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원자로내부구조물의 동적해석을 위한 비선형모델
A Non-linear Model for Dynamic Analysis of Reactor Internals

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ABSTRACT

A non-linear mathematical model has been developed for the dynamic analysis of the reactor internals. The model includes a lumped mass and stiffness with non-linear members such as gap-spring. As hydrodynamic couplings have also been considered in the model, the effect of fluid/structure interaction between internals components due to their immersion in a confining fluid can be studied for the dynamic response analysis. The reactor internals responses for seismic and pipe break excitations have been calculated for the case of with- and without-hydrodynamic couplings.

1. INTRODUCTION

The reactor internals include the core support barrel (CSB) assembly, the lower support structure & ICI nozzle assembly, the core shroud, and the upper guide structure (UGS) assembly. The core support barrel is a right circular cylinder supported by a ring flange from a ledge on the reactor vessel. It carries the entire weight of the core. The lower support structure (LSS) transmits the weight of the core to the core support barrel by means of a beam structure. The core shroud surrounds the core and minimizes the amount of bypass flow. The upper guide structure provides a flow shroud for the control element assemblies (CEAs), and limits upward motion of the fuel assemblies during pressure transients. Lateral snubbers are provided at the lower end of the core support barrel assembly.

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All of these internals structures are immersed in a fluid and its fluid/structure interaction should be accounted for the dynamic responses under seismic and pipe break excitations.

This paper presents the mathematical model for the time history analysis of the reactor internals and also the methodology for accounting for the fluid/structure interaction effects on the internals and fuel responses. The responses of reactor internals due to seismic and pipe break excitations are investigated.

2. MODEL DEVELOPMENT

The mathematical model of the internals consists of lumped masses and elastic beam elements to represent the beam-like behavior of the internals, and non-linear elements to simulate the effects of gaps between components. Typical component gaps represented by non-linear elements are the core support barrel, pressure vessel snubber gap and core shroud guide lug gap. The gaps between the core shroud and core support barrel or the core support plate and core support barrel are sufficiently large that no contacting occurs. However, for every analysis performed, this assumption is verified by confirming that the relative deflections of component are in fact smaller than existing gaps.

At appropriate locations within the internals and core, nodes are chosen to lump the weights of the structure. The criterion for choosing the number and location of mass points is to provide for accurate representation of the dynamically significant modes of vibration for each of the internals components. For the beam element connecting two nodes, properties are calculated for moments of inertia, cross-sectional areas, effective shear areas, stiffnesses and length.

Stiffnesses for the complex internals structures such as UGS and CSB flanges, CSB snubber, hold-down ring and CEA guide tubes are determined by finite element analyses. Unit deflections and rotations are applied and the resulting reaction forces are calculated. These results are then used to derive the equivalent member properties for the structures.

The CSB upper region is modeled to account for the possible interactions between the CSB upper flange, UGS upper flange, hold-down ring and the RV ledge using the non-linear, hysteresis and friction elements. But if justified by analysis, it can be modeled as one mass point because the break size decreased.

A typical coupled internals and core model in the horizontal direction is shown in Fig.1. The actual arrangement and detail in the model may vary with the function of plant design, and the magnitude and nature of the pipe break excitation. For example, the loads on CEA guide tubes during an inlet break can be negligible because it is assumed that there is negligible crossflow at the outlet nozzle plenum for inlet break. That's why the model of CEA guide tubes is represented by single beam element in the analysis of inlet break.

