Fluid-Structure Coupled Vibration and Nonlinear Response Characteristics of Co-axial Cylindrical Vessels

Mayumi FUKUYAMA, Masaki NAKAGAWA
Hitachi, Ltd., Tokyo, Japan

1 INTRODUCTION

The purpose of this study is to investigate the dynamic interaction between a reactor vessel and equipment in elastic and inelastic domains when subjected to earthquakes. Two types of coupled two-degree-of-freedom systems are considered. One represents co-axial cylindrical vessels, such as a reactor vessel and a thermal shield. A narrow gap between them is filled with liquid and an interaction between structures occurs due to the liquid. The other type represents a reactor vessel and self-standing core components supported by the vessel.

It is also our purpose to evaluate the seismic safety margin of a reactor vessel against buckling, including postbuckling behavior. The evaluation is based on nonlinear seismic responses of a single-degree-of-freedom system with nonlinear restoring forces.(Akiyama, et al. ;1987) It is considered that reduction in the inelastic response compared to the linear response occurs in prebuckling domain, depending on the energy absorption capacity of the inelastic deformation. The reduction is considered being dependent of the input motion and is taken into the critical design concept.

With inelastic response analyses considering interaction effects, the seismic safety margin on two-degree-of-freedom models will be discussed.

2 MODELS

Co-axial cylindrical vessels are illustrated in Fig. 1. Each vessel is suspended from a deck, and the deck is supported by a foundation. When they are subjected to horizontal excitations, the outer vessel supports the dead mass of liquid and the mass of rigid core, and the inner vessel supports the inert force of liquid contained inside. The equivalent dynamic system(model 1) is considered(Fig. 2). Masses are supported by a foundation with springs and are coupled by fluid. Subscript 1 denotes the outer vessel and subscript 2 the inner one. The effects of liquid filled between them are represented by virtual masses m_{11}, m_{22}, and m_{12}. The non diagonal term m_{12} represents the coupling and the diagonal terms m_{11} and m_{22} represent the added masses to the structures. Suppose the relative displacements of components are X_1 and X_2, and the base displacement is Y, then, the equations of motion are given by :

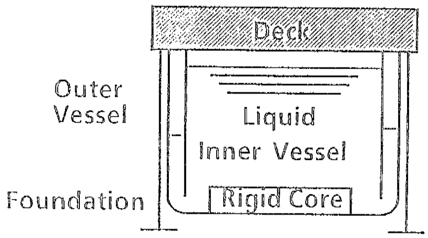

Fig. 1 Co-axial Cylindrical Vessels

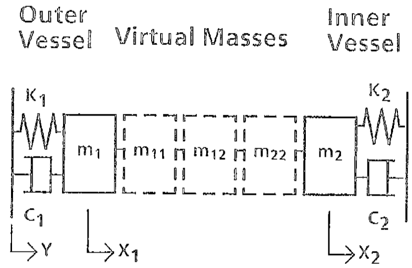

Fig. 2 Model 1

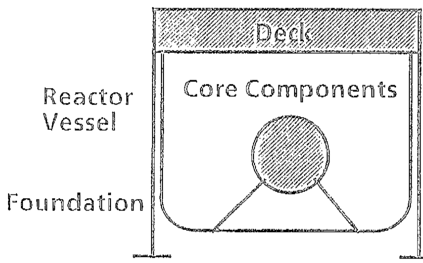

Fig. 3 A Reactor Vessel and Core Components

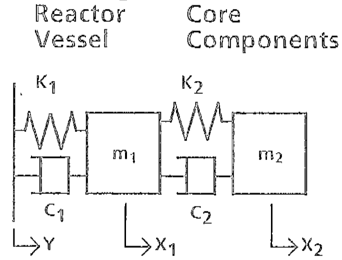

Fig. 4 Model 2

$$\begin{bmatrix} m_1+m_{11} & m_{12} \\ m_{12} & m_2+m_{22} \end{bmatrix}\begin{bmatrix} \ddot{X}_1 \\ \ddot{X}_2 \end{bmatrix}+\begin{bmatrix} C_1 & 0 \\ 0 & C_2 \end{bmatrix}\begin{bmatrix} \dot{X}_1 \\ \dot{X}_2 \end{bmatrix}+\begin{bmatrix} K_1 & 0 \\ 0 & K_2 \end{bmatrix}\begin{bmatrix} X_1 \\ X_2 \end{bmatrix}$$

$$=-\begin{bmatrix} m_1+m_{11} & m_{12} \\ m_{12} & m_2+m_{22} \end{bmatrix}\begin{bmatrix} \ddot{Y} \\ \ddot{Y} \end{bmatrix} \quad (1)$$

