Fluid-Coupled Vibration Analysis of Reduced Models of Pool-Type LMFBR

A. Sakurai, C. Kurihara
Central Research Institute of Electric Power Industry,
1646 Abiko, Abiko-shi, Chiba 270-11, Japan
M. Nakagawa
Mechanical Engineering Research Laboratory, Hitachi, Ltd.,
502, Kandatsu-machi, Tsuchiura-shi, Ibaraki 300, Japan
H. Kawashima, M. Madokoro
Hitachi Works, Hitachi, Ltd., 3-1-1, Saiwai-cho, Hitachi-shi, Ibaraki 317, Japan

Abstract

Fluid-structure coupled vibration is one of the main factors in evaluating the seismic strength of a pool-type liquid metal fast breeder reactor. Fundamental vibration characteristics of vessel's internal structures like the core, intermediate heat exchangers and pumps are affected by reactor vessel motion caused by the coupling effect of liquid sodium. To verify the coupling effect, vibration tests are conducted using 1/20 scale simplified models of a demonstration fast breeder reactor. Analytical results using three-dimensional finite element models agree well with the experimental ones.

1. Introduction

The Central Research Institute of the Electric Power Industry (CRIEPI) has been studying the feasibility of a large scale pool-type liquid metal fast breeder reactor (LMFBR) since 1981. Structural integrity for seismic load is of great importance to the safety and reliability of large scale pool-type LMFBRs. Since these reactors have to accommodate severe seismic loads in Japan, more precise structural analysis including fluid-coupled vibration is required for economical design. [1] [2]

When evaluating the seismic response of the reactor, liquid sodium plays an essential part in structural vibration. In a pool-type LMFBR, primary system components and the internal structures are immersed in liquid sodium confined by the reactor vessel. The vibration characteristics of the structures in the liquid are different from those outside the liquid because of the interaction with the liquid. The effects of liquid sodium on the vibration characteristics of the reactor vessel and internal structures must be taken into account when designing the reactor components to withstand the severe seismic loads.

The fluid coupled effects by the two-degrees-of-freedom system, roughly corresponding to the coupled parts in the LMFBR structure, were described in a previous report.[3] This paper describes fluid-structure coupled vibration analysis and reports the results of vibration tests using 1/20 scale demonstration FBR simplified models of the reactor vessel and vessel internal structures like core, intermediate heat exchangers (IHXs), and primary pumps. These experimental results are then compared with the analysis using three-dimensional finite element models.

2. Experiments

In order to examine the dynamic properties of the fluid coupled system, vibration tests using three test models were preformed.

2.1 IHX (pump) model

The IHX (pump) model (Fig.1) was used to examine the coupling effect between the lower end of the IHX and core support structure. One steel pipe 100 mm in diameter was fixed to the top of the rigid water tank. The lower end of the pipe was surrounded by the outer cylinder with 10 mm clearance. The outer cylinder was attached to the weight which was supported by the four rods from the tank base plate. The weight represents the core motion. The IHX's response in the coupled mode was compared to the response without the outer cylinder.

2.2 Core-Reactor vessel model

A diagram of the core-reactor vessel model is shown in Fig.2. The model is related to the core vertical motion in the vessel, especially where the core is supported by the core support structure from the vessel side wall. On the core support plate there were four flow channels with 200 mm length. Two sets of flow channels with different diameters were used. To clarify the effect of the rigidity of the vessel bottom plate on the coupling vibrtion mode, two kinds of vessel bottom heads were used in the vibration test.

2.3 Reactor vessel-Guard vessel model

The reactor vessel (R/V)-guard vessel (G/V) model with a semi-spherical vessel bottom plate is shown schematically in Fig.3. This model was used to verify the support effect by the G/V through the liquid for the horizontal vibration of the R/V. The cavity between the two vessels was filled with water and its surface level was selected. The G/V was supported by the two rectangular plates fixed to the base plate.

These models were subjected to sine-sweep tests using a 20 ton bi-axial shaking table, and the acceleration responses were measured. Experimental results are shown in Section 4 and compared to the analytical reaults.

