CONF-790800--8

BNL-NUREG-25845

A THREE-DIMENSIONAL COMPUTER CODE FOR THE NONLINEAR DYNAMIC RESPONSE OF AN HTGR CORE

M. Subudhi, L. Lasker, B. Koplik, J. Curreri, H. Goradia

Structural Analysis Group
Department of Nuclear Energy
Brookhaven National Laboratory
Upton, NY 11973
U.S.A.

Abstract

A three-dimensional dynamic code has been developed to determine the nonlinear response of an HTGR core. The HTGR core consists of several thousands of hexagonal core blocks. These are arranged in layers stacked together. Each layer contains many core blocks surrounded on their outer periphery by reflector blocks. The entire assembly is contained within a prestressed concrete reactor vessel. Gaps exist between adjacent blocks in any horizontal plane. Each core block in a given layer is connected to the blocks directly above and below it via three dowell pins.

The present analytical study is directed towards an investigation of the nonlinear response of the reactor core blocks in the event of a seismic occurrence. The computer code is developed for a specific mathematical model which represents a vertical arrangement of layers of blocks. This comprises a "block module" of core elements which would be obtained by cutting a cylindrical portion consisting of seven fuel blocks per layer. It is anticipated that a number of such modules properly arranged could represent the entire core. Hence, the predicted response of this module would exhibit the response characteristics of the core.

The basic block element employed is a finite discrete mass having five degrees of freedom, rotations about the vertical axis being excluded. The governing equations for each mass contain terms from the inertia effect, the restoring forces, and the surrounding wall input forces. This program sets up five second order ordinary differential equations for each mass, which are further broken into ten first order ODE's. The GEAR, multistep integration package for stiff ODE, was used for solving these equations.

A basic force algorithm is written for vertical force and for horizontal plane forces for a typical layer of blocks. Each layer of seven hexagonal blocks is arranged with one in the center surrounded by the remaining six. The entire module is contained in an 18-faced constraint wall. The wall can move with any assigned input time history.

In any horizontal layer, there are sixty separate surfaces for any potential contact between any two adjacent surfaces. When such contact occurs, the blocks involved experience a compressive force between them. Since this force is equal and opposite in nature, it need not be calculated twice for individual surface points of contact whenever two adjacent blocks are involved. Each block face contact is simulated by two gapped-restoring elements attached at the top and bottom ends of the block. These restoring elements are arranged among the seven blocks in such a way that for any layer there exist thirty independent interelement forces to be calculated at each end of the block. In case of vertical forces each block is attached with six vertical restoring elements at the six corner points. It should be noted that each restoring element has gap elements in the springs and exhibits only compressive action.

The results obtained were compared with those derived from an existing two-dimensional code (OSCVERT). In one plane of symmetry there are three masses whose motions simulate close to the two-dimensional results. However, a coupling from the third direction has been indicated from the three-dimensional results.

Work performed under the auspices of the U.S. Nuclear Regulatory Commission.

1. Introduction

This paper describes a three-dimensional FORTRAN computer code (OSC3D) which was developed to determine the nonlinear response characteristics of an HTGR core. OSC3D is an extended version of two existing codes OSCIL and OSCVERT [1] designed to predict the dynamic response of a horizontal one-dimensional nonlinear spring-mass system and a two-dimensional system including large planar rotations respectively.

The HTGR core shown in Fig. 1 consists of several thousand hexagonal core blocks surrounded on their outer periphery by reflector blocks. Several investigators [2,3,4] have studied the nonlinear dynamic response of these blocks by analyzing simple one- or two-dimensional mathematical models as well as by performing scale model tests with models simulating either a vertical or horizontal plane of the core. The present study involves a step advance of the previous attempts by considering an analytical model which consists of several layer of blocks, each layer having seven blocks in a horizontal plane. Each block possesses two horizontal and two rotational degrees of freedom coupled with the vertical degree of freedom, the rotation about the vertical axis being excluded.

Fig. 2 shows a horizontal slice of the entire core. The view indicates that the fuel blocks in each layer are arranged in approximately 55 block cells, each cell consisting of seven blocks. The present analytical study is directed towards an investigation of the nonlinear response of one such block cell in the event of a seismic occurrence. The computer code is developed for this specific mathematical model which represents a vertical arrangement of layers of blocks. This comprises the "BLOCK MODULE" of the core elements which would be obtained by cutting a cylindrical portion consisting of seven fuel blocks per layer. In other words, a number of such modules properly arranged could represent the entire core. Hence, the predicted response of this module would exhibit the response characteristics of the core.

