The Use of MSC/NASTRAN to Determine the Impact Response of a Reactor Core Due to Seismic Loading

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ABSTRACT

The finite element analysis methodology used to determine the nonlinear mechanical response of pressurized water reactor (PWR) fuel assemblies is described. The models include nonlinearities such as impacting among the various structural components and permanent deformation of fuel assembly spacer grids during impact loading. The primary results obtained are fuel assembly impact forces and spacer grid crushing loads. The fuel assembly is modeled using a modal synthesis simulation. A combination of finite element representation of the fuel assembly and experimental results is used to develop this model. The synthesized fuel assembly is then combined with nonlinear spacer grid models to form the overall core response model for evaluation with MSC/NASTRAN. The applicability of this finite element analysis methodology is demonstrated by evaluation of a Nuclear Regulatory Commission (NRC) standard problem.

INTRODUCTION

Advanced Nuclear Fuels Corp (ANF) has a wide product range of fuel assemblies for use in commercial reactors. Each fuel assembly contains Zircaloy-clad UO_2 fuel rods in an array that can vary from 8x8 to 17x17 depending on the fuel assembly type. These are retained in a structure of Zircaloy or Inconel spacer grids attached to Zircaloy guide tubes. The spacer grids are spaced along the length of the fuel assembly to separate the fuel rod array. The guide tubes are mechanically fastened at each end to stainless steel tie plates which interface with the core support plates.

As part of the ANF reactor core safety analysis, a program was established to identify the dynamic characteristics of the fuel assembly and its interaction with the reactor core. Determination of the fuel assembly response to impact with adjacent fuel assemblies is important to satisfy the condition that no breach of the fuel rods will occur and that the insertion of control rods or blades will not be prevented.

The analysis methods and results presented in this paper are for a NRC PWR standard problem. A flow diagram depicting the analysis procedure is shown in Figure 1.

REACTOR CORE AND INPUT LOADS

The reactor core for the standard problem consists of thirteen (13) fuel assemblies with five (5) fuel assemblies on the largest diameter. The gaps between the peripheral fuel assemblies and the baffle or core barrel are 0.06 inches, the gaps between the fuel assemblies are 0.03 inches. Figure 2 shows the reactor core's cross section and the direction and phasing of the input displacements to the core support plates and core barrel. The assumed input displacement function is analytically defined below:

$$X(t) = 0.20 \sin 20.0t + 0.10 \sin 100.0t - 0.0259 \sin 540.0t \qquad (1)$$

The displacement function is a combined sine wave having three components with the frequency content of 3.2, 16 and 86 hz. A time delay of 0.006 seconds is imposed on the displacement functions applied to the upper and lower core plates.

FUEL ASSEMBLY DESCRIPTION

The fuel assembly's length and spacer locations are shown in Figure 3. The fuel assembly's weight is 1,855 lbs with its mass distribution given as lumped masses located at nodal locations. The cross sectional dimensions of the fuel assembly (such as cladding diameters) are not given because the standard problem is setup so that the primary deformations of the fuel assembly can be modeled with prescribed fuel assembly characteristics. Accordingly, for this solution to the problem, the stiffness characteristics are defined by the clamped-clamped natural frequencies of 3, 5, 7, 9 & 11 hz.

SPACER GRID DESCRIPTION

Schematic diagrams for the standard problem's load deflection characteristics of the spacer grid are shown in Figure 4. The in-grid deflections are the deflections of the fuel rods with respect to the spacer grid. The through grid deflections represent the distortion of the spacer grid. Both the in-grid and through-grid spacer load-deflection responses are considered. The through-grid stiffness is represented by a bi-linear spring which represents the possible collapse of the spacer grid. Viscous damping values are also given for the in-grid and through-grid loading conditions. The viscous damping in the through-grid response is only activated when the gaps between the spacers are closed.

FORMULATION OF THE REACTOR CORE MODEL FOR EVALUATION WITH MSC/NASTRAN

The structural reactor core model for a row of fuel assemblies with core plate motion excitation and assembly-assembly or assembly-core barrel impact can be evaluated with MSC/NASTRAN.(1) Linear scalar elements are used to represent the modal dynamic damping characteristics. The modal shape functions are used to relate the modal and physical coordinates. The modal dynamic characteristics of the fuel assemblies are transformed into mass, damping and stiffness matrices in terms of the physical coordinates with the multiple restraint conditions. The impact forces acting on these assemblies from the grid spacer and gap impact requires the use of non-linear scalar elements evaluated in terms of the physical coordinates. The resultant system structural model considering the excitation by the motion of the core plates can be evaluated using the existing features of the MSC/ NASTRAN code. The five fuel assembly reactor core model is shown in Figure 5.