3. Analytical method and models

The liquid is treated as virtual mass which permits interaction between structures and the liquid to be incorporated into the vibration analysis. The virtual mass is computed by finite element method (FEM) on the assumption that the liquid is incompressible and inviscid. The virtual mass is given to every element of the structure forming the boundary of fluid area.

Interaction force caused by the motion of the other boundary structures is expressed by the non-diagonal elements of the virtual mass matrix. Once the virtual mass matrix is calculated, and this matrix is added to the structural mass matrix, then the equation of motion of the fluid-coupled system is determined. The natural frequencies and responses can be calculated by solving the equation.

The three dimensional FEM models of the liquid in the vessel with a flat bottom plate, and the liquid in the cavity between the R/V and the G/V are shown in Fig.4.

4. Results and discussion

4.1 IHX (pump) model

The experimental results of resonance curves for the IHX in water are shown in Fig.5, and Fig.6 shows the natural frequencies compared to the analytical results. In the coupled mode, the IHX maximum response appears at the frequency of the second mode which is higher than that without the core, as shown in Fig.5. The second mode frequency is almost equal to that of the core without the IHX in water.

The lower end of the IHX and the outer cylinder are coupled through the water confined to the narrow annulus gap between the two components. The response of the IHX is then governed by the core which has a larger mass and higher natural frequency than those of the IHX. Due to this coupling effect, the resonance frequency of the IHX can be raised to the core natural frequency, and its response can be reduced to about the same amplitude as that of the core.

4.2 Core-Reactor vessel model

In this model, two vertical vibration modes for the core and the reactor vessel are considered. The natural frequencies are shown in Fig.7 for the ratio of the flow channel length (L) to the cross sectional area (A). The natural frequency of the first mode decreases with increases in the ratio of L to A. The second mode natural frequency is not greatly affected by the flow channel conditions.

The mode shapes of the vessel with a flat bottom plate are shown in Fig.8. The first mode is out-of-phase motion in which the core and the vessel bottom move in opposite directions. The second mode is in-phase motion, and the core and the vessel bottom vibrate without changing the volume in the region between the core support plate and the vessel bottom plate. This mode is predominant in the response for the ground input motion.

The natural frequencies of the semi-spherical vessel head model are higher than those of the flat bottom vessel. This indicates that the core can be supported by the vessel bottom plate without changing the core support structure if the vessel is filled with liquid.

4.3 Reactor vessel-Guard vessel model

The natural frequencies for the water level in the guard vessel are shown in Fig.9. The natural frequency of the reactor vessel's maximum response increases slightly as the water level increases, and approaches that frequency when the two vessels are connected mechanically.

Supporting the reactor vessel by the water in the guard vessel has almost the same effect as mechanical connection between the two vessels. The support effect of the liquid is pronounced when the coupling mode shape of the two vessels is in-phase motion.
The analytical results concerning the mode shapes are shown in Fig.10.

If it is possible to give more rigidity to the guard vessel, the reactor can be supported effectively without using such mechanical supports as aseismic keys which connect the reactor vessel to the guard vessel.

5. Conclusion

Fundamental dynamic properties of the fluid coupled system corresponding to the pool-type LMFBR's structure are verified by vibration tests of reduced models and vibration analyses.

(1) The lower ends of the IHXs and pumps are coupled to the core through the liquid and their responses are reduced to about the same amplitude as that of the core.

(2) The core is supported by the vessel bottom plate through the liquid in the vertical direction. Its natural frequency is raised by increasing vessel bottom plate rigidity without changing the core support structure.

(3) The reactor vessel is supported by the guard vessel when the cavity between the two vessels is filled with liquid.

These coupled vibration effects were analysed using the three dimensional FEM code which treats the liquid as virtual mass. On the basis of these results, application of the fluid-structure coupled vibration effects to the seismic design of LMFBR is considered one of the most useful ways to improve reliability of advanced temperature structures.

References

[1] Sakurai, A., "Japanese Activities and Viewpoint on Seismic Design", IAE International Symposium on LMFBR Developement, Tokyo, Japan, 1984.

[2] Hattori, S., et al., "Structural Analysis of a Seismic Resistant Pool Reactor Concept", 7th SMiRT, Chicago, 1983, paper K5/9.