2. Model Description

Fig. 3 shows a 'block module' with four layers. Each layer of seven hexagonal blocks is arranged with one in the center surrounded by the remaining six. The entire module is contained in a constraint wall having 18 faces as shown in Fig. 4. Gaps exist between adjacent blocks in any horizontal plane. Each core block in a given layer is connected to the blocks directly above and below it via dowell pins. The bottom most layer is connected to the constraint wall via dowell pins. The wall can move with any assigned input time history.

The basic block element employed is a regular hexagonal solid element with an equal side length of 'b' and height of '2h'. It is a finite discrete mass having five degrees of freedom, rotations about the vertical axis being excluded. It is modelled with springs and dampers to simulate the stiffness effects of the finite body at the time of impact with the adjacent blocks. Each block has sets of such restoring elements at its top and bottom face levels. One dowell pin, instead of three as in the case of a real block, is attached at the center of the lower face at each block.

A basic force algorithm was written for vertical and horizontal plane forces for a typical layer of blocks. In the case of vertical forces each block has six equal vertical restoring elements, each defined by a linear spring and a damping coefficient attached to its bottom face. These and in fact all restoring elements are designed to develop a displacement and velocity dependent restoring force when under a state of compression but null force when under tension (i.e., under tension a gap forms between adjacent elements). The six elements are located at the six corner points of the hexagonal base.

In any horizontal layer as shown in Fig. 4, there are sixty separate surfaces for potential contact between adjacent surfaces. This includes seven masses with six faces each and an 18-faced constraint wall. Each block face contact is simulated by gapped-restoring elements attached at the top and bottom of the block, which exhibit only compressive force to the surfaces in contact. There exists initial gaps in these restoring elements because of the actual core block arrangements. Two kinds of contacts can occur during the dynamic motion of the module: One between two adjacent block faces and the other between a block face and the constraint wall face. Thus there exist thirty independent interelement contact forces to be calculated at each layer of the block module as can be seen from Fig. 4. In order to calculate these independent forces, the restoring elements are arranged among the blocks in a definite fashion. The algorithm adopted is shown in Fig. 4. The face identification number of each block and the block identification numbers are also indicated in the sketch. For the six outer blocks, the face number corresponding to the block identification number does not possess any restoring element since the force on this face is calculated from the adjacent block which has the restoring element. Also, the central block (#7) does not have any restoring elements attached to it since the faces adjacent to it already possesses these from the outer blocks. Thus only the outer six blocks with five restoring elements in each need be considered for the force calculations. Since these forces are equal and opposite in nature, they need not be calculated twice for individual surface points of contact whenever two adjacent blocks are involved. When the contact occurs between the wall and a block face, the motion of the wall is transmitted to these adjacent blocks via these restoring elements.

The dowell pins, three per element in a real core, are represented by a single central pin having the circuler restoring elements with gaps. The pin forces are calculated in a fashion similar to above. Interelement pin clearance is present and the function of pins is to keep the column aligned in the vertical direction while however inducing rotations.

3. Governing Equations of Motion

In all the restoring elements, spring constants simulate the elastic properties of the core blocks. The dynamics of the system is determined by the solution of the set of second order nonlinear ordinary differential equations. These governing equations are given by

$$M_i \ddot{X}_i + R_i\,(X_1 \ldots X_N,\quad \dot{X}_1 \ldots \dot{X}_N) = F_i\,(X_W, \dot{X}_W) \qquad (1)$$

$$i = 1,2 \ldots N$$

where

- M_i - generalized mass
- X_i - generalized displacement of a mass (degree of freedom)
- $\dot{X}_i$, $\ddot{X}_i$ - generalized velocity and acceleration respectively
- R_i - total generalized restoring forces in the direction of X_i of the corresponding mass
- X_W, $\dot{X}_W$ - generalized displacement and velocity of the constraint wall
- F_i - total disturbing forces exerted by the constraint wall in the direction of X_i of the corresponding mass
- N - total number of differential equations for a 'block module' under investigation and equal to (5 x n) where 'n' is the number of blocks in the module

Each additional layer adds 35 equations to the system. Each restoring force equation has many terms arising from the base springs, dowell pins, corner springs and gravity. The governing equations for each mass contain terms from the inertia effect, the restoring forces, and the surrounding wall input forces.

