DEVELOPMENT OF SAFA, A SEISMIC ANALYSIS PROGRAM FOR FBR CORE COMPONENTS

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ABSTRACT

A computer program, SAFA (Seismic Analysis program for Fuel Assemblies), is developed to analyze core component vibration of fast breeder reactor (FBR) core components during seismic excitation. Since an FBR core is composed of as many as one thousand core assemblies (fuel assemblies, blanket assemblies, neutron shield assemblies, etc.), which are immersed in a coolant fluid, FBR core seismic analysis must treat the vibration generated in a large-number-degree-of-freedom system with impacts under fluid-structure interaction.

SAFA models subassemblies as finite element method beam elements. Fluid interaction force is considered as added mass and time integration is done using mode superposition and the *Nigam* method. Load pad impact is modeled using a gap, a linear spring, and a linear damper. It also uses a new method to determine the nonlinear impact force that eliminates having to use convergence iteration.

Comparison of the experiment results and those of the developed program show that the program predicts the experimental results well.

1 INTRODUCTION

A fast breeder reactor (FBR) core is composed of as many as one thousand core components, including fuel assemblies, blanket assemblies, and neutron shield assemblies, all of which are immersed in a coolant fluid (liquid sodium). A schematic view of an FBR core is shown in Figure 1. The subassemblies have load pads that transfer contact forces to adjacent subassemblies. These structural characteristics cause the subassemblies to vibrate like cantilevers with load pad impacts under fluid-structure interaction when an earthquake excites the structure. Since the seismic integrity of the core components is an important factor in FBR design, various researches have been done on developing and testing seismic analysis codes for FBR cores. [13, 9, 1, 10, 14, 15]

The following items must be considered when simulating the seismic response of the structural characteristics.

1. How to model the fluid interaction force?
2. How to deal with the large number of degrees of freedom?
3. How to integrate the equation of motion in terms of time?
4. How to determine the nonlinear force caused by impacts?

We have developed a computer seismic analysis program for fuel assemblies, SAFA, in which subassemblies are modeled as finite element method (FEM) beam elements and fluid interaction force is considered as added mass. The modal superposition method is used to reduce the number of degrees of freedom (DOF). Time integration is done using the method proposed by Nigam [12] (referred to as the *Nigam* method in the following discussion). The impact phenomenon for a pair of load pads is modeled using a gap, a linear spring, and a linear damper.

Convergence iteration is normally used to calculate the impact force because load pad impact is nonlinear, although it is a time-consuming method. In SAFA, however, a new method for determining the nonlinear force without convergence iteration is used.

This paper describes the SAFA program and discussed the experimental results that conform its validity.

2 PROGRAM DESCRIPTION

2.1 Consideration of fluid force

Fluid force is taken into account as added mass in SAFA because the fluid force is approximately proportional to the acceleration of structures. By this assumption, the equation of motion becomes

$$(\mathbf{M} + \mathbf{M}_v) \ddot{\mathbf{x}} + \mathbf{C} \dot{\mathbf{x}} + \mathbf{K} \mathbf{x} + \mathbf{q} = -\mathbf{f}, \quad (1)$$

where $\mathbf{M}$ and $\mathbf{M}_v$ are mass and added mass matrices, respectively, $\mathbf{C}$ is a damping matrix, $\mathbf{K}$ is a stiffness matrix, $\mathbf{x}$ is a relative displacement vector, $\mathbf{f}$ is the earthquake-generated external force vector, and $\mathbf{q}$ is the impact force vector.

Two types of added mass can be optionally selected. One is a three-dimensional added mass matrix, with which the interaction between the subassemblies and the core barrel due to fluid force can be precisely considered. [5, 6, 4] Although the added mass matrix can be calculated by using another FEM code, the calculation requires so much memory and so much computational time that the number of DOF is limited at present. It is expected, however, that further improvements in calculation methods and computer technology will allow us to calculate the actual size of FBR core structures.

The other type of added mass is a concentrated added mass. This is a simplified method for treating the fluid structure interaction, by which the natural frequency of the first mode of the subassemblies can be simulated. This allows the seismic response to be calculated to a certain accuracy when the concentrated added mass is properly defined, because the first natural frequency is an important factor in the seismic response of subassemblies. [11] Several methods for determining the added mass based on the structural conditions have been proposed. [17, 3, 4, 6]

2.2 Reduction in the number of degrees of freedom

The modal superposition method [16] is employed by SAFA to transfer the coupled multi-degree-of-freedom system described by Equation 1 to a set of single-degree-of-freedom (SDOF) systems in the modal space. Time integration of the equations of motion are then conducted in modal space and the SDOF system responses are transformed back to the original space in order to determine the seismic responses of the subassemblies.

Although as many eigen modes as the number of the system DOF can be determined by modal analysis, some of the modes contribute little to the seismic response. These modes are therefore eliminated in the calculation to reduce the number of DOF, which reduces the computation time.

2.3 Time integration

Since the system is transformed to SDOF systems, as discussed above, the *Nigam* method can be used. The main advantage of the *Nigam* method is that time integration can be done using with a simple matrix calculation, as long as it is an SDOF system.

