EFFECT OF CLEARANCE AND DISTRIBUTION OF MASS ON THE DYNAMIC RESPONSE OF AN HTGR CORE

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SUMMARY

One of the primary factors in determining the structural integrity and, consequently, the safety of an HTGR is the dynamic response of the core when subjected to a seismic excitation. The HTGR core can be modeled as a multi-mass system with clearance gaps between adjacent elements and surrounded on its outer periphery by reflector blocks, restraining spring packs, and finally the PCRV vessel. Under operational conditions the magnitude of the clearances change. In addition the total clearance can change substantially during the active lifetime of the fuel elements due to radiation effects.

Earthquake input motions to this type of core arrangement will result in multiple impacts between adjacent elements as well as between the reflector blocks and the restraining spring packs. The highly complex nonlinear response associated with the multiple collisions across the clearance gaps as well as with the spring packs is the subject matter of this paper. Of particular interest is the effect that variations in clearance and the choice of number of masses in the model have on the dynamic response of the HTGR core.

To simulate the response of this system, a model using a single row, or slice, of horizontal elements was adopted for the dynamic investigations. Actual clearances as well as the total mass of a typical horizontal slice were used. The input motion was supplied by the horizontal displacement of the core vessel which in this case was chosen as a sine wave of constant amplitude. However, the frequency of the input was changed for each analysis. Interelemental elastic and damping coefficients were derived from the element geometry and material characteristics. Coefficient of restitution data was obtained from a model test using graphite. The viscous interelemental damping coefficients in the analytical model were adjusted to duplicate the energy dissipated during a collision in the model test. The viscous damping coefficients of the ground-motion dampers were evaluated on the basis that they would dissipate the same energy per cycle as ground friction.

A computer program OSCIL, (BNL-21023, Jan. 1976), was developed to solve for the response of the system. Using the program, the resonant frequency vs clearance characteristics of the system was determined by noting the frequency at which the maximum force is developed across the boundary springs for a given clearance. By varying the clearance from 0 to 130% of nominal (100% clearance corresponds to 4.6 inches for the full core), the dependence of resonant frequency on total clearance is clearly established. Results for the model chosen, with a fixed input amplitude, show that the resonant frequency varies from 11.4 rad/sec for zero clearance (the natural frequency of the linear system) to 2.5 rad/sec at 100% clearance. Thus, the magnitude of clearance in an HTGR core is shown to have a significant effect on its dynamic response.

In order to investigate the effect of mass lumping core response outputs for models of 5, 7, 9, and 30 masses were investigated with the clearance fixed at 100% of nominal. Results show that when the mass systems are excited at their resonant frequency, all of the systems have similar response characteristics. Indeed, under the conditions stated above, the five-mass system has the same natural frequency as the thirty-mass system and develops the same maximum forces. Therefore, for the existing conditions, a reduced-mass model can be used to represent the dynamic response of the more complex system.

1. Introduction

One of the primary factors in determining the structural integrity and consequently the safety of a High Temperature Gas-Cooled Reactor (HTGR) is the dynamic response of the core when subjected to a seismic excitation. The HTGR core under consideration consists of several thousands of hexagonal elements arranged in vertical stacks containing about eight elements per stack. There are clearance gaps between adjacent elements, which can change substantially due to radiation effects produced during their active lifetime. Surrounding the outer periphery of the core are reflector blocks and restraining spring-pack arrangements which bear against the reactor vessel structure (PCRV). Earthquake input motions to this type of core arrangement will result in multiple impacts between adjacent elements as well as between the reflector blocks and the restraining spring packs. The highly complex nonlinear response associated with the multiple collisions across the clearance gaps and with the spring packs is the subject matter of this paper.

Of particular importance is the ability to analyze a complex nonlinear system with gaps by employing a model with a reduced number of masses. This is necessary inorder to obtain solutions in a time-frame and at a cost which is not too extensive. In addition the effect of variations in total clearance as well as the initial distribution of clearances between adjacent elements is of primary concern. Both of these aspects of the problem are treated in the present analysis.

2. Governing Equations and Computer Code

To simulate the response of this multi-mass system, a model using a single row, or slice, of horizontal elements with gaps was adopted for the dynamic investigations. Previous solutions for the dynamic response of an "N" degree of freedom in-line system of masses and springs subjected to a sinusoidal forcing function have been thoroughly investigated in the literature. Further analysis relating to the dynamics of a mass and spring separated by a gap have received considerable attention and the solutions are well documented. However there is little information available on the response of a multi-mass system in which gaps initially exist between adjacent masses and springs and supports. For the case under consideration the actual clearances as well as the total mass associated with a representative horizontal slice were used. A pictorial representation of the analytical model is shown in Figure 1 which depcits an "N" mass model.