4. Numerical Methods

In OSC3D five second order ordinary differential equations are developed for each mass. These equations fall into the class of stiff differential equations as defined by GEAR [5]. These five second order equations are further broken into ten first order ODE's. The GEAR, multistep integration package for stiff ODE written by A. C. Hindmarsh [6], was used for solving these equations. Use of this method was necessary to ensure convergence and numerical stability of the solutions and it is a major improvement over other single step methods.

A prime feature of GEAR is its ability to solve stiff ODE problems. A set of equations is called stiff if it involves both very rapidly changing terms and very slowly changing terms, all of a decaying nature. In other words, the eigenvalues of the Jacobian matrix have negative real parts. Again the property of stiffness is local, a problem may be stiff in some regions of 't' and not in others. The difficulty with stiff problems is that most conventional methods for solving the ODE's require incremental values of 't' commensurate with the minimum time constant, while the total time range of the problem is commensurate with the maximum time constant. As a result, the problem cannot be run to completion in a reasonable number of steps. With GEAR's methods, the time step can take very small values in order to achieve the convergence and stability of the solution. Moreover, the GEAR package contains variants of Newton's method for iteration purposes to solve stiff systems. It was found that for the type of system under consideration, GEAR had the best capabilities for solving the ODE's.

5. Results and Conclusions

Several test runs were made in order to check the reliability of the solutions. The results of a single layered case with sinusoidal wall motion was compared against an equivalent two-dimensional model computer results, for which were obtained using the existing OSCVERT code. Blocks 6, 7 and 3 shown in Fig. 4 correspond to the three masses of the 2D model. The results were published in a quarterly progress report [7]. For the inital time steps there is an excellent correlation between the two results. As the time advances, the effects from the motion of blocks 1, 2, 4 and 5 alter the displacement characteristics of the central three blocks. In addition, strong coupling from the third direction was noticed in the block motion.

The results of a three layered system subjected to a sinusoidal wall motion at a frequency of 8 cps and 0.25 inch amplitude are displayed in Figs. 5 through 7. These are three-dimensional plots showing the two horizontal block responses (i.e., U- and V-directions) as functions of time. In this particular case the wall motion is limited to a horizontal displacement in the U-direction. These time dependent 'snake curves' confirm the anticipated harmonic response characteristics to a period excitation. The sharp changes in these 'snake curves' indicate the collisions either between two blocks or a block and the constraint wall. Again, the uppermost layer experiences larger and more pronounced displacements as compared to the lower layers. The symmetry between the blocks 1 and 5, 2 and 4 can also be noted.

With regard to execution time, it varies widely depending on problem size and the number of collisions occurring in each time step. In particular, addition of the third dimension causes a great increase in the number of collisions. When a collision occurs, the time for convergence is considerably increased. As an example, the above mentioned problem which constitutes 210 first order ODE's required an average computer time of 150 seconds for executing one time step of 0.01 second.

The code has been programed to permit the analysis of a 10 layered system, the actual core height. However, owing to the large storage requirements, the presently operational version of the code is only suitable for configurations of up to five layers. Even at this level, it was necessary to store the large Jacobian matrix array of the GEAR package in an out-of-core large core memory device. Some storage optimization through the use of a modified GEAR package using a block storage format might be possible.

In conclusion, the program OSC3D successfully incorporates all the features needed for the analysis of a three-dimensional model of an HTGR core. The solutions have been found to converge and are numerically stable. It remains to thoroughly proof test the code by conducting long time runs of multi-layer block configurations. These results will then be verified against experimental results developed with a three-dimensional vibrations' test rig. Eventually, this code will be used in future studies to investigate the effects of a seismic disturbance of the constraint wall. Also, the interaction behavior of block responses will be studied when both horizontal and vertical wall motions are applied simultaneously.

6. References

[1] LASKER, L., BEZLER, P., CURRERI, J., KOPLIK, B., "OSCIL and OSCVERT: Computer Codes to Evaluate the Nonlinear Seismic Response of an HTGR Core," Trans. of the International Conference on SMiRT, San Francisco, CA, paper No K7/2, August 1977.

[2] LEE, T.H., WESLEY, D.A., "Seismic Response of a Stacked HTGR Fuel Column Interacting with a Control Rod," Trans. of the International Conference on SMiRT, San Francisco, CA, paper No K7/6, August 1977.