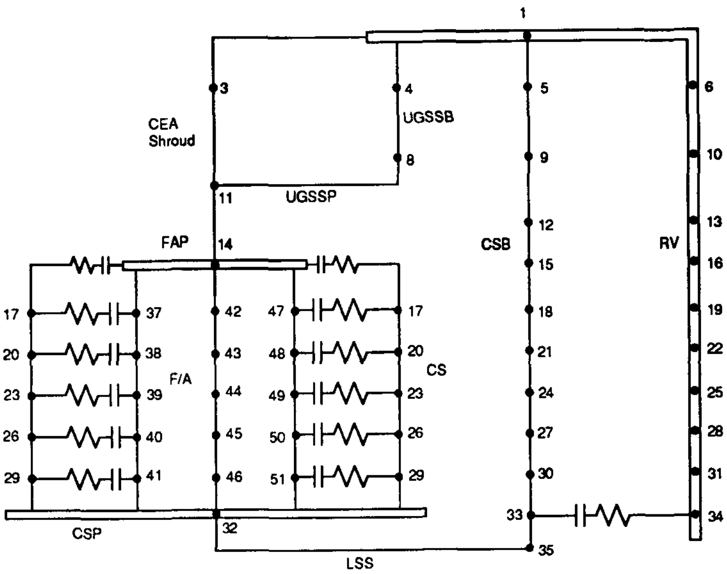

Figure 1. Mathematical model of the reactor internals

3. FLUID EFFECT

It has been shown both analytically and experimentally that immersion of a body in a dense-fluid medium lowers its natural frequency and significantly alters its vibratory response as compared to that in air. The effect is more pronounced where the confining boundaries of the fluid are in close proximity to the vibrating body as in the case for the reactor internals. The method of accounting for the effects of a surrounding fluid on a vibrating system has been to ascribe to the system additional or hydrodynamic mass. The hydrodynamic mass of an immersed system is a function of the dimensions of the real mass and the space between the real mass and confining boundary.

The effects of fluid/structure interaction between internals components due to their immersion in a confining fluid are considered. The hydrodynamic mass matrix is applied to the analytical model representing the reactor internals structures in the horizontal direction. Fluid/structure interaction is characterized by the full hydrodynamic mass matrix including the off-diagonal hydrodynamic coupling terms which will affect significantly the dynamic characteristic of the solid structure with narrow gap or annulus.

Hydrodynamic mass terms are calculated for the lumped mass model considering the solution of two concentric cylinders moving in fluid and including various boundary conditions associated with the fixity of the cylinders and the fluid flow of axial direction. The potential flow theory is used for the formulation of fluid pressures developed in the annulus between the two concentric moving cylinders. The fluid pressure includes the effects of the beam deformation of the cylinders as well as the axial fluid flow in the annulus. The hydrodynamic pressures are converted to added-mass (diagonal) and coupling-mass (hydrocoupling) terms to be added to the mass matrix of the lumped mass model.

The equations of motion account for fluid/structure interaction between two adjacent structures, separated by a fluid-filled gap by applying a hydrodynamic mass matrix to evaluate the fluid forces on the motion of the structure. The mass matrix components are calculated and they determine whether the coupling is 2- or 3-dimensional and the axial fluid boundary conditions at the ends of the annulus.

The 3-dimensional theory accounts for the translation of both the inner and outer cylinders and specification of fluid axial boundary conditions at the ends of the annulus. The continuity equation at any instant of time can be written as :

$$\frac{\partial^2 \phi}{\partial r^2} + \frac{1}{r}\frac{\partial \phi}{\partial r} + \frac{1}{r^2}\frac{\partial^2 \phi}{\partial \theta^2} + \frac{\partial^2 \phi}{\partial z^2} = 0$$

where r, θ, z are polar coordinate system and ϕ is a velocity potential function. The fluid potential is evaluated by applying the fluid boundary conditions to the above equation. The fluid boundary conditions in the axial direction are defined at $z = 0$ and $z = L$. At these locations the boundary conditions define either an open end (i.e., zero pressure) or a closed end (i.e., zero velocity). The fluid boundary conditions at the structural boundaries are given in terms of the radial components of the structural translational velocities [5].

The fluid potential function is used to evaluate the fluid forces per unit length on each of the adjacent structures. The SHOCK code [1] discretizes the structures using a series of beams and nodes. Each node represents the mass properties of a segment of the structure. For example, consider the mass properties at node A_o and A_i are associated with the structural length, L_2 - L_1 (Fig.2). The hydrodynamic forces at nodes A_o and A_i are obtained from the fluid forces per unit length by integrating with respect to z from L_1 to L_2. Therefore, in terms of a 2X2 mass matrix, the hydrodynamic force on nodes A_i and A_o are

$$\begin{bmatrix} F_{A_i} \\ F_{A_o} \end{bmatrix} = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} \begin{bmatrix} \ddot{f}(t)\, x_i \\ \ddot{f}(t)\, x_o \end{bmatrix}$$

where F : fluid reaction force over a segment, L, on a cylinder

f : fluid reaction force per unit length on a cylinder.