STRUCTURAL MODEL FOR THE IMPACT RESPONSE OF THE SPACER GRIDS

The fuel rods and control rod guide tubes are separated by spacer grids. The outer surfaces of these spacer grids extend beyond the bounding surfaces of the fuel rods and are laterally aligned with one another. Thus, the spacer grids are the structural components that contact one another or the core barrel when the lateral excitations of the fuel assemblies are sufficient to cause impacts. The spacers are fabricated from thin strips and contain springs and dimples which space the fuel rods. Thus, the grid spacers are flexible structures which can deform with respect to their bounding strips with this deflection called the through-grid deflections. The relative spacing of the fuel rods and the bounding grid structure are called the in-grid deformations. The majority of the mass of the fuel assembly is situated in the fuel rods. The spacer grid impact model has low mass or inertial loads associated with its deflection.

To model the effects of the gaps, in-grid and through-grid deformations and damping requires a multi-element non-linear model for the spacer grid impact model. The application of this model requires that an additional coordinate be assigned to each spacer. The system model can be formulated for the through-grid response in terms of relative displacements of these extra coordinates. The spring in the through-grid model is active only when the gap between spacers is closed and is bi-linear to account for the collapse or buckled response. The dash pot in this model is also non-linear in that it is only activated when the gap is closed. The schematic representation of the non-linear through-grid model is presented in Figure 4. The MSC/NASTRAN card images for this model are similar to those given in Reference 4. The negative spring concept was used to improve numerical stability. The non-linear damper was set up using NOLIN2 as a switch. The deformations of the fuel assembly are associated with the movement of the fuel rods. The fuel rods are connected to the spacer grid structure locations by the in-grid stiffness, which accounts for the relative movement of the fuel with respect to the spacer grid.

STRUCTURAL MODEL OF THE FUEL ASSEMBLY USING THE MODAL SYNTHESIS METHOD

ANF's general evaluation model uses the modal synthesis approach to develop the structural model for the fuel assembly. In the modal synthesis representation, the vibrational modal shapes and frequencies of the structure in a selected frequency range are used as the degrees of freedom. This type of structural representation permits the number of degrees of freedom of the structural or physical model to be reduced while the accuracy of the dynamic response in the selected frequency range is maintained. The modal representation also facilitates the use of dynamic test data in adjusting model coefficients.

Either an eigenvalue analyses or experimentally determined results that yield the natural frequencies and mode shapes can be used to form the modal representation of the structure. Reference 2 describes ANF's modal analysis and test methods.

Use of the fuel assembly represented by its vibration modes in the reactor core model requires information about the relation between the fuel assembly modal excitation and the physical motions at the core plate supports and at spacer locations. The required data for this modal modeling procedure are the natural frequencies, the mass normalized modal matrix or eigenvectors $[\phi_{ci}]$, and the modal damping. The displacements at connection boundaries and at spacer locations are designated by $\{X_c\}$. The displacements of these points are related to the modal coordinates $\{\xi_i\}$ of the fuel assembly by:

$$X_c = [\Phi_{ci}]\{\xi_i\} \qquad (2)$$

The displacements at the grid locations are required to determine impact forces between spacers or between spacers and the core barrel.

A modal matrix $[\phi]$ was constructed using a free-free uniform beam with modal shape functions that define seven nodal displacements and two rotations in terms of the modal degrees of freedom. Uniform beam segments with lumped masses and rotational inertias were used in the model for the mass inertial properties. This resultant modal matrix may be used to represent the frequency response for a clamped-clamped uniform beam since the non-zero natural frequencies for the two sets of boundary conditions are identical. In the ANF analysis procedure, the boundary coordinates are not fixed as they are for the clamped-clamped boundary condition but must be free to use the general ANF evaluation procedure to satisfy input displacement conditions at the core plates. The rotational coordinates however are fixed for the reactor structural model application and are fixed in the solution procedure by restraint equations. Because of the need to subsequently prescribe the boundary conditions, the modal model of the free-free fuel assembly is modeled in the sample problem with two free body modes and seven modal frequencies which are related to the seven translation and two rotational coordinates. The end translation and end rotation coordinates are explicitly included to allow for the satisfaction of boundary conditions. Figure 7 shows the modal matrix $[\phi]$ which was calculated with the MSC/NASTRAN code. This matrix was taken from the eigenvalue analysis (natural frequency) of a uniform beam representing the NRC sample problem.

This modeling procedure was applied for the standard problem. The generalized dynamic properties were determined for the fuel assembly shown in Figure 3. Equation (2) provides the basic relations needed to transform the modal synthesis model to the physical coordinates at the connection points and spacer locations. This modal synthesis model is used to represent each assembly in the reactor core model (see Figure 5). Multiple constraint equations in MSC/NASTRAN are used to transform the modal coordinates to the physical coordinates that are used to account for the spacer grid interaction and core plate motion. See Reference 1, Section 14.1 for additional information about this method.