[3] ISHIZUKA, E., et al. "Basic Study on Seismic Response of HTGR Core," Trans. of the International Conference on SMiRT, San Francisco, CA, paper No K7/9, August 1977.

[4] BEZLER, P., CURRERI, J., "Subharmonic Excitation in an HTGR Core," Trans. of the International Conference on SMiRT, San Francisco, CA, paper No K7/4, August 1977.

[5] GEAR, C.W., "The Automatic Integration of Ordinary Differential Equations," Comm. of ACM, V 14, No. 3, March 1971.

[6] HINDMARSH, A.C., "GEAR: Ordinary Differential Equation System Solver," Lawrence Livermore Laboratory Report UCID-30001 (Rev. 3), December 1974.

[7] SUBUDHI, M., et al. Reactor Safety Research Programs: Quarterly Progress Report for the Period October 78 - December 78. A BNL Report (to be published).

2-1033-79

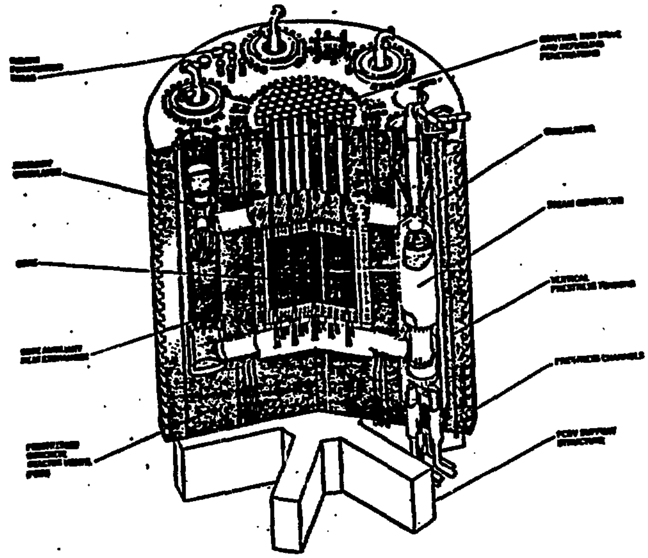


Fig. 1 HTGR NUCLEAR STEAM SYSTEM.

2-1034-79

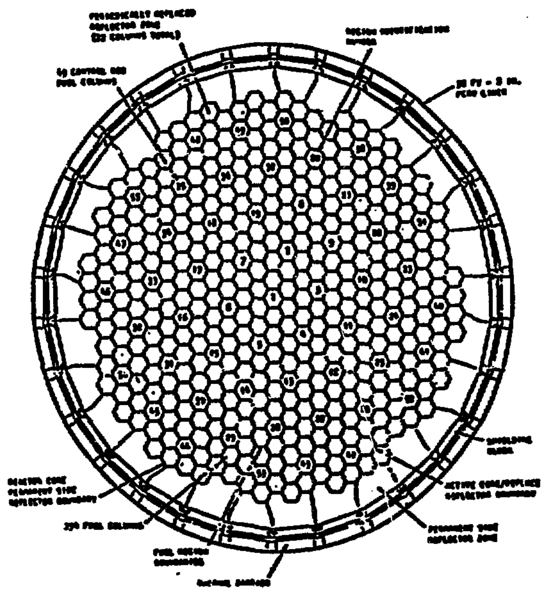
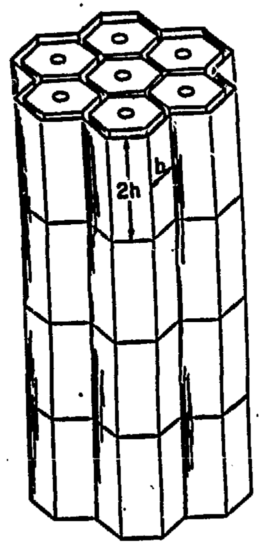
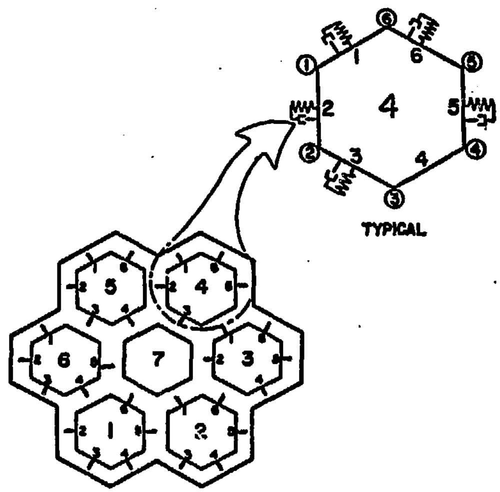