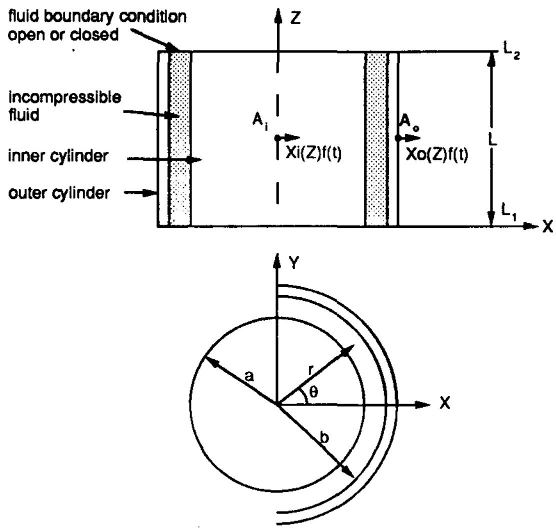

Figure 2. Hydrodynamic mass representation

These equations form the basis for the evaluation of the complete hydrodynamic mass matrices, which are evaluated for four practical cases in the reactor internals such as :

1) outer cylinder fixed ; closed - open fluid annulus,
2) closed - open fluid annulus,
3) contained mass of an outer cylinder with no inner cylinder
4) outer cylinder fixed ; closed - closed fluid annulus.

4. DYNAMIC ANALYSES

Structures and equipment in a nuclear power plant are required to be designed or qualified to resist the combined effects of a large number of loads including static loads (e.g., dead weight, pressure loads and temperature loads) and multiple dynamic loads. The dynamic loads are either transmitted directly to the entire primary structure of a nuclear power plant in the form of vibratory loads or they may be generated within the primary structures due to plant conditions. The dynamic loads which are considered in the design/evaluation include those from natural phenomena like earthquakes, and from plant conditions which are either postulated to occur, for example, the pipe break loads, or those that trigger automatically to prevent accidents within the plant, like the Safety Depressurization System Valve actuation loads.

The seismic design loads may be computed based on either an actual earthquake record calibrated for a given plant site, or an artificial earthquake computable with USNRC Regulatory Guide 1.60 [2] spectra. The pipe break loads which are significant to the design of nuclear power plant structures and equipments are produced by a postulated design basis break. In the recent design of nuclear power plants, main coolant loop double ended guillotine breaks are eliminated from the design basis because of leak-before-break (LBB) concept [3]. Instead, branch line pipe breaks are considered as one of the Level D service loadings. Of the branch line pipe breaks postulated, LBB evaluation is performed for piping systems with a diameter of 10 inches or over and it is anticipated that pipe breaks with a diameter of 10 inches or over be no more considered as design basis. In this case, only the 3 inch pressurizer spray line nozzle break remains in the design basis in the primary side. As the pipe break size becomes smaller, the reactor vessel motions are negligible [4] and the only forcing terms are CSB forces associated with asymmetric pressurization of containment subcompartments due to pipe break accidents. Fig.3 shows the acceleration time histories of RV flange and snubber and the CSB force time history is shown in Fig.4.