DIRECT TRANSIENT ANALYSIS PROCEDURE

The final set of equations of motion in physical coordinates for the five assembly model shown in Figure 5 which includes the spacer grid non-linear force from Figure 4 is:

$$[M]\{x\} + [B]\{\dot{x}\} + [K]\{x\} = \{P_1(t)\} + \{P_n\} \tag{5}$$

where:

$[M]$ = mass matrix

$\{x\}$ = a set of physical coordinates expressed as a column matrix of one term for each node point

$[B]$ = damping matrix

$[K]$ = stiffness matrix

$\{P_1(t)\}$ = is the time-dependent applied force vector

$\{P_n\}$ = is a vector of non-linear forces which are a function of $\{x\}$ and $\{\dot{x}\}$ to model the gaps and one way impact damping

The Direct Transient Analysis capability Rigid Format No. 27 of MSC/NASTRAN was used to solve the equations of motion. MSC/NASTRAN Rigid Format No. 27 was used to evaluate the impact between fuel assemblies. The applied non-linear forces, P_n are evaluated with this option as the variations from a linear response for the spacer grid elements shown in Figure 4. This solution technique eliminates the traditional approach of re-formulating the stiffness matrix for each successive time step. Rigid Format No. 27 uses the Newmark-Beta(1) direct integration procedure.

A nominal time step of $\Delta t = 0.1$ ms was used for these analyses. The effect of this time step on the Newmark-Beta integration procedure was checked by making comparative runs with the time step altered by $\pm$ 25% Δt. The results from these runs were approximately identical and no convergence or stability problems were encountered.

ANALYSIS RESULTS

The response evaluation of the core structural model shown in Fiqure 5 was performed using the sine forcing function given in Equation (1). The maximum inputs are:

Displacement	.326 in	(.0828 m)
Velocity	26.35 in/sec	(6.69 m/sec)
Acceleration	22.22 g's	(22.22 g's)

The forcing function fuel assembly and baffle displacements were applied for 0.5 seconds and the maximum grid impact forces were assumed to occur during this period. The maximum grid impact force at midplane for this asymmetric loading is 3,657 lbs. (16,266N), as shown in Table 1.

When the grid impact forces exceed 2500 lbs (11,120 N) it indicates that the bi-linear property of the spacer grid was used, see Figure 4. The dynamic response of the fuel assembly No. 11 at the mid plane spacer with impact between the fuel assembly and baffle is shown with the input function Equation (1) in Figure 6.

Typically, fuel assembly vendors have developed special purpose computer programs to solve the seismic reactor core problem, primarily because of the high cost of non-linear transient analysis for long seismic events. The NRC developed FAMREC(3) for this purpose and as an audit program to evaluate fuel assembly vendor's solutions. ANF has found using the existing features of MSC/NASTRAN that the seismic reactor core problem can be solved in an efficient manner.

CONCLUSIONS

- A finite element analysis methodology using MSC/NASTRAN was applied to an NRC standard seismic analysis problem.
- The grid impact forces calculated using the program's non-linear scalar elements, and given in this paper, have been found acceptable to the NRC.