Fig. 2 PLAN VIEW OF THE REACTOR CORE



2-999-79

Fig. 3 A BLOCK MODULE WITH FOUR LAYERS



2-1000-79

Fig. 4 HORIZONTAL ARRANGEMENT OF BLOCKS WITH RESTORING ELEMENTS

U-V DISPLACEMENT VS TIME

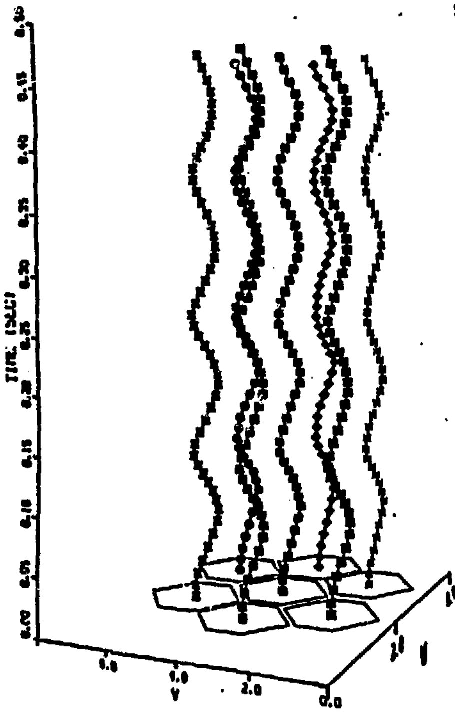


Fig. 5 HORIZONTAL RESPONSE OF BOTTOM LAYER

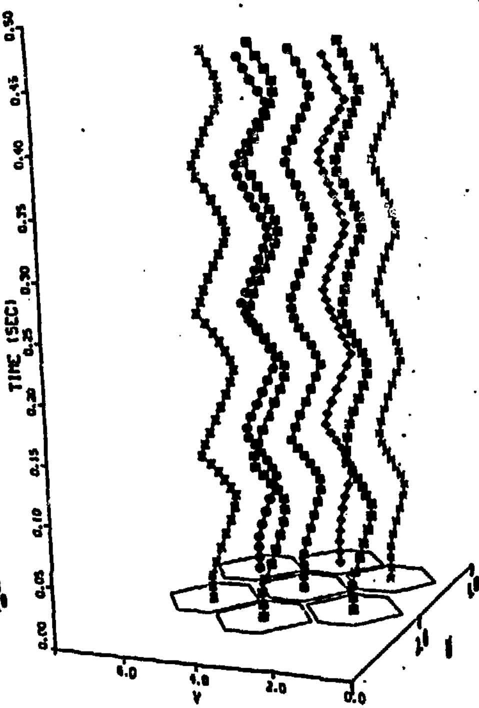


Fig. 6 HORIZONTAL RESPONSE OF MIDDLE LAYER

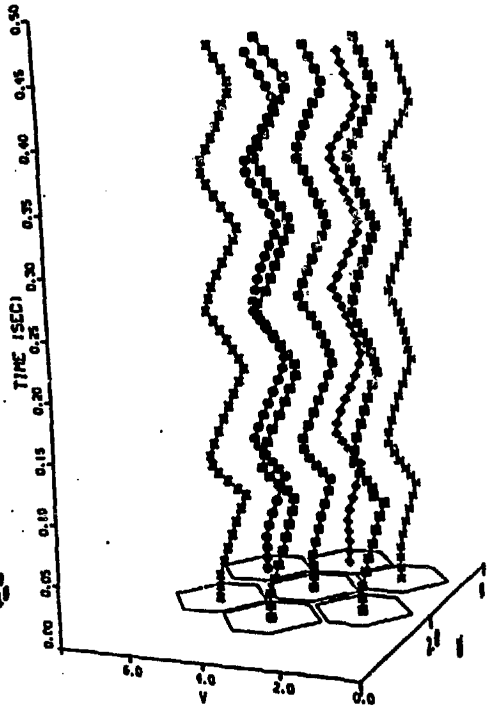


Fig. 7 HORIZONTAL RESPONSE OF TOP LAYER