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Analysis of FBR-core seismic experiments using the SAFA program

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ABSTRACT

This paper reviews the results which we obtained in the coordinated research program on *intercomparison of LMFBR seismic analysis codes* of IAEA using the SAFA program developed by Hitachi, Ltd. The good correlation of the calculated and measured results demonstrated the validity of using SAFA to analyze the seismic-responses of an FBR core. Experiences obtained through the coordinated research program are also discussed.

INTRODUCTION

A coordinated research program (CRP) on *intercomparison of LMFBR seismic analysis codes* was organized by the International Atomic Energy Agency (IAEA) and has been active since 1991 [1], in which the experimental data of PEC, MONJU, and RAPSODIE were provided as problems by ENEA, PNC, and CEA, respectively, and the participants conducted calculations on the problems using their own computer programs. The authors participated in the CRP and made calculations using the SAFA program [2] developed by Hitachi, Ltd. The calculation results correlated well with those measured during comparisons, thus demonstrating the validity of SAFA for analyzing the seismic responses of an FBR core. This paper reviews the results obtained in the CRP as well as describing the SAFA program.

DESCRIPTION OF PROGRAM

A fast breeder reactor (FBR) core is composed of as many as one thousand core components immersed in a coolant fluid (liquid sodium). The subassemblies have load pads that transfer contact forces to adjacent subassemblies, as shown in Fig. 1. When an earthquake excites the structure, these structural characteristics cause the subassemblies to vibrate like cantilevers with load pad impacts under fluid-structure interaction. Therefore, it is important to consider the structural characteristics described above when simulating the seismic response.

We used the SAFA (Seismic Analysis program for Fuel Assemblies) computer program, which was developed by Hitachi, Ltd. to analyze core component vibration in fast breeder reactors during seismic excitation. The core structure shown in Fig. 1 is numerically modeled as shown in Fig. 2. The features of SAFA, which fulfills the requirements for seismic analysis codes of FBR cores discussed above, are briefly described as follows. Detailed discussion on the computer program has been reported elsewhere [2].

Consideration of fluid force

Fluid force, which causes the fluid-coupling effect, is treated as added mass in SAFA because it is approximately proportional to the acceleration of structures. Using this assumption, the equation of motion becomes

$$(\boldsymbol{M} + \boldsymbol{M}_{\mathrm{v}})\ddot{\boldsymbol{x}} + \boldsymbol{C}\dot{\boldsymbol{x}} + \boldsymbol{K}\boldsymbol{x} + \boldsymbol{q} = -\boldsymbol{f}, \tag{1}$$

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

Two types of added mass may be selected. One is a three-dimensional added mass matrix, using which the interaction between the subassemblies and the core barrel, due to fluid force, is able to be precisely considered. It should be noted that the calculation of $\boldsymbol{M}_{\mathrm{v}}$ requires so much memory and so much computational time that the number of degrees of freedom (DOFs) is presently limited. The other type of added mass is a concentrated added mass. This is a simplified method to treat fluid structure interaction, by which the natural frequency of the first mode of the subassemblies can be simulated. This allows seismic response to be calculated to a certain accuracy when concentrated added mass is properly defined, because the first natural frequency is an important factor in the seismic response of subassemblies.

Reduction in the number of degrees of freedom

SAFA employs the modal superposition method [3] to solve the equation of motion. The coupled multiple-degree-of-freedom system described by Eq. (1) is transferred to a set of single-degree-of-freedom (SDOF) systems in modal space. Then the time integration of the equations of motion is conducted in modal space and the SDOF system responses are transformed back to the original space to determine the seismic responses of the subassemblies.