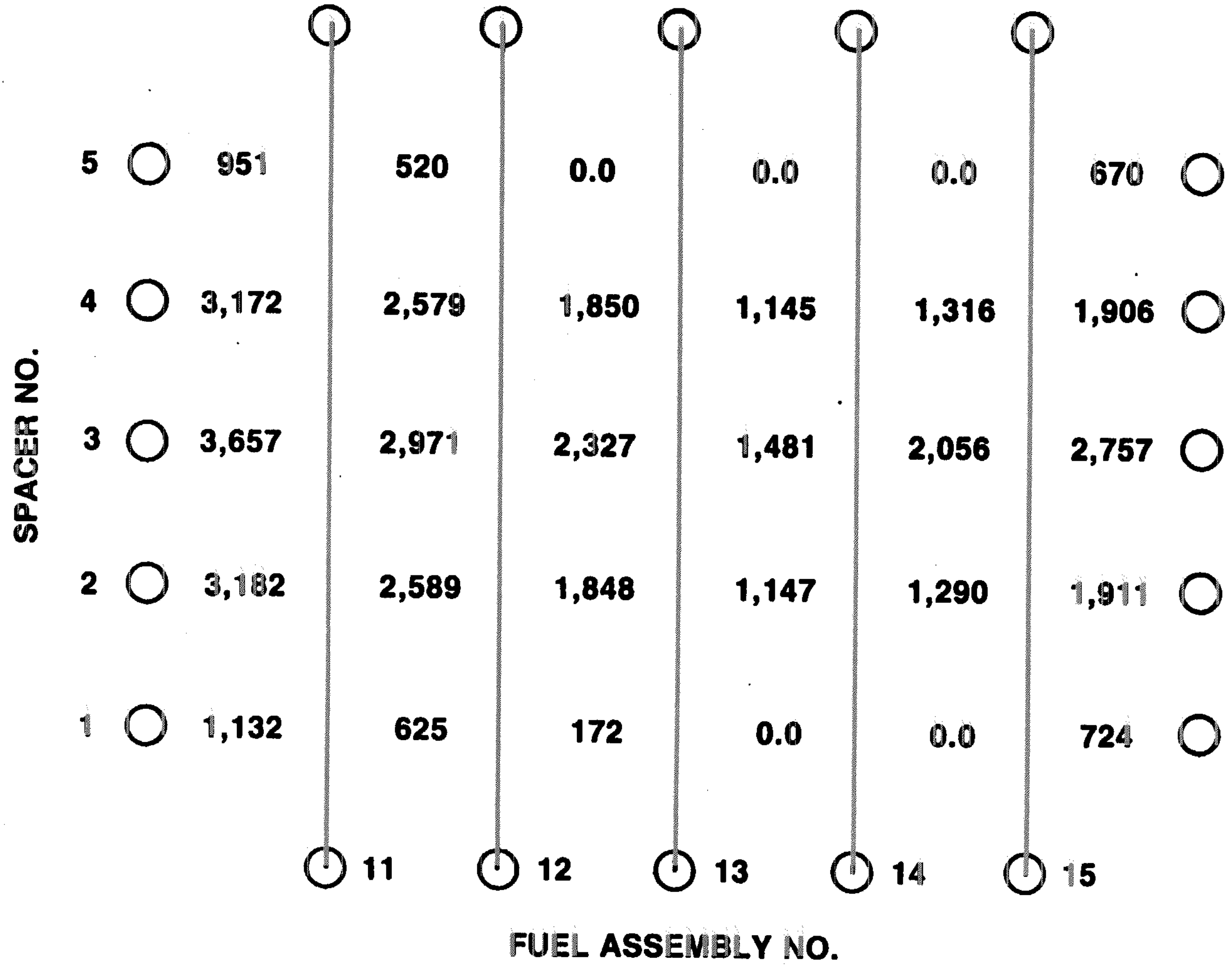
REFERENCES

1) The NASTRAN Theoretical Manual NASA SP-221, 1969.

2) R.G. Hill and J.F. Patterson, "Modal Analysis and Random Vibration Test of a Nuclear Fuel Assembly", Proceedings of the 1st International Modal Analysis Conference, November 1982, pages 103-109.

3) R.L. Grubb, "Pressurized Water Reactor Lateral Core Response Routine, FAMREC (Fuel Assembly Mechanical Response Code)", NUREG/CR-1019, September 1979.

4) R.G. Hill, "Transient Analysis of an IVHM Grapple Impact Test." NASTRAN: Users' Experiences, NASA TM X-2637, 1972, pp. 161-178.



SPACER NO.						
5	951	520	0.0	0.0	0.0	670
4	3,172	2,579	1,850	1,145	1,316	1,906
3	3,657	2,971	2,327	1,481	2,056	2,757
2	3,182	2,589	1,848	1,147	1,290	1,911
1	1,132	625	172	0.0	0.0	724

Table 1 - Asymmetric Loading Study Maximum Spacer Impact Loads - lbs.