The input motion is supplied by the horizontal displacement of the core vessel. The spring packs include the actual elastic members in the core structure as well as the hard elastic stop of the vessel wall itself. Interelemental elastic and damping coefficients are derived from the element geometry and material characteristics. Coefficient of restitution data was obtained from a model test using graphite. The viscous interelemental damping coefficients in the analytical model were adjusted to duplicate the energy dissipated during a collision in the model test. The viscous damping coefficients of the ground-motion dampers were evaluated on the basis that they would dissipate the same energy per cycle as ground friction.

In order to solve for the response of the system, a computer program, OSCIL [1], was developed which is capable of handling configurations up to 70 masses with gaps and includes the interelemental elastic and damping characteristics. The program has the flexibility to handle the inputs and outputs in terms of displacements, velocities, or accelerations as well as forces. If it becomes necessary to accommodate more than 70 masses this can be achieved by increasing the dimensions of the appropriate arrays. The set of coupled differential equations describing the system shown in Figure 1 is given by:

$$M_1\ddot{X}_1 + K_1 (X_1 - XOL) + C_1 (\dot{X}_1 - \dot{XOL}) + K_2 (X_1 - X_2) + C_2(\dot{X}_1 - \dot{X}_2) + CW(1)(\dot{X}_1 - \dot{XOL}) = 0. \quad (1)$$

$$M_i \ddot{X}_i + K_i (X_i - X_{i-1}) + C_i (\dot{X}_i - \dot{X}_{i-1}) + K_{i+1} (X_i - X_{i+1}) + C_{i+1}(\dot{X}_i - \dot{X}_{i+1}) + CW(i)(\dot{X}_i - \dot{XOL}) = 0. \quad \text{where } 2 \le i \le (N-1) \quad (2)$$

$$M_N \ddot{X}_N + K_N (X_N - X_{N-1}) + C_N (\dot{X}_N - \dot{X}_{N-1}) + K_{N+1} (X_N - XOR) + C_{N+1} (\dot{X}_N - \dot{XOR}) + CW(N)(\dot{X}_N - \dot{XOL}) = 0. \quad (3)$$

where XOL, XOR = displacements of left and right driving walls, respectively

M_1, M_N = masses of reflector blocks

M_2, ... $M(N-1)$ = masses of internal blocks

K_1, ... K_N = spring constants

C_1, ... C_N = interelemental spring dampers

CW_1, ... CW_N = ground dampers

The integration scheme used in solving the above equations makes use of the GEAR package written by A. C. Hindmarsh [2]. The package automatically varies the time integration step and the order of integration.

3. Results and Discussion

For this study, harmonic displacements were prescribed as the input by specifying the amplitude and frequency at the reactor vessel wall which is the boundary of the system.

Both numerical and graphical outputs were obtained specifying the displacements and interelemental forces developed for various mass distributions and gap sizes. Results for the lumped mass system under investigation were obtained using the OSCIL Code for the case where total mass, total clearance space, interelemental damping and forcing frequency and amplitude were all held constant. For these runs the total mass was distributed into 5, 7, 9, and 30 individual lumped masses. Results of the analysis are shown in Figure 2, which presents graphical strip charts for reactor vessel inputs as well as core response outputs for the various lumped mass models. In these plots, the strip (or long axis) is the time coordinate, while the dimension across the strip (the short axis) gives the individual mass point displacements. Each mass is represented by a single trace. Where the clearance between adjacent mass points goes to zero, a single trace then shows the path of the clumped masses. In all the strip chart plots, the two boundary or outermost traces, represent the input vessel motions. A comparison of the displacement time-histories of the various mass systems all excited at 11.4 rad/sec, the natural frequency of the identical system without clearance, reveals different response characteristics for the four cases considered. Both the displacements as well as the forces developed vary considerably from case to case. Although only the first five seconds of response are shown in Figure 2, runs have been carried out for as long as thirty seconds [3] with no trend towards any similarity in response developing.