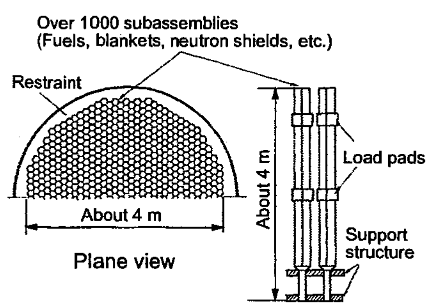


Figure 1: Schematic of FBR core

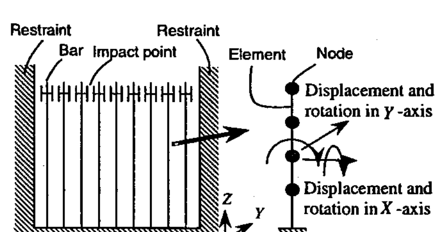


Figure 2: Numerical model in SAFA

Although as many eigen modes as the number of the system DOFs can be determined by modal analysis, some of the modes contribute little to seismic response. These modes have therefore been eliminated from the calculation to reduce the number of DOFs, to reduce computation time.

Time integration

Since the system has been transformed to SDOF systems, as discussed above, the *Nigam* method [4] can be used. The main advantage of this method is that time integration can be done using a simple matrix calculation, as long as an SDOF system is used.

Impact force calculation

The SAFA uses a new method to calculate nonlinear impact forces without iteration [2] as briefly described below.

To simplify explanation, let us consider that the bars are installed in a single row The points of impact are modeled using a gap, a linear spring, and a linear damper as shown in Fig. 2. The vector created by the intersections of impact points at time t_{i+1}, $\Delta\boldsymbol{x}_{i+1}$, can be calculated using the following equation:

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

where Δt is the time step, $\Delta\boldsymbol{x}'_{i+1}$ is the intersection vector calculated by neglecting the impact force, and $\boldsymbol{I}$ is the unit matrix, $\boldsymbol{P}_0$, $\boldsymbol{P}_1$, and $\boldsymbol{P}$ 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. $\boldsymbol{S}_k$ and $\boldsymbol{S}_c$ are diagonal matrices consisting respectively of impact point stiffness and damping. Using the results of Eq. (2), the impact force vector at time t_{i+1}, $\boldsymbol{q}$, can be written as follows:

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

Applying the calculated vector to Eq. (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.

CALCULATION RESULTS

The organizations conducting the experiments provided the structural data and the excitation acceleration for the calculations. The calculation and experimental results compared in terms of displacement, acceleration, impact force, and so on. The results have been already reported in *IAEA-TECDOCs* [5]–[7]. Some examples of the results are shown and discussed below. In general, the results calculated using SAFA were close to the measured values within a certain degree of accuracy. Therefore, we concluded that SAFA can be used in practical seismic-response analysis of FBR cores.

PEC experiments

In PEC experiments, 19 subassemblies were excited using a shaking table in water without restraint, as shown in Fig. 3 [5].

Maximum displacements calculated with several different calculation models are compared with those measured in Fig. 4. The results are close, and the calculated values are a little smaller than the measured ones. This may be because the damping ratios used in the calculations are higher than the actual ones. In addition, the estimation error of the natural frequency in the calculation may also cause the difference. Both discrepancies originate from errors in the subassembly characteristics used in the calculations. This will be discussed in more detail later.

MONJU experiments

For MONJU, two series of shaking-table experiments were conducted [7]; each is a set of experiments in both air and water, one using a single-row setup consisting of 29 subassemblies with restraint, and the other using a cluster configuration consisting of 37 subassemblies with restraint. The schematic of the single-row experiment is shown in Fig. 5.

As an example of the results, the maximum values for displacement obtained by a single-row in-air calculation are compared in Fig. 6, and examples of displacement time histories are shown in Fig. 7. The results are close to measured ones not only in the maximums, but also in the shapes of the record.

RAPSODIE experiments

The RAPSODIE mock-up was composed of 271 subassemblies including 91 fuel models and 180 neutron-shield models. The mock-up was excited in both air and water on a shaking table. The configuration of subassemblies is shown in Fig. 8.

Maximum displacements at the top level in air are compared in Fig. 9, as an example. The calculation provided values close to the experimental ones and could simulate the restraint effect of the neutron-shield well.