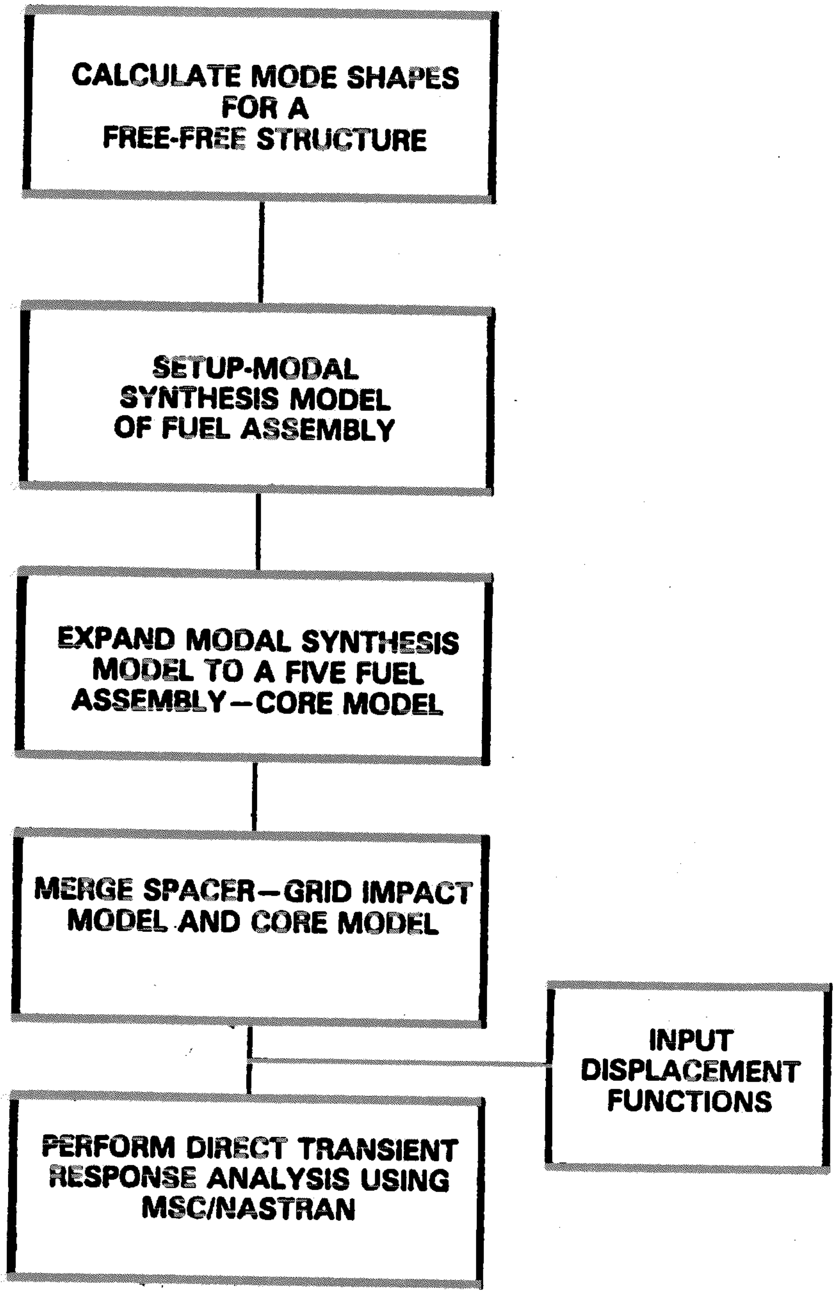


Figure 1 Flow Diagram For Dynamic Analysis of the NRC Sample Problems

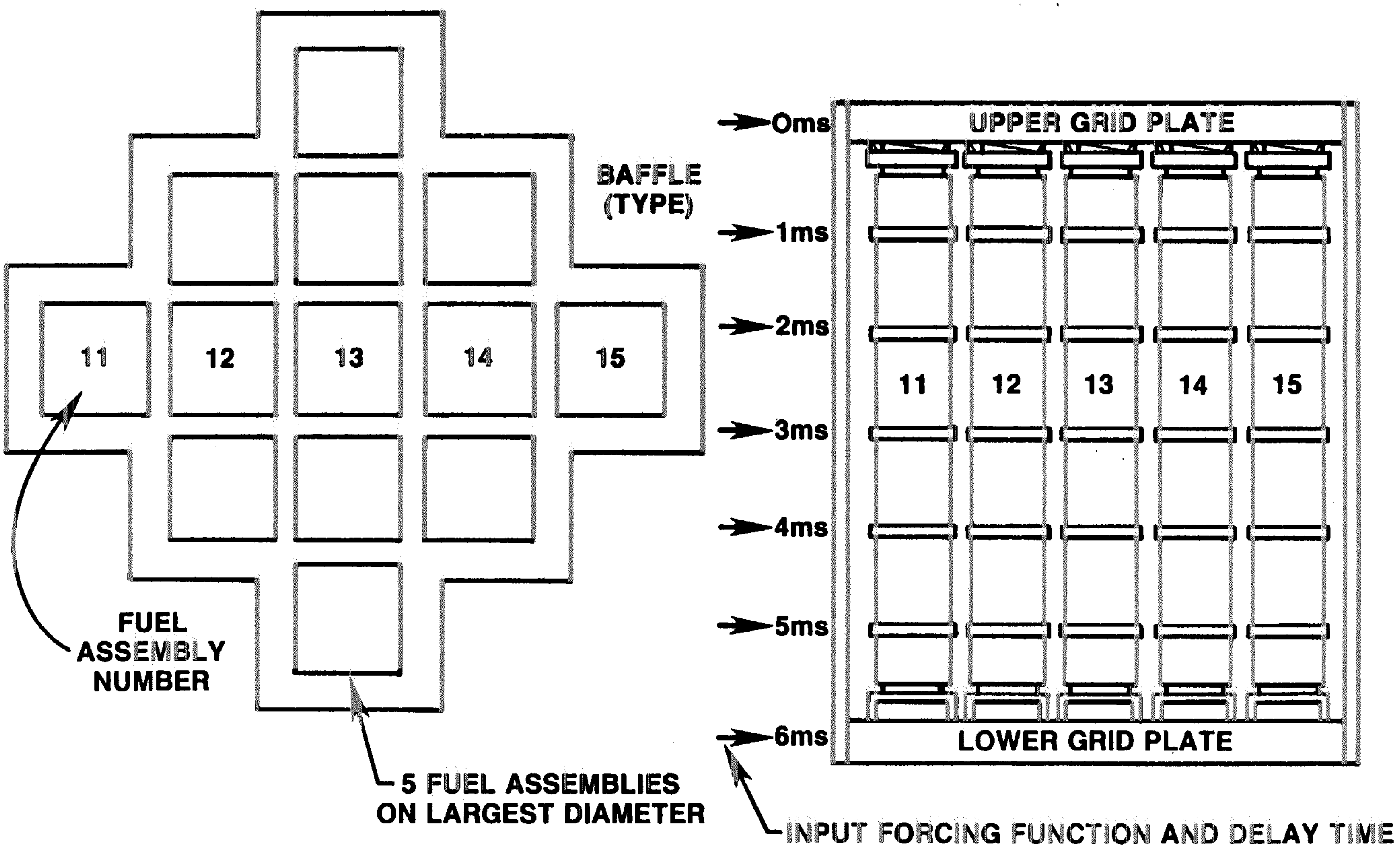


Figure 2 - Reactor Core Cross Section

FUEL ASSEMBLY NATURAL
FREQUENCIES 3, 5, 7, 9, & 11 hz
THE MODE SHAPES IN AIR ARE IDENTICAL
TO THOSE FOR A UNIFORM CLAMPED-CLAMPED BEAM
DAMPING 12% IN AIR
22% IN WATER
$E = 1.0 \times 10^7$ LBS/IN^2
I = UNKNOWN