A reactor vessel and self-standing core components are illustrated in Fig. 3 and their equivalent dynamic system(model 2) is illustrated in Fig. 4. Subscript 1 and 2 denote the reactor vessel and core components. Masses are coupled by the spring with stiffness K_2. The equations of motion are given by :

$$\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix}\begin{bmatrix} \ddot{X}_1 \\ \ddot{X}_2 \end{bmatrix}+\begin{bmatrix} C_1 & 0 \\ 0 & C_2 \end{bmatrix}\begin{bmatrix} \dot{X}_1 \\ \dot{X}_2 \end{bmatrix}+\begin{bmatrix} K_1+K_2 & -K_2 \\ -K_2 & K_2 \end{bmatrix}\begin{bmatrix} X_1 \\ X_2 \end{bmatrix}=-\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix}\begin{bmatrix} \ddot{Y} \\ \ddot{Y} \end{bmatrix} \quad (2)$$

The force deformation characteristics of a reactor vessel and hysteresis rules are shown in Fig. 5. It is a simplified model for inelastic buckling of thin cylindrical shells.(Nakagawa et al. ;1989) The system yields buckling load at the displacement δ_e without inelastic deformation and δ_{cr} is the buckling displacement. Nonlinear characteristics are expressed by the parameter $\mu=\delta_{cr}/\delta_e$. After buckling, the restoring force decreases with an increasing displacement, and energy input by excitations is absorbed by hysteresis loops.

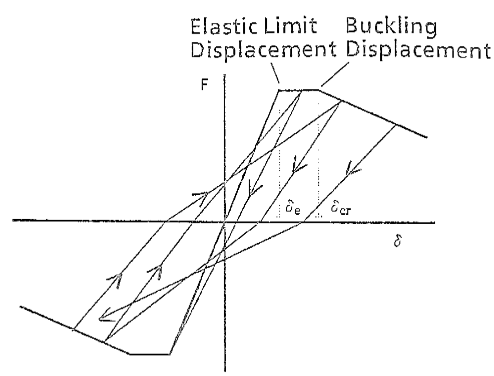

Fig. 5 Force-Deformation Characteristics

3 RESULTS

3.1 Elastic Response Analyses

Table 1 Structural Parameters(Model 1)

m_1	(Kg)	1.567×10^6
m_2	(Kg)	4.880×10^5
K_1	(N/m)	6.251×10^6
K_2	(N/m)	3.536×10^6

Elastic response analyses are carried out on model 1 using a response spectrum method for various depths of liquid filled in a narrow annular between two vessels. The structural parameters are shown in Table 1. The virtual masses are calculated by the 2D theory. The liquid depth treated here does not correspond to an actual 3D value. Thus the liquid depth is called equivalent liquid depth L and it operates the virtual masses. Responses are obtained by modal superposition. A response acceleration spectrum considered as design one is constant with the 1G level for a wide frequency range. Figure 6 demonstrates the loads supported by the outer and inner vessels for various equivalent liquid depths. Without the inner vessel, the interaction would not occur and the outer vessel would behave like a single-degree-of-freedom(SDOF) system supporting m1 under 1G excitation. It is shown in Fig. 6 that the load supported by the outer vessel is reduced depending on L. When L is small, the interaction has a small effect, and the load supported by the outer vessel is almost equal to m_1. With increasing L, the load first becomes minimum and then increases. Maximum reduction in the load is 40% compared to that of the model without interaction.

Modal contributions to the response of the outer vessel for various L values are shown in Fig. 7. The modal contribution is indicated by the product of the participation factor and the normalized modal shape of the subject node. The total sum of modal contributions of the subject node is 1. When L is small or large, contribution from one mode is dominant. When contributions from each mode are equal, the load supported by the outer vessel becomes minimum. Thus, the interaction effect is indicated by modal contributions.

