K35/4

A Study on Analytical Methods to Evaluate Sloshing Phenomena of Base Isolated LMFBR

K. ISHIDA, H. SHIOJIRI
Central Research Institute of Electric Power Industry, Abiko, Japan
M. MADOKORO, T. YASHIRO
Hitachi, Ltd., Hitachi, Japan

ABSTRACT

Applying a decoupling method to vibration analysis of nuclear plants has the advantage of improving plant design efficiency as compared with use of a coupling methods.

In this paper, the applicability of the decoupling method to sloshing analysis in a seismically isolated LMFBR is shown analytically.

Furthermore, this paper presents characteristics of sloshing phenomena and points out the necessity of taking account of high natural frequency modes in modeling of sloshing behavior.

1 INTRODUCTION

Seismic isolation is one of the most effective methods of reducing seismic load. Applying this method to a FBR plant promotes enlargement of siting, design standardization and increased reliability during earthquakes.

However, to realize a FBR plant with a seismic isolation system, it is necessary to verify the applicability of conventional design methods for reactor building and nuclear components as well as the reliability of isolation devices.

A pool type LMFBR contains liquid sodium in a thin walled vessel, and its sloshing period is longer than that of a LWR and a loop type LMFBR.

Accordingly, when the pool type LMFBR is subjected to a slightly longer period of seismic motion, the wave height of liquid during sloshing may rise significantly(Yashiro et al.1987). In nuclear component design, a method for evaluating the sloshing phenomena during an earthquake is required for the purpose of securing structural integrity.

In existing nuclear plants without seismic isolation systems, a decoupling method which calculates seismic responses of building and components separately has traditionally been used for vibration analysis because of its simplicity.

In this paper, the applicability of the method to evaluation of the sloshing phenomena in a base isolated FBR is examined. In addition, the characteristics of the sloshing phenomena are studied, and points to be attended to in analysis of the sloshing phenomena using the decoupling method are presented.

2. APPLICABILITY OF THE DECOUPLING METHOD

The sloshing phenomena of liquid in various pools in reactor buildings during an earthquake have traditionally been evaluated by using a decoupling method which calculates responses of building and components separately.

In the decoupling method,first,seismic response on an operating floor is calculated using a vibration model of the building, then the responses of the sloshing wave height and convective pressure of sodium liquid are calcutated by inputting the obtained seismic loads on the operating floor.

This decoupling method is often used so as to avoid large scale calculations required for the change of design specification.

In a base isolated FBR plant, however, the sloshing frequency of liquid sodium is close to the isolation frequency. As a result, the variation of sloshing period occurs in the coupled and decoupled analyses, so the applicability of the decoupling method comes into question.

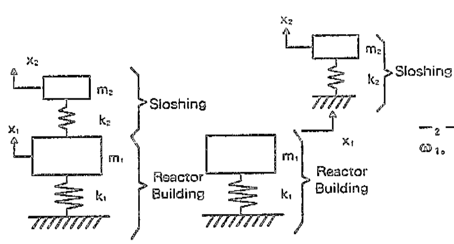
2.1 Analytical model

The applicability of the decoupling method can be judged from the variation of natural frequency of the sloshing phenomena between coupled and decoupled models as shown in reference (Aziz and Duff. 1978).

Figure 1 shows a two degree of freedom vibration model consisting of a reactor building(supporting system) and liquid in a component(supported system).

In this analytical model, the mass of reactor structure is regarded as a rigid body, and assembled into the reactor building model, because the natural frequency of the reactor structure is far from that of the sloshing phenomena.

Equation 1 shows a vibration equation of the coupling model shown in Fig.1.(a). Equation 3 shows the variation of the natural frequency between the coupled and the decoupled models.



(a) Coupling Model (b) Decoupling Model

Fig.1 Analytical Model

$$\begin{vmatrix} k_1 + k_2 - \omega^2 m_1 & -k_2 \\ -k_2 & k_2 - \omega^2 m_2 \end{vmatrix} = 0 \quad \cdots\cdots (1)$$

$$\bar{\omega}_1^2, \bar{\omega}_2^2 = \frac{1}{2}\{1 + \mu + \theta^2 \pm \sqrt{(1 + \mu + \theta)^2 - 4\theta^2}\}\ \omega_2^2 \quad \cdots (2)$$

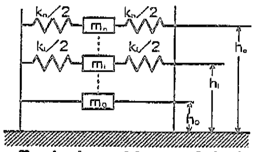
$$\omega_1^2 = \frac{k_1}{m_1},\ \omega_2^2 = \frac{k_2}{m_2}\ \mu = \frac{m_2}{m_1},\ \theta = \frac{\omega_1}{\omega_2}$$

$$\alpha = 1 - \sqrt{\frac{\bar{\omega}_2^2}{\omega_2^2}}$$

$$= 1 - \frac{1}{2}\sqrt{\{1 + \mu + \theta^2 - \sqrt{(1 + \mu + \theta)^2 - 4\theta^2}\}} \quad \cdots\cdots (3)$$

Table 1 shows the analytical conditions of reactor building and sloshing model in the analytical model shown in Fig.1.