[3] Hattori, S., et al., "Fluid-Structure Coupled Vibration and Aseismic Analysis of the Reactor of Pool-Type LMFBR", 7th SMiRT, Chicago, 1983, paper E6/5.

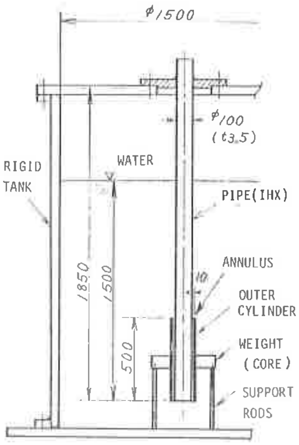


Fig.1 Schematic of the IHX Model

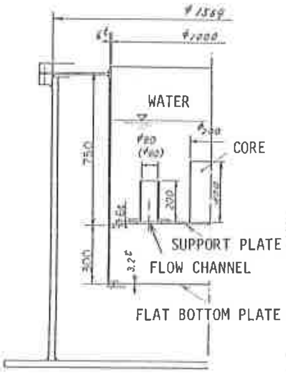


Fig.2 Schematic of the Core-R/V Model

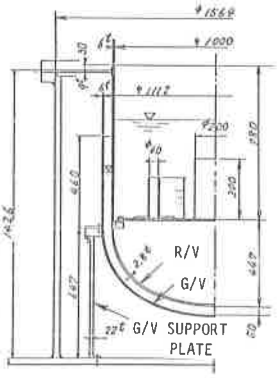
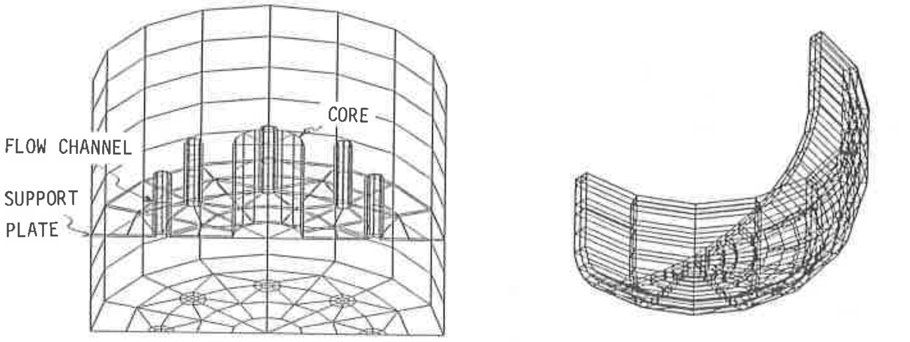


Fig.3 Schematic of the R/V-G/V Model



(a) Fluid Boundary of the Core-R/V Model with Flat Bottom Plate

(b) Fluid Model in the Guard Vessel (Water Level: 797 mm)