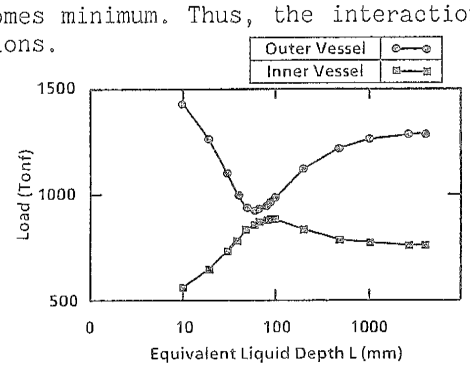

Fig. 6 Loads Supported by Each Vessel for Various L(Model 1)

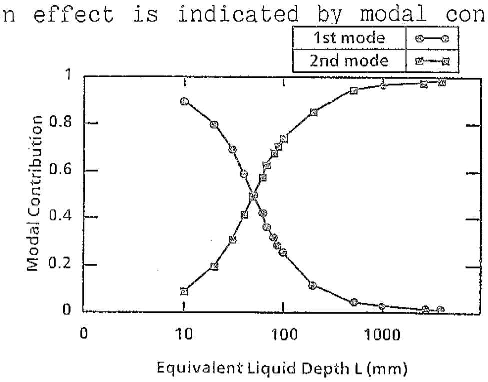

Fig. 7 Modal Contributions of Outer Vessel

3.2 Non-linear Response Analyses

Inelastic response analyses are performed on model 1 by the time history method. The parameters are the equivalent liquid depth L and the input acceleration level. An acceleration response spectrum of input motion is shown in Fig. 8. It is almost constant for a wide frequency range.

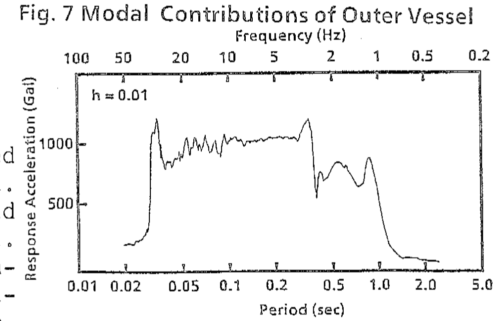

Fig. 8 Response Acceleration Spectrum

The maximum response displacements of the outer vessel and the maximum input acceleration are shown in Fig. 9. Responses of SDOF corresponding to the model without interaction are also shown. When the maximum displacement is smaller than δ_e, the system remains elastic. When the maximum displacement exceeds δ_e, the system is in an inelastic domain. When the maximum displacement attains δ_{cr}, the buckling occurs. The elastic response for L=90 is the smallest. Inelastic responses, however, make little difference regardless of L.

In order to estimate the seismic margin of a reactor vessel and to cancel the differences in elastic responses caused by the interaction effect, the input accelerations are normalized by acceleration α_e for each L which yields buckling load without any inelastic deformations and is the critical acceleration of the design method based on the linear concept. The normalized response characteristics are shown in Fig. 10. It is shown that the responses in a prebuckling domain are smaller than elastic response. But the response displacement increases rapidly in an inelastic domain on model L=90, in which interaction takes effect in an elastic domain.

Inelastic time history analyses are also performed on model 2. The parameters are the natural frequency F_2 of the core component when decoupled, and the input acceleration level. The structural parameters are shown in Table 2. Input acceleration and maximum response displacements are shown in Fig. 11. Also shown are responses of a single-degree-of-freedom

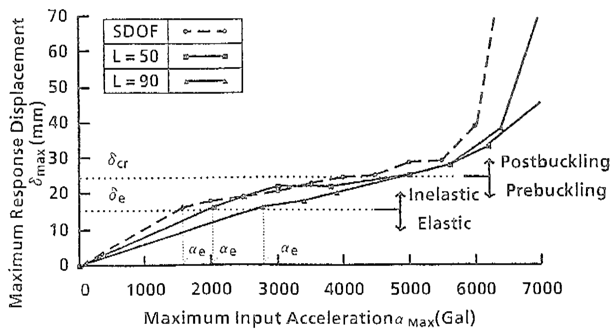

Fig. 9 Response Characteristics for Various L (Model 1)