The effective mass of the ith mode of the sloshing model can be calculated by equation 4 which is derived by combining the potential theory and mass spring vibration model for sloshing phenomena. Equation 5 shows the sloshing natural frequency of the ith mode which is derived by the potential theory (Sogabe et al. 1977).



- Equivalent Mass of i th Mode

$$m_i = \frac{2}{\varepsilon_i^2 - 1} \; \frac{\tanh\left(\varepsilon_i \frac{H}{R}\right)}{\varepsilon_i \frac{H}{R}} = m \quad \cdots\cdots (4)$$

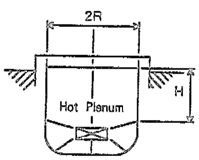
- Natual Frequency of i th Mode

$$f_i = \frac{1}{2\pi}\sqrt{\frac{\varepsilon_i g}{R}\tanh\left(\frac{\varepsilon_i H}{R}\right)} \quad \cdots\cdots (5)$$

with values of ε_i
$\varepsilon_1 = 1.841$, $\varepsilon_2 = 5.331$,
$\varepsilon_3 = 8.536$

H ; Height of Vessel
R ; Radius of Vessel
m ; Dead Mass of Hot Plenum

Table 1 Analytical Conditions

Sloshing Model	 • Dimensions R = 8000mm H = 5800mm • Weight of Hot Plenum : 956T
Reactor Building	• Weight : 157000T (Including Components Weight) • Characteristics of Isolation Device f_1 = 1.0Hz (Pre − Yield) f_2 = 0.5Hz (Post − Yield)

2.2 Analytical results

Table 2 shows the ratio (μ) of the effective mass corresponding to the i th sloshing modes and the mass of reactor building, and the ratio ($1/\theta$) of the sloshing frequency to the isolation frequency of reactor building. Here, the isolation devices are assumed to have bilinear spring characteristics with the horizontal vibrating frequencies of f_1=1Hz and f_2=0.5Hz as shown in Table 1. So the natural frequency ratios ($1/\theta$) at isolation frequencies f_1 and f_2 were evaluated.

Figure 2 indicates the relationship of the mass ratio and the frequency ratio between reactor building(supporting system) and components(supported system) when the variation of the frequency was α=5%, 1% and 0.5%.

This figure also indicates the region appropriate to the use of the decouplig method and the evaluation standard curve proposed by the NRC.

In the base isolated FBR plant, α can be suppressed to less than about 1/10 of the evaluation standard as shown in Fig.2

Although the obtained ratio ($1/\theta$) of sloshing frequency to the isolation frequency was close to unity, the mass ratio (μ) was so small that the value of α entered the decoupling region.

Table 2 Mass Ratio and Frequency Ratio of Sloshing Model to Reactor Building

Mode	Sloshing Natural Frequency fi (Hz)	Equivalent Mass (kg)	Mass Ratio	Frequency Ratio	
	①	②	②/MB	①/f_1	①/f_2
1	0.22	53204.0	3.32×10^{-3}	0.22	0.44
2	0.40	1836.7	1.15×10^{-4}	0.4	0.8
3	0.51	438.8	2.73×10^{-5}	0.51	1.02
Remarks			Mass of Reactor Building MB = 1.6×10^{8}kg	Natural Frequency of Isolation Device f_1 = 1Hz f_2 = 0.5Hz	

3. PROPOSITION OF ANALYTICAL MODEL FOR SLOSHONG PHENOMENA

The sloshing response of sodium liquid in a vessel can be evaluated by the Housner theory and the finite element method(FEM)etc.

Among these methods, the Housner theory has been most frequently used in LWR plants due to its simplicity.

In this study, to show the characteristics of sloshing phenomena in the base isolated FBR plant, the sloshing responses of sodium in the vessel were analyzed using the FEM and the Housner theory.

