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Effects of Interaction between Structure and Equipment on Seismic Response

Kwangsub Jung [a], In-Kil Choi [a], Seung-Hyun Eem [a*]
[a]*Korea Atomic Energy Research Institute, 111 Daedeok-daero 989, Yuseong-gu, Daejeon 34057, Republic of Korea*
[*]*Corresponding author: eemsh@kaeri.re.kr*

1. Introduction

Nuclear power plants consist of many structures and equipment. Seismic performances of the safety-related structures and equipment are verified through seismic response analysis. The seismic response analysis is performed with coupled or uncoupled model for the structure and equipment connected to the structure. The coupled model is used when the effect of interaction between structure and equipment are high. The uncoupled model is used when the effect of interaction is negligible. The effect of interaction depends on the mass and natural frequency of the structure and equipment[1, 2].

In this work, we analyze the seismic responses of structure and equipment associated with coupled and uncoupled models through the time integration method. The effects of mass, natural frequency, and coupling method on acceleration responses are delineated.

2. Methods and Results

2.1 Coupled and Uncoupled Model

Models for dynamic coupling between structure and equipment are described in Fig. 1. In model A, the structure and equipment are separated. The seismic response of the equipment is obtained by using the response of the structure as input. In model B, the only difference from model A is the mass of the structure. The mass of the equipment is lumped into the mass of the structure. Model C shows the two degrees-of-freedom system for the structure and equipment. The natural frequencies of the structure and equipment for models are as follows.

$$\omega_p = \sqrt{\frac{k_p}{m_p}},\ \omega_s = \sqrt{\frac{k_s}{m_s}},\ \omega_{p,B} = \sqrt{\frac{k_p}{m_p+m_s}}$$

$$\omega_{1,2} = \sqrt{\frac{\omega_p^2+(1+R_m)\omega_s^2 \pm \sqrt{(\omega_p^2+(1+R_m)\omega_s^2)^2-4\omega_p^2\omega_s^2}}{2}}$$

$$R_m = \frac{m_s}{m_p},\ R_f = \frac{\omega_s}{\omega_p} \tag{1}$$

where m_p, k_p, m_s, and k_s are the mass and stiffness of the structure and equipment, respectively; R_m and R_f are the mass ratio and frequency ratio; ω_p and ω_s are the natural angular frequencies of the structure and equipment in model A; $\omega_{p,B}$ is the natural angular frequency of the structure in model B; ω_1 and ω_2 are the first and second natural angular frequencies in model C.

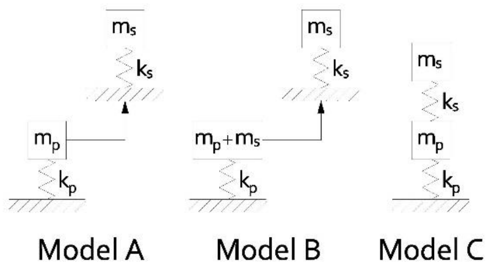

Fig. 1. Models for dynamic coupling of structure and equipment: uncoupled model A, uncoupled lumped model B, and coupled model C

2.2 Methods

Accelerations of the structure and equipment are computed through the seismic response analysis for the coupled and uncoupled models. As shown in Fig. 2, ground acceleration time history of earthquake is generated based on the U.S. NRC regulatory guide 1.60[3]. 30 different input accelerations are used in this work. Equations of motions for models A, B, and C are described in Eqs. (2), (3), and (4), respectively.

$$\begin{aligned} m_p\ddot{y}_p + c_p\dot{y}_p + k_p y_p &= -m_p\ddot{x}_g \\ m_s\ddot{y}_s + c_s\dot{y}_s + k_s y_s &= -m_s(\ddot{x}_g + \ddot{y}_p) \end{aligned} \tag{2}$$

$$\begin{aligned} (m_p + m_s)\ddot{y}_p + c_p\dot{y}_p + k_p y_p &= -(m_p + m_s)\ddot{x}_g \\ m_s\ddot{y}_s + c_s\dot{y}_s + k_s y_s &= -m_s(\ddot{x}_g + \ddot{y}_p) \end{aligned} \tag{3}$$

$$\begin{aligned} m_p\ddot{y}_p + c_p\dot{y}_p + k_p y_p - c_s\dot{y}_s - k_s y_s &= -m_p\ddot{x}_g \\ m_s(\ddot{y}_p + \ddot{y}_s) + c_s\dot{y}_s + k_s y_s &= -m_s\ddot{x}_g \end{aligned} \tag{4}$$

where x_g is ground acceleration, c_p and c_s are damping coefficients of the structure and equipment. In this work, damping ratios of the structure and equipment are 5% and 3%, respectively. y_p and y_s are relative displacements of the structure and equipment. The responses of the structure and equipment are computed by using the Newmark method. Parameters are used as $\beta = 1/12$, $\gamma = 1/2$, and $\Delta t = 0.005$. Mass ratios from 10^{-3} to 1 and frequency ratios from 0 to 5 are considered so that the effects of mass ratio and frequency ratio can be outlined. The peak amplitude of time history graph is chosen as response to each earthquake. The average value over 30 different earthquakes is taken as the response acceleration.