EXPERIENCES OBTAINED FROM THE CALCULATIONS

In the design of FBR core components, we must evaluate seismic response to ensure structural integrity. Since it is almost impossible to do this experimentally due to the scale and weight of the components, we need analytical or calculation methods. However,

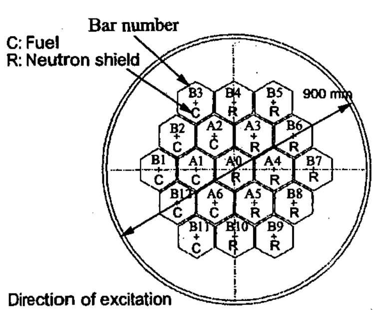


Figure 3: Experimental model of PEC experiments

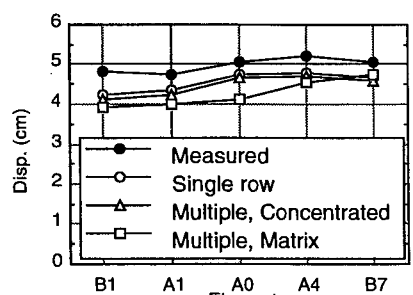


Figure 4: Maximum displacement at top (PEC)

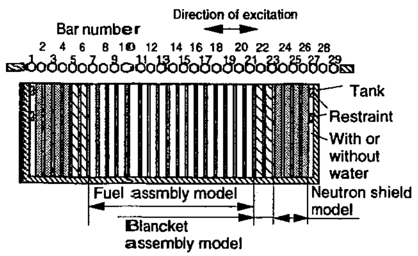


Figure 5: Schematic of single-row experiments (MONJU)

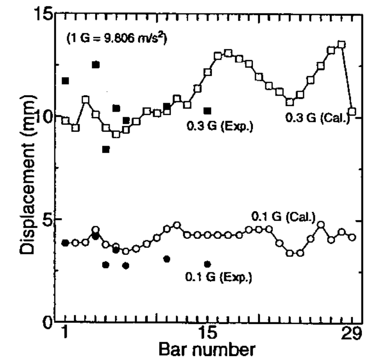
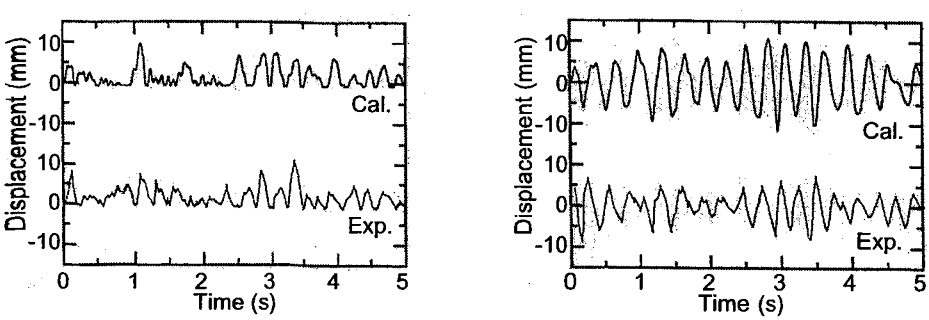


Figure 6: Maximum displacement (single row in air, MONJU)



(a) Edge elements (No. 1)

(b) Center element (No. 15)

Figure 7: Comparison of displacement time history (single row in air, MONJU)

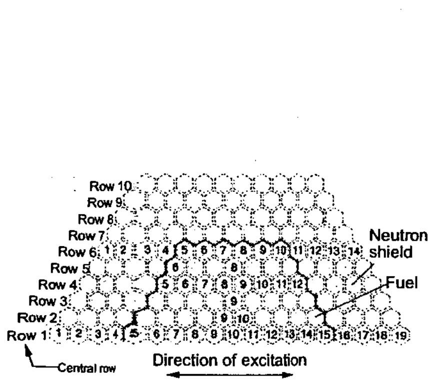


Figure 8: Configuration of subassemblies (RAPSODIE)