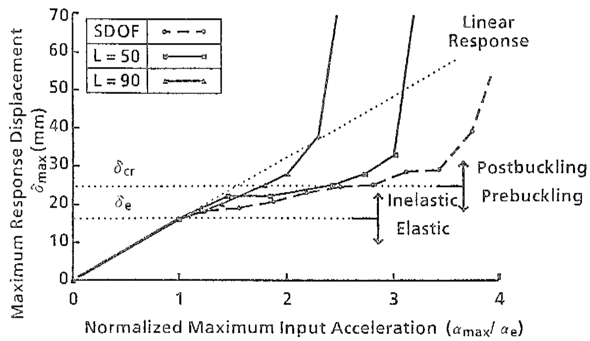

Fig. 10 Normalized Response Characteristics (Model 1)

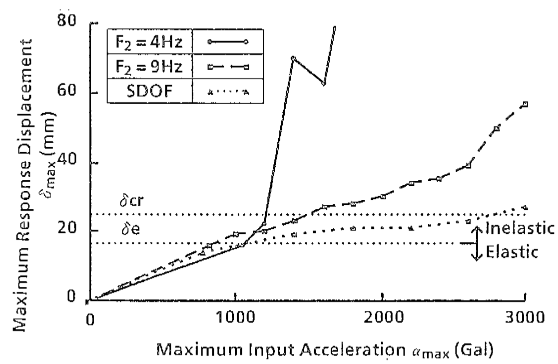

Fig. 11 Response Characteristics for Various F_2 (Model 2)

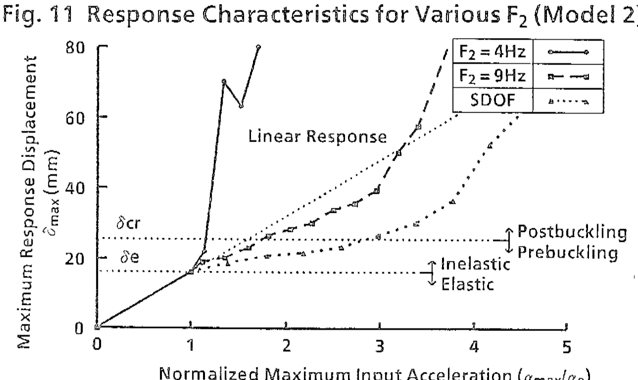

Fig. 12 Normalized Response Characteristics(Model 2)

system corresponding to a model with m_1 and m_2 coupled rigidly. When F_2 is 4Hz, the elastic response is smaller. On the other hand, when F_2 is 9Hz, it is almost equal to the response of SDOF.

Table 2 Structural Parameters(Model 2)

m_1	(Kg)	4.880×10^5
m_2	(Kg)	1.567×10^6
K_1	(N/m)	6.251×10^6

Normalized input acceleration and response displacements are shown in Fig.12. The response displacement increases rapidly with an increase in the intensity of input motions on F2=4Hz. In this case, the inelastic response is greater than the elastic response in prebuckling domain. When F_2 is 9Hz, two masses are coupled rigidly and behave like a single mass.

The reduction in responses depending on the interaction effect does not occur in the inelastic domain. This is because vibration modes change in an inelastic domain. Fig. 13 shows changing equivalent characteristic frequencies as deformation of a reactor vessel advances. As the maximum displacement of a reactor vessel increases, its apparent frequency decreases. An equivalent characteristic frequency also decreases with increasing deformation. Fig. 14 shows the changing of modal contributions of a reactor vessel with advancing deformation. The contribution from the 1st mode increases and that of the 2nd mode decreases when deformation advances. The acceleration response spectrum shown in Fig. 8 is constant regardless of resonant frequency, however the energy input changes depending on the frequency. The energy spectrum of input motion is shown as an equivalent velocity term(Fig. 15). The energy spectrum increases when the frequency decreases. The energy input from the 1st mode increase greatly as the deformation advances. This is because the modal contribution from the 1st mode increases with advancing deformation and with the energy spectrum increase that occurs due to decreasing resonant frequency. On the other hand, the energy input from the 2nd mode hardly changes. The decrease in modal contribution and the increase in energy spectrum cancel each other. If the decrease in modal contribution exceeds the increase in energy spectrum, the energy input from the 2nd mode decreases slightly and vice versa. It is said that the total energy from both modes increases as deformation advances.