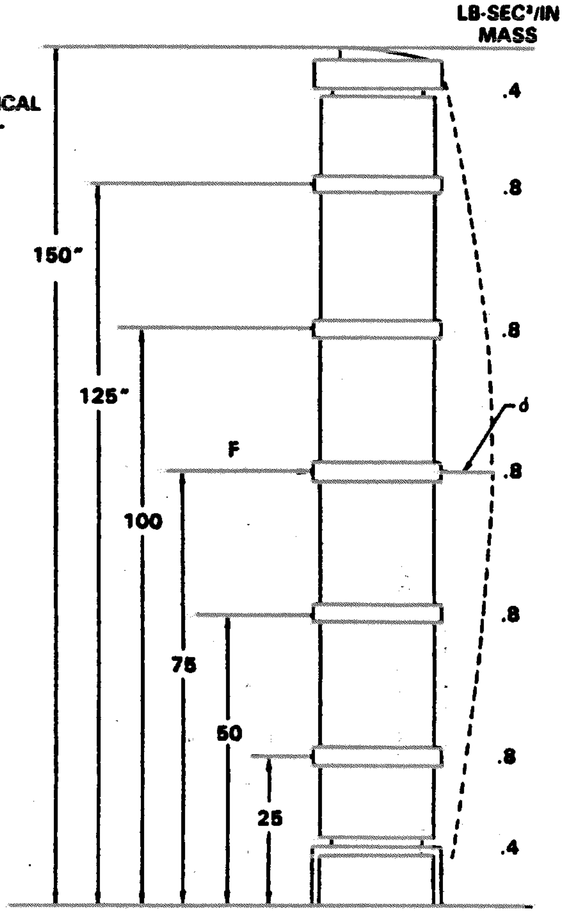
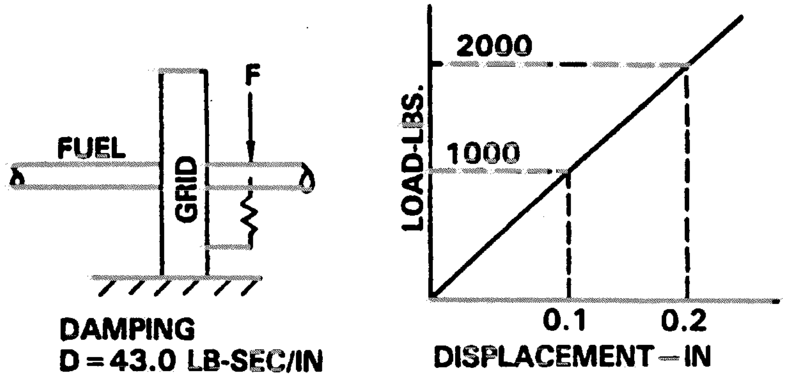
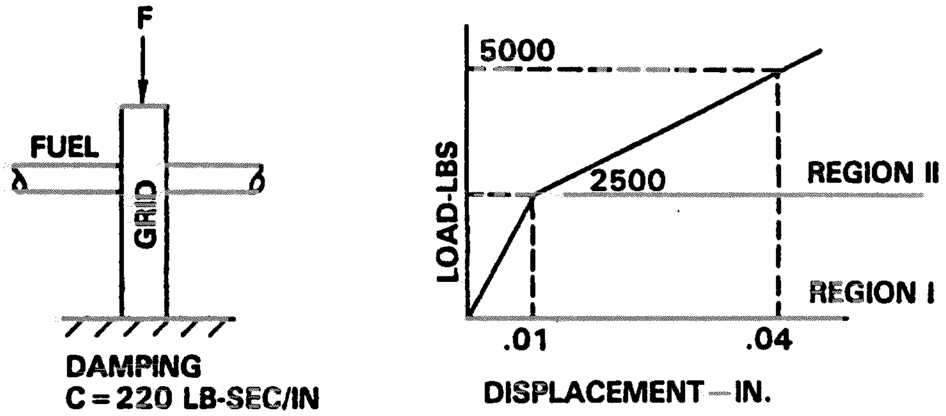