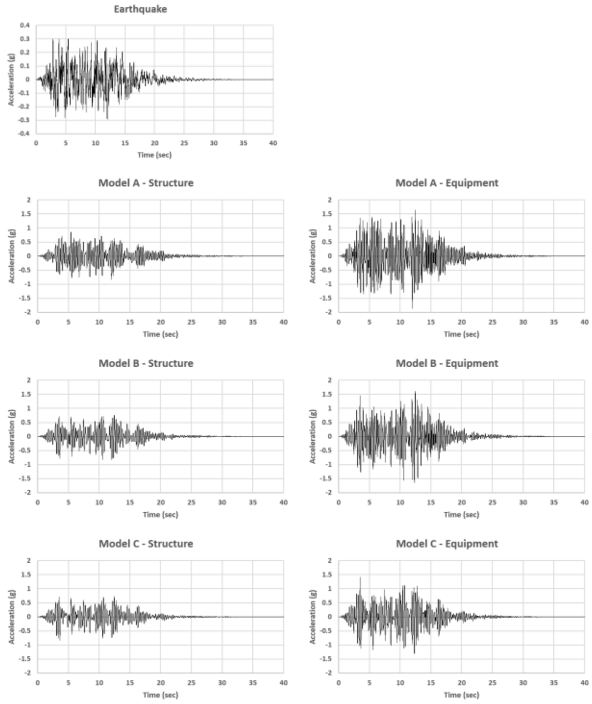

Fig. 2. Time history of ground acceleration and response accelerations of the structure and equipment in models A, B, and C with mass ratio 0.1 and frequency ratio 1.2

2.3 Seismic Responses

Figures 3-5 show the average response acceleration as a function of frequency ratio and mass ratio for the structure of models A, B, and C, respectively. In model A, the acceleration of the structure is not dependent on frequency ratio nor mass ratio. Input ground acceleration determines the response of the structure. In model B, the acceleration of the structure is dependent on mass ratio. As shown in Eq. (1), the natural frequency of the structure in model B is a function of the mass ratio. The response acceleration of the structure in model C is dependent on mass ratio and frequency ratio. As the frequency ratio becomes closer to 1 and the mass ratio becomes larger, the responses of uncoupled models A and B overestimate the true value of coupled model. Model A underestimates the response as mass ratio becomes closer to 1 and frequency ratio becomes higher. Model B overestimates the response as the mass ratio becomes closer to 1 and the frequency ratio becomes lower.

The response acceleration for the equipment of each model is shown in Figs. 6-8. The acceleration of the equipment in model A is dependent on the frequency ratio. A resonance is shown near the frequency ratio, $R_f = 1$. In model B, the acceleration of the equipment is dependent on both the mass ratio and the frequency ratio. In coupled model C, the equipment works as the dynamic absorber. The responses of uncoupled models are similar to that of coupled model when the mass ratio is small or the frequency ratio is far from unity. Both uncoupled models A and B overestimate the response of equipment with mass ratio closer to 1 and frequency ratio near resonance.

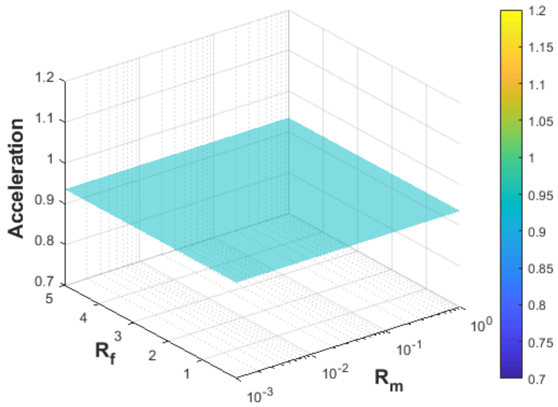

Fig. 3. Response acceleration as a function of frequency ratio and mass ratio for the structure of uncoupled model A