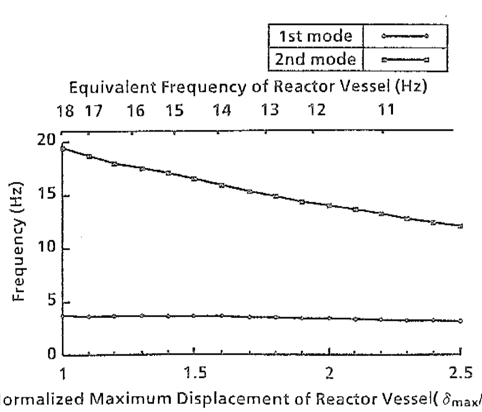

Fig. 13 Equivalent Characteristic Frequency in Inelastic Domain(Model 2 $F_2=4$Hz)

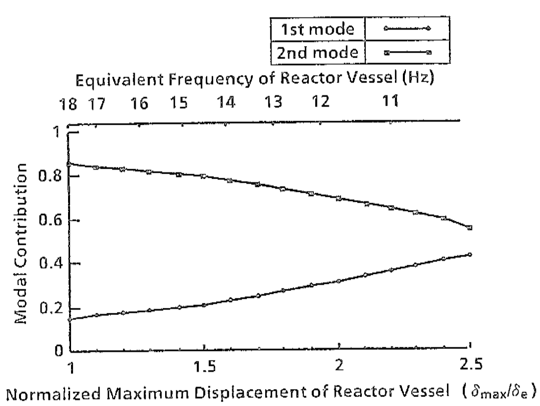

Fig. 14 Equivalent Modal Contributions in Inelastic Domain(Model 2 $F_2=4$Hz)

Why the difference in postbuckling behavior between F_2=4Hz and F_2=9Hz occurs is that the increase ratio of the total input energy of the 4Hz model is larger than that of the 9Hz model. On the 4Hz model, both energy inputs from each mode increase. In addition, the energy input increase ratio of the 4Hz model from the 1st mode is larger than that of the 9Hz model. On the 9Hz model, the decrease in modal contribution from the 2nd mode exceeds the energy spectrum increase. Thus, the energy input from the 2nd mode decreases.

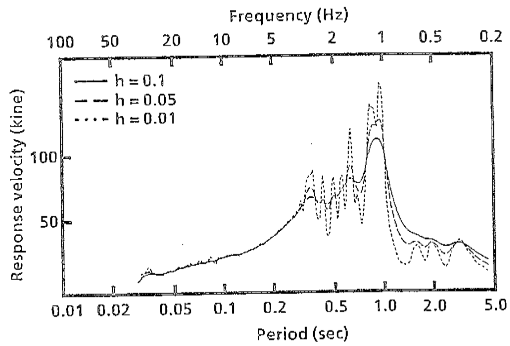

Fig. 15 Energy Velocity Spectrum

4 CONCLUSIONS

(1) The seismic force applied to the vessel can be reduced by the fluid coupled effect and by modal contribution effect. The vessel can withstands greater seismic excitation.

(2) When the reduction in responses is large compared to the model without interaction in the elastic domain, the increment of response per unit increase of excitation in the inelastic domain including postbuckling behavior becomes large.

(3) The drastic increase in response displacement in the inelastic domain on the interaction models is explained by the equivalent modal contributions and by the energy input. And this characteristics cannot be explained by the behavior of single-degree-of-freedom system.

REFERENCES

H.Akiyama, et al.(1987), "Postbuckling behaviors of steel cylindrical shells during earthquakes", Trans. of the 9th-SMIRT, vol. K1, p415~420

M.Nakagawa, et al.(1989), "Postbuckling behavior of short cylindrical shells under lateral seismic loads", Trans. of the 10th-SMIRT, vol. E09/4, p235~240