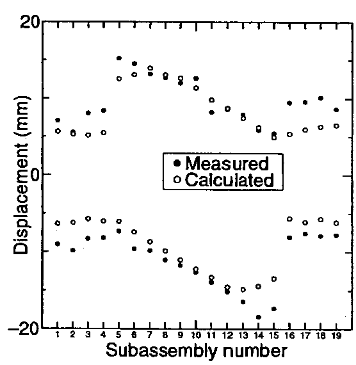
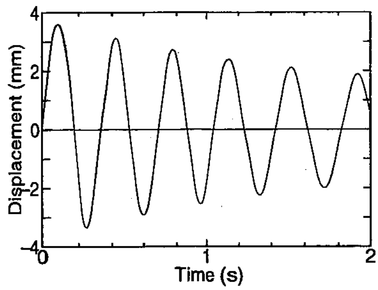
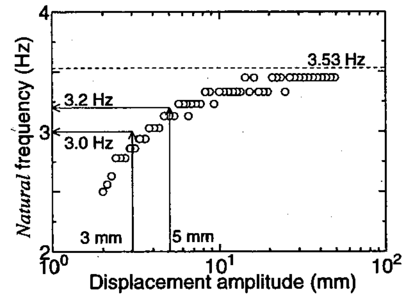


Figure 9: Maximum and minimum displacement in air (RAPSODIE)



(a) Example time history of free vibration



(b) *Natural frequency* determined from free vibration calculation

Figure 10: Calculation results for free vibration

some of input data (like vibration characteristics of subassemblies) are difficult to determine analytically, so they should be determined experimentally. Considering the above, integrity verifications should be conducted in the following steps:

1. Experiment to obtain information for making numerical model.
2. Establishment of numerical models reflecting above experimental results.
3. Calculation of seismic response of core components using determined numerical models.

Concerning with the third step, we verified through the CRP that the SAFA program as well as the other participating computer codes can output results that correlate well to the experimental ones as long as the good input data are used. In other words, the first and second steps are important to achieve reliable response prediction. However, in the CRP, we had some difficulties in the definition of numerical input data. Here, the experiences relating to the establishment of the input data are discussed.

Identification of subassembly vibration characteristics

The most important information for making input data is the vibration characteristics of each subassembly, that is, the natural frequency and damping.

Since subassemblies are modeled using beam finite-element, the natural frequency can be determined from structural parameters like mass and stiffness when boundary conditions are clearly determined. However, the subassemblies of FBRs are usually inserted into holes of the support structure and supported with a small gap at the entrance nozzle (see Fig. 1), which causes a nonlinearity in the models. This gap must be considered when making the calculation model. Consider, for example, the MONJU experimental model. Free vibration of a subassembly was calculated, of which an example time history is shown in Fig. 10–(a). Due to the nonlinearity caused by the gaps, the period between zero-crossings increases with the decay in the displacement amplitude. The relation between *natural frequency*, which is calculated from the period between zero-crossings, and displacement amplitude, is shown in Fig. 10–(b). One method for taking the gap effect into account is replacing the gap with a spring that gives a natural frequency corresponding to the assumed displacement amplitude in the seismic response.

Damping, which is the other important vibration parameter, cannot usually be determined without experiments. it is also affected by the same nonlinearity of the support conditions. For instance, the damping ratios of PEC subassemblies determined by random excitation are shown as a function of root-mean-square of response displacement in Fig. 11. In determining the damping value used in calculations, the similar consideration on the gap effect should be applied.

Needless to say, the nonlinearities discussed above depend on the core structure design. Therefore, the determination of vibration characteristics, through experiments using one or several subassemblies at actual size, will be required to estimate seismic response of the FBR core of a future design.