Fig.4 Finite Element Model of Fluid

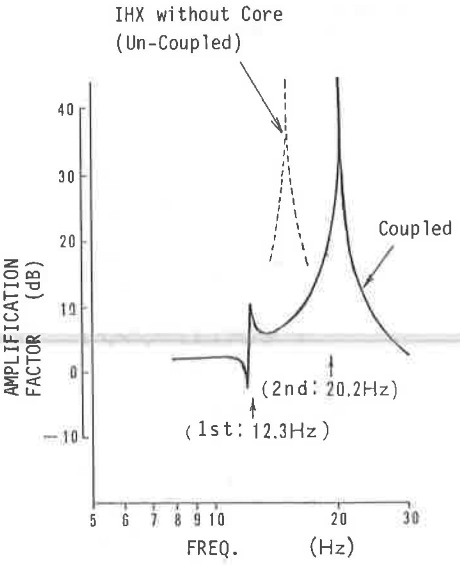


Fig.5 Resonance Curves of the IHX Lower End

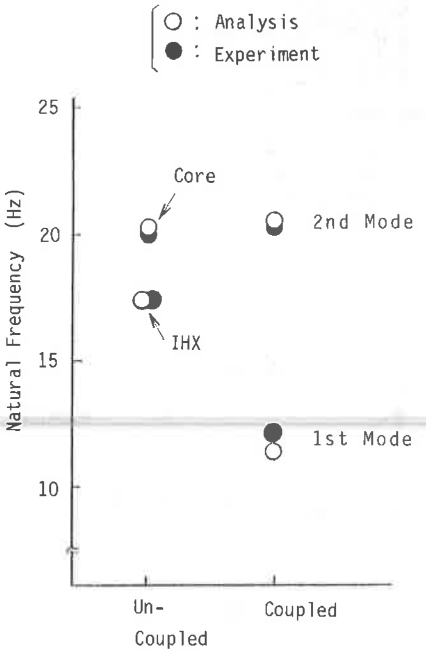
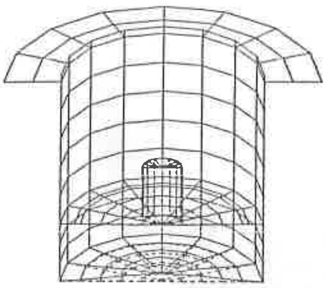
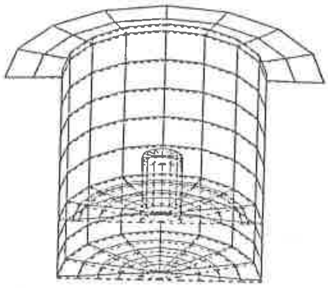


Fig.6 Natural Frequency of the IHX Model



(a) 1st Mode 4.1 Hz



(b) 2nd Mode 17.7 Hz

Fig.8 Vibration Mode Shape of the Flat Bottom Vessel (Analysis)

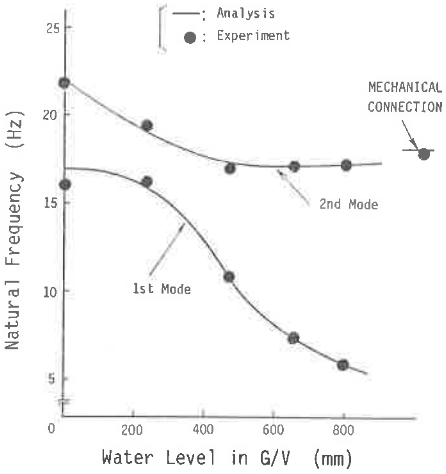


Fig.9 Natural Frequency of the R/V-G/V Model

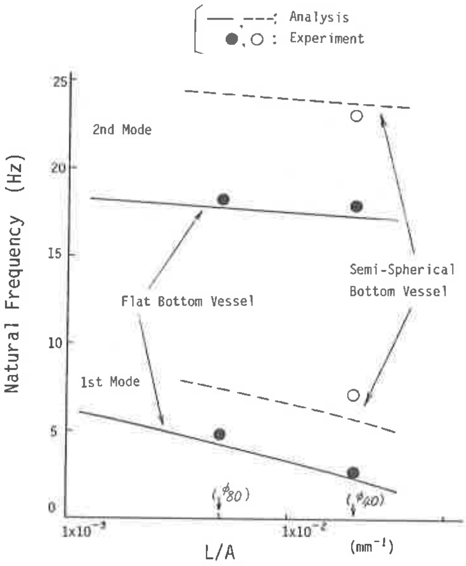
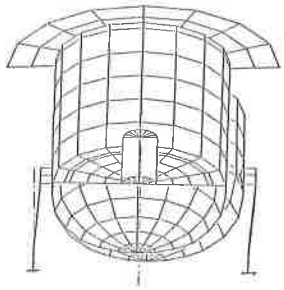
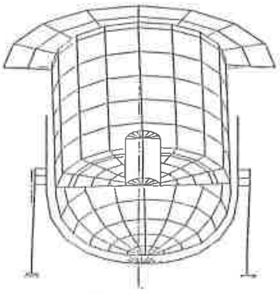


Fig.7 Natural Frequency of the Core-R/V Model



(a) 1st Mode 6.1 Hz



(b) 2nd Mode 17.4 Hz

Fig.10 Vibration Mode Shape of the R/V-G/V Model (Analysis, Water Level: 797mm)