In Figure 3 the dynamic responses of the identical lumped mass systems are shown for an excitation at the resonant frequency (or frequency of maximum response) with all other parameters remaining fixed. It shows that, at this frequency, responses of all the mass systems have similar characteristics. Indeed, under the conditions stated above, the five-mass system has the same natural frequency as the thirty-mass system. In addition, an examination of the forces developed at the wall of the vessel shows that the maximum forces are the same for each of the mass representations. Therefore, at resonance, a model using a reduced number of masses is capable of representing the dynamic response of the more complex system. This is found to be true despite the high degree of nonlinearity associated with a spring characteristic which represents a stiff structural member adjacent to a free space. The importance of this conclusion is clearly demonstrated by the fact that the requirements for computer time would be prohibitive if a model using a reduced number of masses was not applicable. Further study shows that for extended runs at the resonant frequency, starting with different initial positions of the masses, the initial transients have largely disappeared after only ten seconds and identical steady-state motions are obtained. This is shown to be true for the entire spectrum of initial spacing of masses, from equally spaced to all masses clumped together, as long as the total clearance is held constant. This result, which demonstrates that the resonant frequency of the system is not altered if the total clearance is held constant, is also independent of the mass model chosen.

In order to demonstrate the general application of the OSCIL program an earthquake time-history was generated from the ground velocity spectra and applied as an input to a seven-mass core representation. The response to the earthquake excitation is shown in Figure 4 where it is seen that the masses move in a transient fashion. However, it can be noted that they do exhibit essentially resonant behavior at two separate time intervals even though the length of run is for only 10 seconds. At 2.4 seconds, hard contact is made on the left wall. Strong motion continues for about 2 seconds after which time the masses traverse the core gap with less violent motion. Again at 7 seconds, hard contact is established, once more resulting in large forces.

Although the distribution of initial spacing of masses alone does not alter the dynamic response characteristics, varying the total clearance has a dramatic effect on the resonant frequency of the non-linear system for a fixed input amplitude. Starting with a linear system without clearance, the resonant frequency was shown to be reduced by a factor of four as the total clearance was increased to 100% of nominal clearance. The results are plotted in Figure 5 with the resonant frequency dropping from 11.4 rad/sec without clearance to 2.52 rad/sec under conditions of nominal clearance. The procedure clearly establishes the dependence of resonant frequency and the development of peak forces on total clearance. Since during the lifetime of the HTGR core clearances may develop, further runs have been carried out for as much as 130% of nominal clearance [4]. As seen in Figure 5, although a very small clearance induces only slight departures from resonance, as the total clearance increases, the system becomes highly non-linear and the resonant frequency drops off significantly.

In conclusion, the present study demonstrates the successful implementation of an analytical model for the dynamic response of a multi-mass system with gaps such as an HTGR core, by using considerably fewer masses than the actual system, even though the problem is highly non-linear. The reduced mass model is capable of accurately predicting resonant frequencies and maximum induced forces for clearances that vary during the operational lifetime of the system.

References

[1] "OSCIL: One-Dimensional Spring-Mass System Simulator for Seismic Analysis of High Temperature Gas-Cooled Reactor Cores", L. Lasker, Ed., BNL 21023, January, 1976.

[2] "GEAR: Ordinary Differential Equation System Solver," A. C. Hindmarsh, Lawrence Livermore Laboratory, UCID - 30001, Rev. 3, Dec. 1974.

[3] HTGR Safety Evaluation Division, Brookhaven National Laboratory, Quarterly Report, BNL 50460, November, 1975.

[4] HTGR Safety Evaluation Division, Brookhaven National Laboratory, Quarterly Report, BNL 50479, January, 1976.