Furthermore, the points to be attended to regarding the modeling of sloshing phenomena were examined using these analyses.

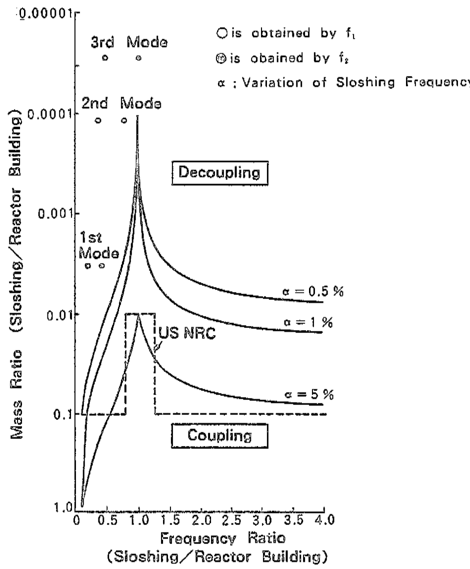


Fig.2 Variation of Sloshing Frequency Depending on the Mass Ratio and the Frequency Ratio

3.1 Analytical conditions

Figure 3 shows the pool type FBR reactor structure. The region of sloshing analysis is shown by hatching in this figure.

Seismic responses in this region were analyzed by the mode superposition method with modal damping of 0.1%.

A slightly longer period of earthquake based on observation records of the Japan Sea Central Earthquake which occurred in 1983 (Mj=7.7, observation site; Furoufushi, Shiranuka) and Mexico Earthquake which occurred in 1985 (Ms=8.1, La Union), was employed in the analysis. (Ishida et al.1987)

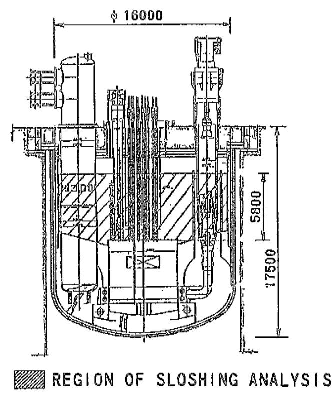


Fig.3 Reactor Structure

3.2 Analytical results

3.2.1 Characteristics of seismic sloshing pehnomena

The sloshing responses of liquid sodium in the hatched region were analyzed by the FEM. In the analysis, seismic waves on the ground (CASE A) and the operating floor (CASE B) were used as seismic loads for the purpose of obtaining characteristics of the seismic sloshing phenomena in the base isolated FBR plant.

Figure 4 (a), (b) show the time histories of sloshing wave heights analyzed using the seismic waves on the ground and the operating floor in La Union records respectively. High frequency mode waves were observed in the waveforms of the free liquid surface of sodium as shown in CASE B of Fig.4.

Table 3 shows the comparison between the maximum sloshing wave heights in CASE A and B. The seismic isolation amplified the wave height by 40% at most due to the excitation of the high frequency modes, as shown in Table 3.

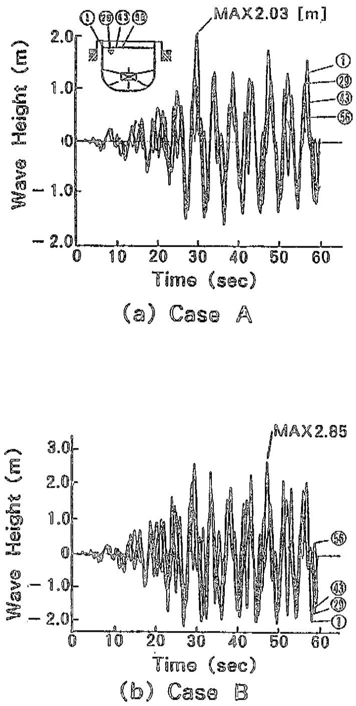


Fig.4 Time History of Wave Height(Mexico S_1)

Table 3 Sloshing Maximum Wave Height

Eathquake Wave	Maximum Wave Height (m) Case A	Maximum Wave Height (m) Case B	Amplification factor (%)
Mexico	2.03 (29.9sec)	2.85 (47.7sec)	40
Furoufushi	2.2 (58.9sec)	2.72 (58.7sec)	24
Shiranuka	2.2 (83.1sec)	2.98 (78.5sec)	35
Remarks	Caused by ground Motion	Caused by Eathquake wave through the Isolation System	