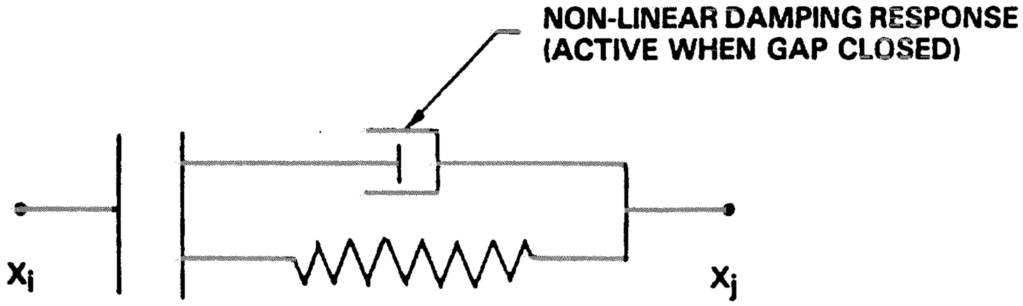
Figure 3 Fuel Assembly Mechanical Properties



IN-GRID STIFFNESS



THROUGH-GRID STIFFNESS



THROUGH-GRID MODEL

Figure 4 Spacer Mechanical Properties

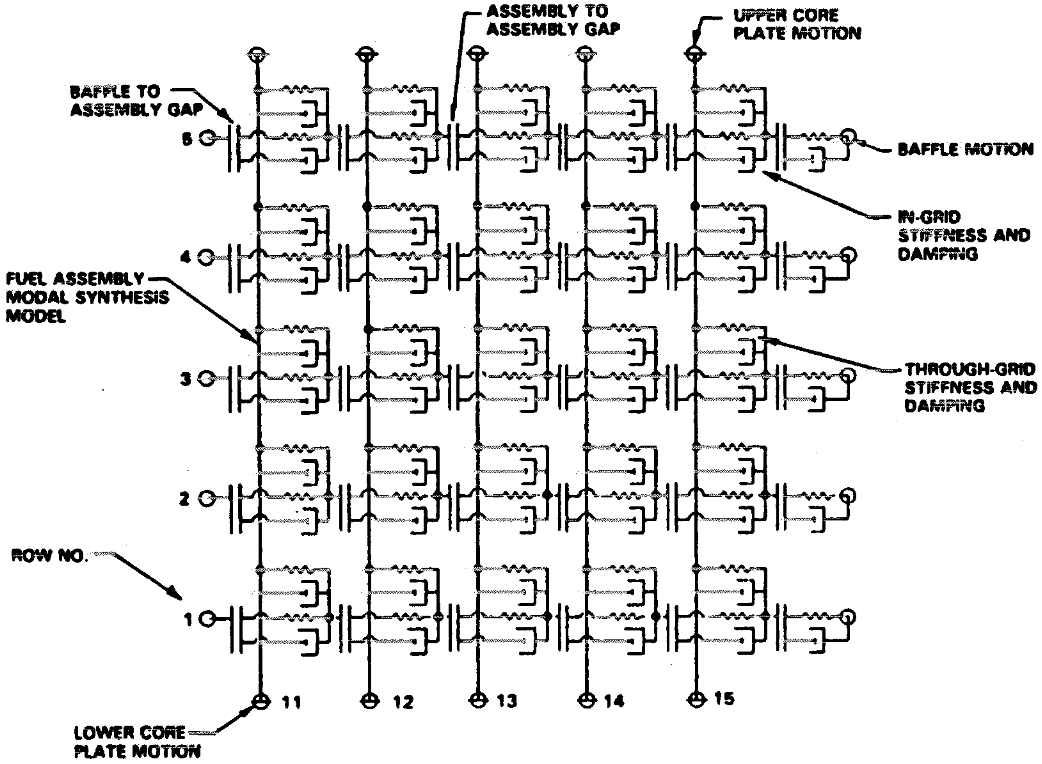


Figure 5 Schematic Diagram For A Five Assembly Spacer Grid Structural Model

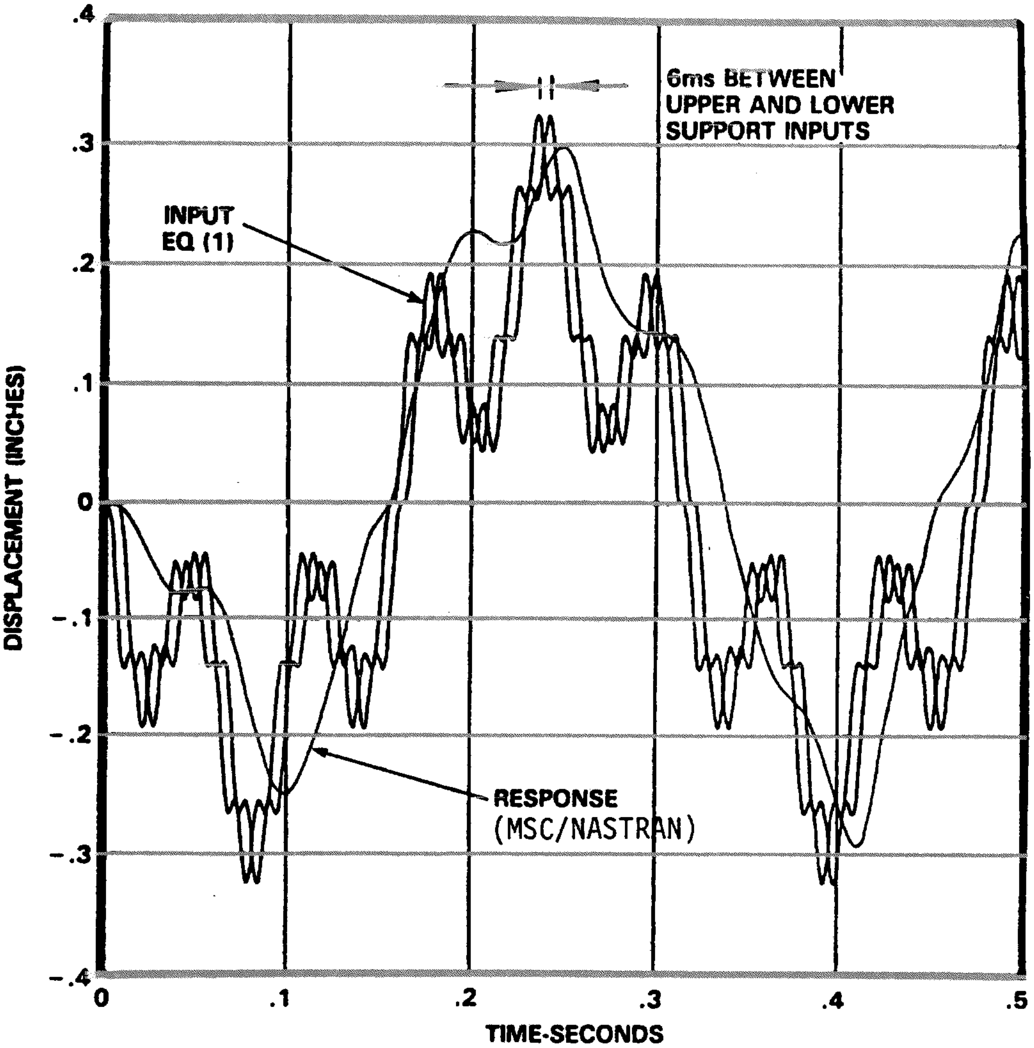
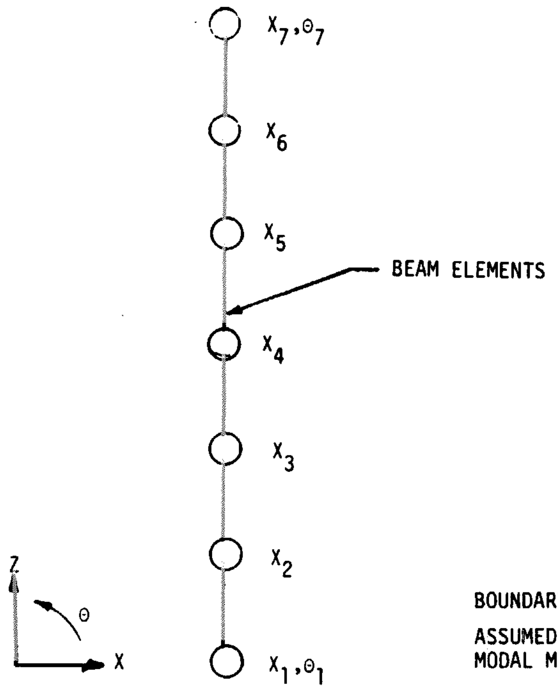


Figure 6 Input Function & Displacement Response



	ϕ_1	ϕ_2	ϕ_3	ϕ_4	ϕ_5	ϕ_6	ϕ_7	ϕ_8	ϕ_9
X_1	.456	-.744	-.743	.567	.414	-.293	.210	-.153	.115
θ_1	0.0	.010	.024	-.034	-.040	.043	-.044	.044	-.044
X_2	.456	-.496	-.171	-.198	-.329	.287	-.146	-.013	.141
X_3	.456	-.248	.273	-.413	-.015	-.325	.301	-.015	-.212
X_4	.456	0.0	.443	0.0	.444	0.0	-.321	0.0	.257
X_5	.456	-.248	.273	.413	-.015	.325	.301	.015	-.212
X_6	.456	.496	-.171	.198	-.329	-.287	-.146	.013	.141
X_7	.456	.744	-.743	-.567	.414	.293	.210	.153	.115
θ_7	0.0	.010	-.024	-.034	.040	.043	.044	.044	.044

NOTE: (1) Seven significant places used in analysis, three places shown above.

BOUNDARY CONDITIONS ARE FREE-FREE

ASSUMED STRUCTURAL MODEL TO DETERMINE
MODAL MATRIX $[\phi_{ci}]$

BOUNDARY DISPLACEMENTS X_1, X_7
BOUNDARY ROTATIONS Θ_1, Θ_7
SPACER NODES X_2 THROUGH X_6

Figure 7 **Free-Free NASTRAN Structural Model**