Fluid-coupling effect

Another important question for seismic analysis of FBR core is how to deal with the fluid-coupling effect caused by liquid sodium. As described in Eq. (1), the fluid force can be modeled using an added-mass matrix. Although an accurate matrix can be calculated by an FEM calculation, this is almost impossible for actual-sized core structure because of its calculation load. Therefore, a simple but precise method is required from the design point of view. One solution is to use concentrated added mass, with which, as discussed earlier, the natural frequency of the first mode of the subassemblies can be simulated when properly defined. The input-reduction effect of the *buoyancy-like* force resulting from fluid coupling should also be considered.

In the CRP, we found that the interpretation of the fluid-coupling effect significantly affects for the calculation results. Figure 12, for example, shows , as the function of damping ratio used in calculation, the maximum results for the central element obtained by several programs. It can be seen that the results largely depend on whether the input reduction was considered. Another influencing factor is the damping ratio of the subassemblies. Although the minimum value in Fig. 12 is 2%, this value may be lower still because the damping in this experiment depends on the displacement amplitude, as shown in Fig. 11. Therefore, results may depend not so much on the program itself but on the input data.

Several experiments on the evaluation of fluid forces acting on subassemblies have been conducted in an attempt to develop and improve analytical and computational methods. However, further experiments are needed to verify these methods and to obtain better parameters for use in designing of FBR cores.

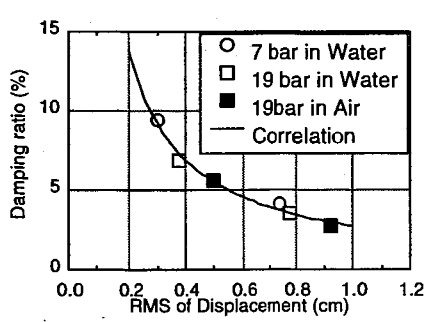


Figure 11: Damping ratio for displacement (PEC)

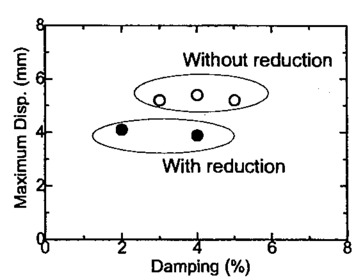


Figure 12: Maximum displacement of central element (PEC)

CONCLUSIONS

An IAEA organized coordinated research program on *intercomparison of LMFBR seismic analysis codes* has been performed since 1991. During this research program, the participants have used their own computer programs to solve PEC, MONJU, and RAPSODIE problems.

This paper reviewed the results calculated using the SAFA program developed by Hitachi, Ltd. Foe every problems, the calculated results were close to measured values within an acceptable degree of accuracy. Therefore, it can be concluded that SAFA can practice to analyze seismic responses of FBR cores for practical use.

Discussion within the CRP reveals that there are two important aspects in making calculation models. One is identification of subassembly vibration characteristics and the other is evaluation and interpretation of the fluid-coupling effect.

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REFERENCES

1. Morishita, M. et al. 1997. Main Features and Results of the IAEA Coordinated Research Program on Intercomparison of LMFBR Seismic Analysis Codes. *Proc. 14th Int'l Conf. on Struct. Mech. in Reactor Technol.*: Lyon.
2. Horiuchi, T. et al. 1995. Development of SAFA, A Seismic Analysis Program for FBR Core Components. *Nucl. Eng. Des.*, 157: 37–48.
3. Shar, V. N. et al. 1979. Modal Superposition Method for Computationally Economical Nonlinear Structural Analysis. *Trans. ASME, J. Press. Vessel Technol.*, 101: 134–141.
4. Nigam, N. C. & Jennings, P. C. 1969. Calculation of Response Spectra from Strong Motion Earthquake Records, *Bull. Seism. Soc. of Am.*, 59: 902.
5. IAEA-TECDOC-798. 1995. *Intercomparison of liquid metal fast reactor seismic analysis codes, Volume 1*: IAEA.
6. IAEA-TECDOC-829. 1995. *Intercomparison of liquid metal fast reactor seismic analysis codes, Volume 2*: IAEA.
7. IAEA-TECDOC-882. 1996. *Intercomparison of liquid metal fast reactor seismic analysis codes, Volume 3*: IAEA.