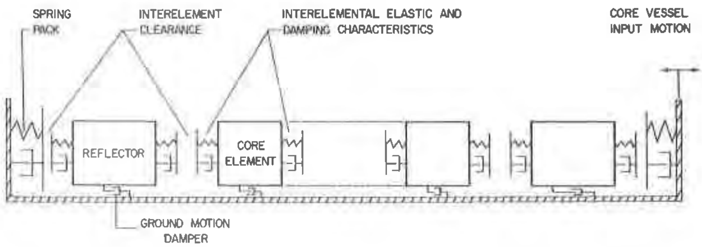

Figure 1 "N" Mass Model

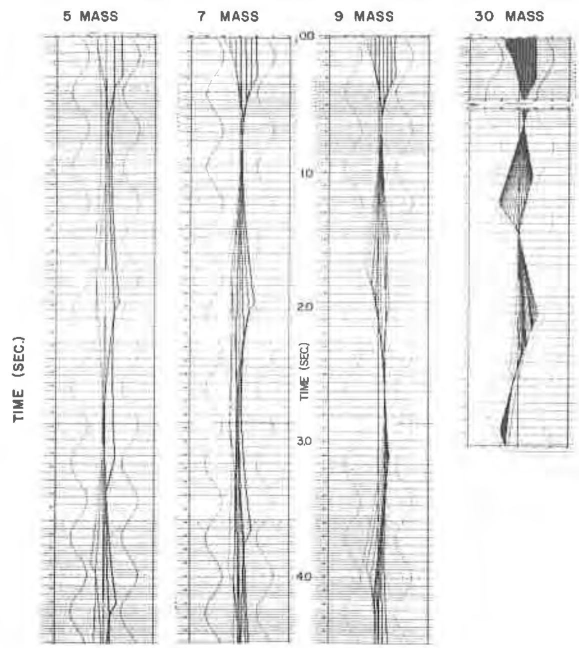

Figure 2 Dynamic Response of Different Mass Models at 11.4 $\frac{rad}{sec.}$

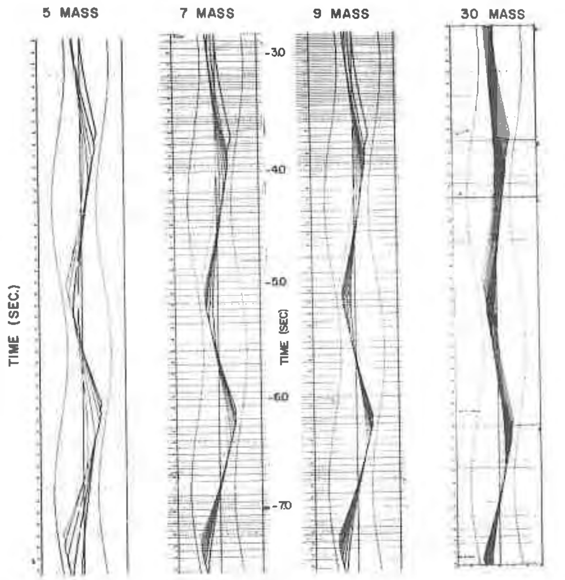

Figure 3 Dynamic Response of Mass Models at Resonance

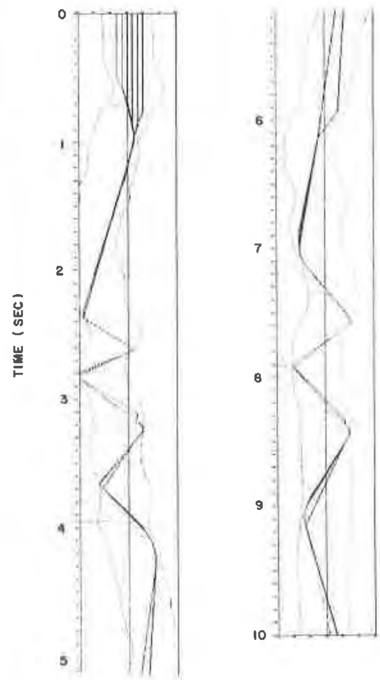

Figure 4 Core Response to Seismic Event

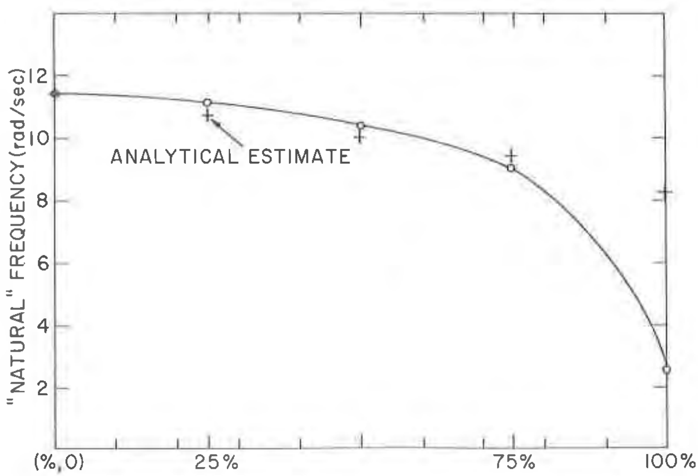

Figure 5 Natural Frequency vs. Clearance