2.4 Impact force calculation

Since FBR core structural systems are nonlinear due to the impact forces, conventional codes use the convergence iteration method, which is, however, time-consuming when the number of impact points is large. SAFA uses a new method by which the nonlinear forces can be calculated without iteration. [7] This method is briefly described as follows. It is assumed that the bars are installed in a single row in order to simplify the explanation.

The impact points are modeled using a gap, a linear spring, and a linear damper as shown in Figure 2. The vector create by the intersections of impact points at time t_{i+1} , $\Delta \mathbf{x}_{i+1}$, can be

calculated using the following equation:

$$\Delta \mathbf{x}_{i+1} = (\mathbf{I} - \mathbf{P}_1 \mathbf{S}_k - \mathbf{P} \mathbf{S}_c / \Delta t)^{-1} \{ \Delta \mathbf{x}'_{i+1} + (\mathbf{P}_0 \mathbf{S}_k - \mathbf{P} \mathbf{S}_c / \Delta t) \Delta \mathbf{x}_i \}, \quad (2)$$

where Δt is the time step, $\Delta \mathbf{x}'_{i+1}$ is the intersection vector calculated by neglecting impact force, and $\mathbf{I}$ is the unit matrix, $\mathbf{P}_0$, $\mathbf{P}_1$, and $\mathbf{P}$ are *influence coefficient matrices* which can be calculated from the modal natural frequencies, the modal damping ratios, the modal vectors, the calculation time step, and so on. $\mathbf{S}_k$ and $\mathbf{S}_c$ are diagonal matrices consisting of the impact point stiffness and damping, respectively.

Using the results of Equation 2, the impact force vector at time t_{i+1} , $\mathbf{q}$, can be written as follows:

$$\mathbf{q} = (\mathbf{S}_k + \mathbf{S}_c / \Delta t) \Delta \mathbf{x}_{i+1} - (\mathbf{S}_c / \Delta t) \Delta \mathbf{x}_i. \quad (3)$$

Applying the calculated vector to Equation 1 allows the seismic response to be computed. This method can be expanded to bars in a matrix arrangement, such as in an actual FBR core structure. [8]

3 CALCULATIONAL EXAMPLES

This section compares two calculation examples with the experimental results. One calculation model is a system of 11 bars in a single row. This example evaluates the accuracy of the SAFA calculation method in terms of impact vibration. The other is a system of 127 bars in a hexagonal matrix arrangement. This example evaluates the ability of SAFA to handle a large-number-degree-of-freedom system in a two-dimensional arrangement.

3.1 Analysis of bars in a single row

The experimental model used for this is shown in Figure 3. Eleven plates were installed between two restraints. A spring and a load cell were attached at the top of each bar as shown in the figure. This made it possible to measure impact forces. In addition, displacement transducers were installed at six of the eleven bars. The experiment details were reported elsewhere. [2]

A comparison between the experimental and calculated results is shown in Figure 4. The calculated results match the experimental ones well. The maximum impact forces at the restraints and the maximum displacement of the center bar are shown in Figures 5 and 6, respectively. The calculated and experimental results are in good agreement in both figures. These results show that SAFA can simulate the seismic response of a group of bars.

3.2 Analysis of bars in a matrix arrangement

The experimental model used for this is shown in Figure 7; 127 hexagonal bars were installed inside a restraint. A shaking table was used to generate vibration of the system, which caused load pad impact between adjacent bars and bars and the restraint. The experiment details were reported elsewhere. [11] The experimental and calculated impact forces are compared in Figures 8 and 9. It should be noted that a half structural model was used in the calculations, which eliminated the symmetrical degrees of freedom.

The maximum impact force at Point A at various exciting frequencies and acceleration amplitudes is shown in Figure 8. The calculated results are close to the experimental ones. The maximum impact forces at Points A through G under a 6-Hz, 500-cm/s² excitation are shown in Figure 9. The calculated results simulate well the distribution of the experiment, that is, the impact force at the center row is larger than at the edge. The discrepancy may be caused by the nonlinearity of the subassembly models, which is not taken into consideration in the present calculation.

These comparisons show that SAFA can handle large-number-degree-of-freedom systems in a two-dimensional arrangement, such as the computational example discussed above.

4 CONCLUSION

A computer program, SAFA (Seismic Analysis program for Fuel Assemblies), was developed to analyze the vibration of FBR core components during seismic excitation. SAFA uses a new method to determine the nonlinear impact force without using convergence iteration.

Comparison of the experiment results and those of the developed program show that the program predicts the experimental results well.

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Figure 1: Schematic view of an FBR core component

Figure 3: Experimental model for vibration of bars in a single row

Figure 5: Maximum impact force at restraints

Figure 6: Maximum displacement of center bar

Figure 2: Impact model in SAFA

Figure 4: Time histories of impact force and displacement

Figure 7: Experimental model for bar vibration in matrix arrangement

Figure 8: Maximum impact force at various excitations

Figure 9: Maximum impact force at various impact points