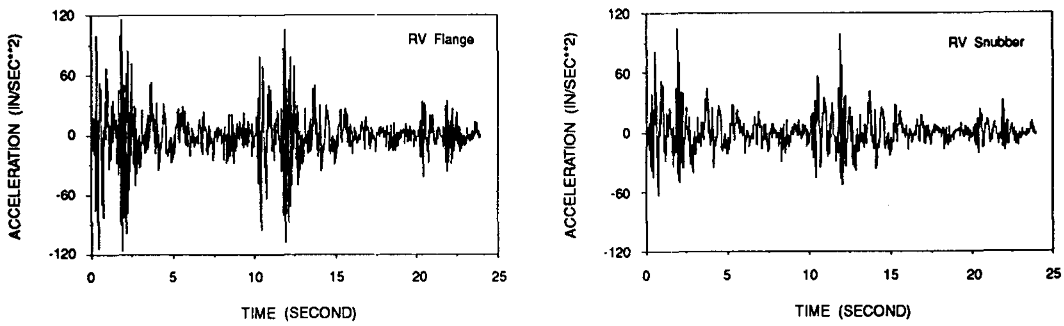

Figure 3. Acceleration time histories of RV flange and snubber

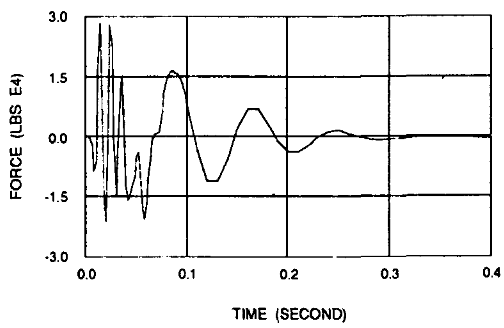

Figure 4. CSB force time history

5. RESULTS AND DISCUSSION

The maximum loads of each component are summarized in Tables 1 and 2. The comparison of the responses for the seismic excitation shows that the higher responses are obtained in the with-hydrodynamic coupling case than without-case. This indicates that the RV motions, which are used as forcing functions, are transmitted by the RV flange and snubber as well as hydrodynamic couplings and generate a large displacement of overall internals structures.

Table 1. Maximum loads of reactor internals for seismic excitation

Component	*SHEAR (lbxE5)*		*MOMENT (in-lbxE5)*	
	w/	*w/o*	*w/*	*w/o*
CSB Upper Flange	*6.35*	*2.49*	*44.39*	*39.74*
CSB Upper Cylinder	*6.35*	*2.49*	*43.47*	*32.89*
CSB Nozzle Cylinder	*3.44*	*1.91*	*37.96*	*25.63*
CSB Center Cylinder	*4.40*	*1.48*	*33.22*	*15.48*
CSB Lower Cylinder	*4.33*	*1.26*	*41.54*	*19.21*
CSB Lower Flange	*5.80*	*3.10*	*47.46*	*21.34*
CSB Snubber	*3.86*	*2.96*	-	-
LSS	*4.91*	*2.65*	*47.79*	*20.48*
Core Shroud	*4.18*	*1.94*	*41.41*	*17.73*
UGS Upper Flange	*6.49*	*1.44*	*48.54*	*18.54*
UGS Lower Flange	*1.35*	*1.24*	*7.43*	*3.10*
CEA Guide Tube	*1.20*	*.60*	*7.01*	*3.31*
CEA Shroud Assembly	*.90*	*.70*	*3.81*	*2.93*

Table 2. Maximum loads of reactor internals for pipe break excitation

Component	*SHEAR (lbxE5)*		*MOMENT (in-lbxE5)*	
	w/	*w/o*	*w/*	*w/o*
CSB Upper Flange	*.20*	*.38*	*2.10*	*8.14*
CSB Upper Cylinder	*.20*	*.37*	*1.85*	*6.67*
CSB Nozzle Cylinder	*.19*	*.30*	*1.64*	*5.18*
CSB Center Cylinder	*.15*	*.25*	*.90*	*2.86*
CSB Lower Cylinder	*.09*	*.25*	*.74*	*.38*
CSB Lower Flange	*.10*	*.26*	*.86*	*.78*
CSB Snubber	*.00*	*.00*	-	-
LSS	*.07*	*.17*	*.86*	*.82*
Core Shroud	*.09*	*.08*	*.76*	*.59*
UGS Upper Flange	*.20*	*.19*	*1.42*	*2.42*
UGS Lower Flange	*.05*	*.13*	*.98*	*.62*
CEA Guide Tube	*.01*	*.04*	*.02*	*.12*
CEA Shroud Assembly	*.01*	*.05*	*.10*	*.50*

But the pipe break responses show the opposite characteristics, or the loads for without-hydrodynamic coupling case are higher than with-case. This is explained by the fact that CSB forces are transmitted through hydrodynamic coupling terms to RV which is very stiff comparing with internals structures.

The relative displacement and/or shear force time histories of RV to CSB snubber indicate that the hydrodynamic coupling terms act as a snubber which restraints the motion of the CSB. The degree of this snubber effect by hydrodynamic couplings depends on the locations of the forcing functions which are applied to the internals.

6. CONCLUSION

The mathematical model has been developed for the dynamic analysis of the reactor internals. The effect of fluid/structure interaction due to their immersion in a confining fluid was considered for the dynamic responses. The internals responses for seismic and pipe break excitations were obtained for the case of with- and without-hydrodynamic couplings. The results show that seismic responses are higher for with-hydrodynamic couplings case than without-case, but the pipe break responses show the opposite characteristics.

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