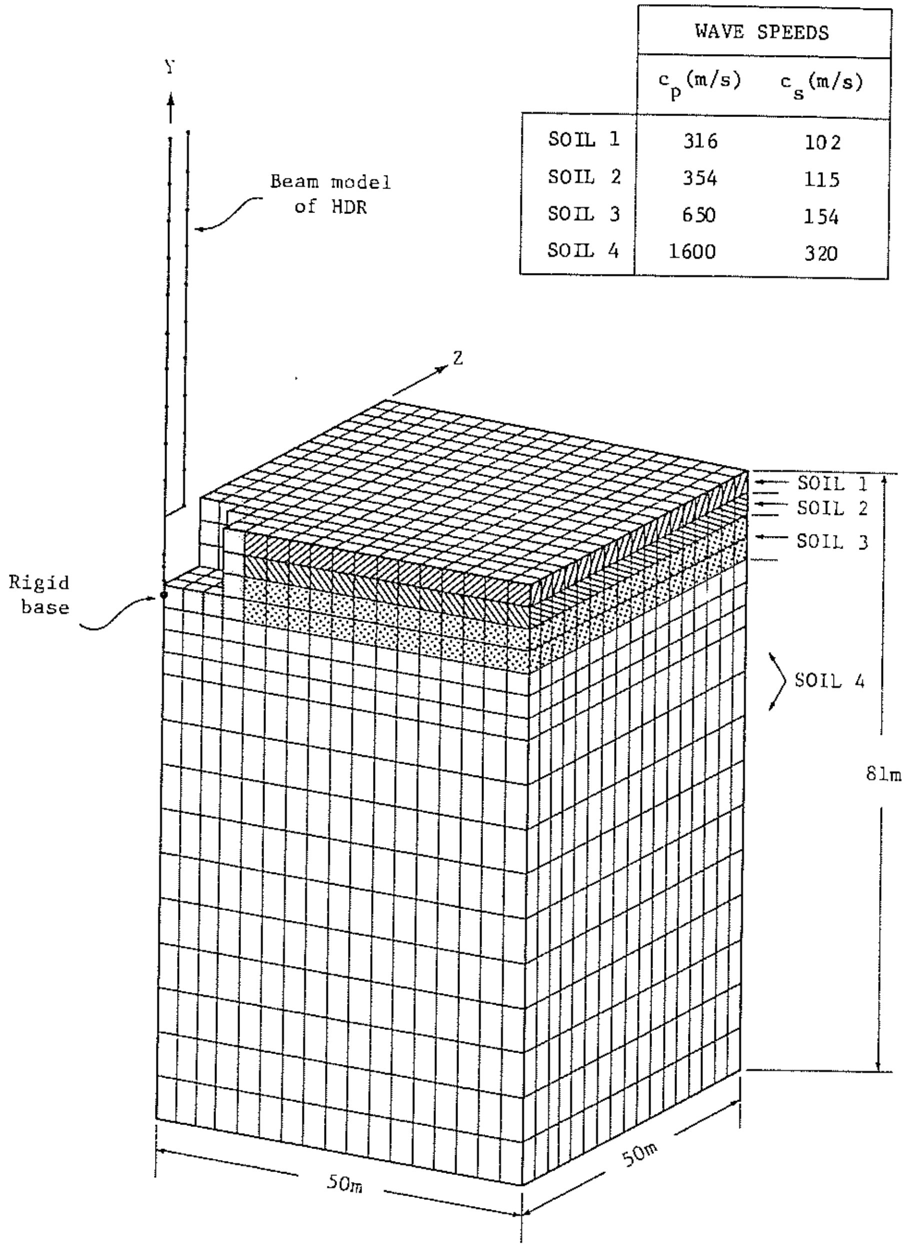
a. Containment b. Mode 1 (1.52 Hz) c. Mode 2 (2.63 Hz)

Fig. 2. HDR containment building and its first two deformational modes (measured in-situ).



a. Beam model b. Mode 1 (1.83 Hz) c. Mode 2 (3.04 Hz)

Fig. 3. Beam model representation of HDR containment building and its first two fixed base modes.



	WAVE SPEEDS	
	c_p(m/s)	c_s(m/s)
SOIL 1	316	102
SOIL 2	354	115
SOIL 3	650	154
SOIL 4	1600	320

Fig. 4. FLEX grid used to compute Green's functions for HDR foundation response (shown with beam model of structure).

Table I

Percent Critical Damping

	Mode 1	Mode 2
Total system damping (measured)	4.2	2.1
Radiation damping (computed)	2.2	0.2
Residual damping (total - radiation)	2.0	1.9

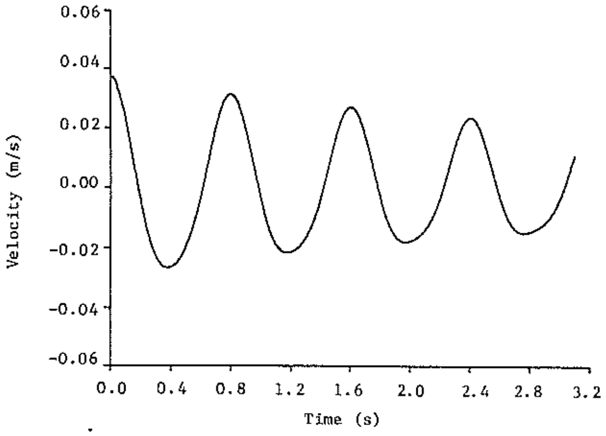


Fig. 5. Free vibration response at top of outer containment (first mode initialized). Radiation damping estimated to be 2.2% of critical.

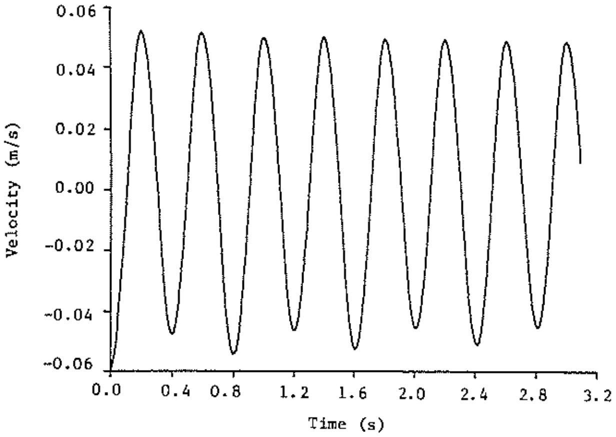


Fig. 6. Free vibration response at operating floor of inner containment (second mode initialized). Radiation damping estimated to be 0.2% of critical.