Sloshing Natual Frequency and Period

Mode	Period (sec)	Frequency (Hz)
1	4.50	0.22
2	2.56	0.41
3	1.93	0.52
4	1.61	0.62
5	1.35	0.74
6	1.13	0.88

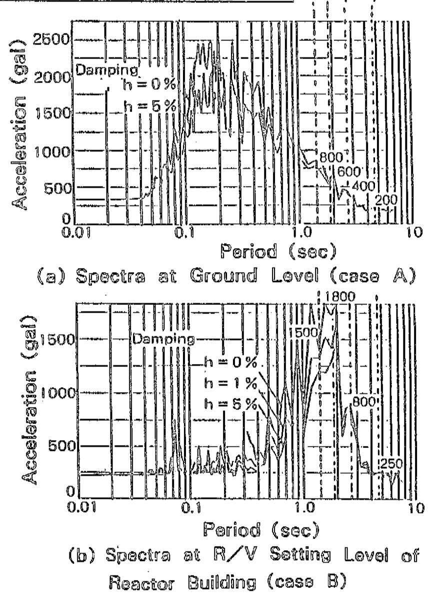


Fig.5 Floor Response Spectra

Figure 5 shows the design basis floor responses to the seismic waves on the ground and the operating floor in La Union records.

Maximum acceleration existed in the frequency range from 0.5 to 1.0 Hz in the design basis floor response spectra on the operating floor as shown in Fig.5 (b).

Furthermore, the high frequency modes were noticeably excited by the seismic loads. So these high frequency modes are not negligible to avoid the underestimation of the sloshing wave height.

3.2.2 Remarks to be observed in sloshing analysis

Table 4 shows the contribution of each mode to the sloshing wave height due to the earthquake based on La Union records . It also contains the maximum sloshing wave height obtained by the Housner theory; the seismic wave on the operating floor was used in this analysis . From this table, the following phenomena should be noted.

The contribution of the high frequency mode to the sloshing wave height is large in the base isolated FBR plant, as shown in Table 4.

The sloshing wave height obtained by the Housner theory is smaller than the result obtained by the FEM.

This is because the Housner theory deals with the sloshing analytical model in which the mass producing the convective force, called equivalent oscillation weight, is connected to the walls of the pool by springs with only the 1st sloshing natural vibration frequency.

As mentioned above, the design basis floor response on the operating floor had an acceleration peak in the high frequency range, so the sloshing responses must be calculated using the analytical method in which high frequency modes are suitably modelized to obtain the sloshing wave height accurately.

Table 4 Contribution of High Frequency Mode to Maximum Wave Height

Method	Seismic Load	Maximum Wave Height (m)	1st Mode (m)	Heigh Frequency Mode (m)	Contribution of High Frequency(%)
FEM	case A	2.03	1.43	0.6	29.6
	case B	2.85	1.61	1.24	43.5
Housner Theory	case B	2.02	–		

4. CONCLUSION

From these results, the following conclusions can be drawn.

(1) The sloshing frequency was close to the isolation frequency. However, the variation of sloshing frequency between the coupled and the decoupled models was small enough to be able to apply the decoupling method to the sloshing analysis in a base isolated FBR .

(2) The sloshing wave height during an earthquake was amplified by as much as 40% by the isolation system as compared with the result obtained using the seismic waves on the ground.
It was confirmed that the amplification of the wave height was due to the excitation of high frequency modes.

(3) Since the design basis floor response on the operating floor had an acceleration peak in the neighborhood of the sloshing high frequency modes, the sloshing phenomena in a base isolated FBR plant should be evaluated using the analytical model in which high frequency modes are suitably introduced.

ACKNOWLEDGMENTS

This research is a part of a research project "Demonstration Test of Seismic Isolation System for Fast Breeder Reactor" sponsored by Ministry of International Trade and Industry.

REFERENCES

T.Yashiro et al.(1987):A Stady on Non-Linear Sloshing of Pool Type LMFBR Coolant, 9th SMiRT Conference.

T.S.Aziz,C.G.Duff(1978):Decoupling Criteria for Seismic Analysis of Nuclear Power Plant Systems,ASME 78-PVP-27.

K.Ishida et al.(1989):Tentative Design Response Spectrum for Seismically Isolated FBR,10th SMiRT Conference.

K.Sogabe et al.(1977):A Fundamental Study on the Aseismic Design of Liquid Storages.Report of the Institute of Industrial Science of the University of Tokyo.

G.W.Housner (1963):Dynamic Analysis of Fluids in Containers Subjected to Acceleration,Nuclear Reactors and Earthquake,TID-7021.