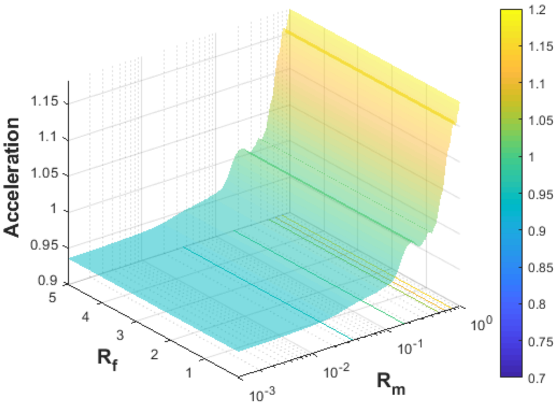

Fig. 4. Response acceleration as a function of frequency ratio and mass ratio for the structure of uncoupled model B

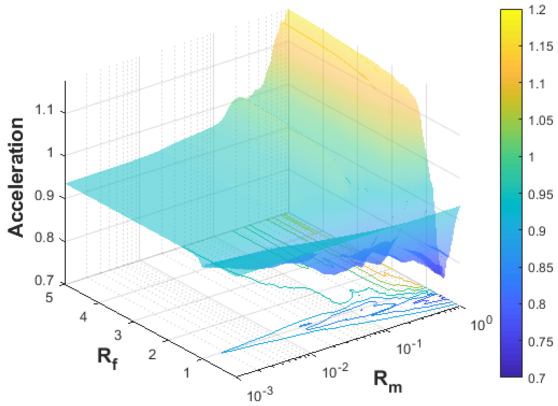

Fig. 5. Response acceleration as a function of frequency ratio and mass ratio for the structure of coupled model C

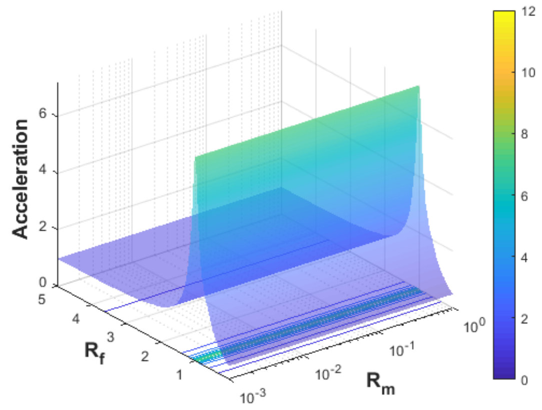

Fig. 6. Response acceleration as a function of frequency ratio and mass ratio for the equipment of uncoupled model A

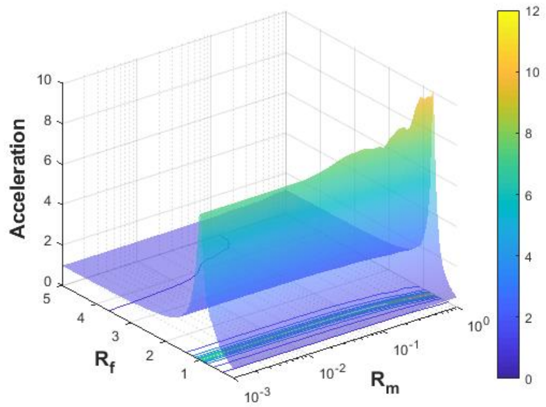

Fig. 7. Response acceleration as a function of frequency ratio and mass ratio for the equipment of uncoupled model B

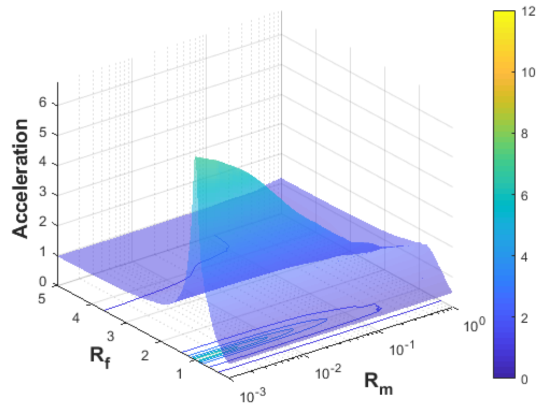

Fig. 8. Response acceleration as a function of frequency ratio and mass ratio for the equipment of coupled model C

3. Conclusions

Seismic responses due to the dynamic coupling between a safety-related structure and equipment connected to the structure are analyzed. Acceleration responses of the structure and equipment for a coupled model and two different decoupled models are computed by using the time integration method. As the frequency ratio becomes closer to 1 and the mass ratio becomes larger, the responses of uncoupled models overestimate the true response of coupled model. Uncoupled model underestimates the response as mass ratio becomes closer to 1 and frequency ratio becomes higher. Uncoupled lumped model overestimates the response as mass ratio becomes closer to 1 and frequency ratio becomes lower. Both uncoupled models overestimate the response of equipment with mass ratio closer to 1 and frequency ratio near resonance. These results can be helpful in determining dynamic coupling and predicting seismic response of uncoupled models.

Acknowledgment

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