Effects of Ground Motion Input on Responses of Structure and Equipment

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1. Introduction

Seismic responses of a structure and equipment connected to the structure are analyzed by using coupled or uncoupled model. The dynamic coupling criteria is based on the interaction between structure and equipment in two degrees-of-freedom system. [1, 2] In the criteria of ASCE-4, the uncoupled model is available when the error in the natural frequency of structure is less than 10%. Seismic responses due to the dynamic coupling models are affected by mass ratio and frequency ratio between the structure and equipment. [3] Errors in responses of uncoupled equipment are larger than those for structure under earthquakes based on U.S. NRC regulatory guide 1.60 [4].

In this work, seismic responses of two degrees-of-freedom system are analyzed. Ground motions with different frequencies and spectral shapes are considered as input.

2. Methods and Results

The uncoupled model behaves like two single-degree-of-freedom systems in cascade with no feedback from equipment to the structure. [5] In the uncoupled model, the structure and equipment are separated and the seismic response of equipment is obtained by using the response of the structure as input. The coupled model is the two-degrees-of-freedom system.

2.1 Harmonic Excitation

For simplicity, ground motion input is considered as simple harmonic motion with a constant amplitude. [5] The ground acceleration can be described as

$$\ddot{x}_g(t) = e^{i\omega t} \tag{1}$$

where ω is the angular frequency of harmonic excitation. The excitation is the real part of Eq. 1. Relative displacements and accelerations of the structure and equipment are expressed with complex transfer functions as

$$\begin{aligned} y_p(t) &= H_{y_p}(\omega)e^{i\omega t},\ \ \ddot{x}_p(t) = H_{\ddot{x}_p}(\omega)e^{i\omega t} \\ y_s(t) &= H_{y_s}(\omega)e^{i\omega t},\ \ \ddot{x}_s(t) = H_{\ddot{x}_s}(\omega)e^{i\omega t} \end{aligned} \tag{2}$$

where x and y indicate the absolute and relative displacements and the subscripts p and s indicate the structure and equipment, respectively. Each response is the real part of Eq. 2. The amplitude of response is absolute value of each transfer function. The transfer functions for the uncoupled model are obtained as

$$\begin{aligned} H_{y_p}(\omega) &= \frac{-1}{-\omega^2 + 2i\zeta_p\omega_p\omega + \omega_p^2} \\ H_{\ddot{x}_p}(\omega) &= -\left(2i\zeta_p\omega_p\omega + \omega_p^2\right)H_{y_p}(\omega) \\ H_{y_s}(\omega) &= \frac{-H_{\ddot{x}_p}(\omega)}{-\omega^2 + 2i\zeta_s\omega_s\omega + \omega_s^2} \\ H_{\ddot{x}_s}(\omega) &= -\left(2i\zeta_s\omega_s\omega + \omega_s^2\right)H_{y_s}(\omega) \end{aligned} \tag{3}$$

for the natural angular frequencies ω_p and ω_s, and the damping ratios ζ_p and ζ_s. The transfer functions for the coupled model are

$$\begin{aligned} H_{y_p}(\omega) &= [\omega^2 - i\omega(1+\mu)2\zeta_s\omega_s - (1+\mu)\omega_s^2]/\Delta \\ H_{y_s}(\omega) &= \left(-i\omega 2\zeta_p\omega_p - \omega_p^2\right)/\Delta \\ H_{\ddot{x}_p}(\omega) &= [-i\omega^3 2\zeta_p\omega_p - \omega^2\left(\omega_p^2 + 4\zeta_p\zeta_s\omega_p\omega_s\right) \\ &\quad + i\omega\left(2\zeta_p\omega_p\omega_s^2 + 2\zeta_s\omega_s\omega_p^2\right) + \omega_p^2\omega_s^2]/\Delta \\ H_{\ddot{x}_s}(\omega) &= [-\omega^2 4\zeta_p\zeta_s\omega_p\omega_s + i\omega(2\zeta_p\omega_p\omega_s^2 \\ &\quad + 2\zeta_s\omega_s\omega_p^2) + \omega_p^2\omega_s^2]/\Delta \end{aligned} \tag{4}$$

where μ is mass ratio between the structure and equipment and the denominator is

$$\begin{aligned} \Delta &= \omega^4 - i\omega^3\left[2\zeta_p\omega_p + 2(1+\mu)\zeta_s\omega_s\right] \\ &\quad -\omega^2\left[\omega_p^2 + (1+\mu)\omega_s^2 + 4\zeta_p\zeta_s\omega_p\omega_s\right] \\ &\quad + i\omega\left[2\zeta_p\omega_p\omega_s^2 + 2\zeta_s\omega_s\omega_p^2\right] + \omega_p^2\omega_s^2 \end{aligned} \tag{5}$$

In this work, damping ratios of the structure and equipment are 5% and 3%, respectively. The natural frequencies are 6 Hz for structure and 8, 12, 16 Hz for equipment corresponding to frequency ratios from 1.33 to 2.67. Mass ratios from 0.01 to 0.1 are considered. In the dynamic coupling criteria [1, 2], those frequency ratios and mass ratios are suitable for the uncoupled model.

Figures 1 and 2 show response accelerations of structure and equipment for both coupled and uncoupled models as functions of frequency of harmonic excitation. The response of structure has a peak at the natural frequency of the structure due to resonance. The resonance of equipment does not affect the response of the structure in the uncoupled model. For equipment, two peaks are observed at both natural frequencies for the structure and equipment. The difference between the coupled and uncoupled models depends on the input frequency and the mass ratio. Error levels in the response acceleration of the uncoupled model compared to that of the coupled model are calculated as shown in Figs. 3 and 4. The response error of the uncoupled model depends on the input frequency. The error is large between the natural frequencies of structure and equipment. The peak error is 27% for the frequency ratio of 1.33 and the mass ratio of 0.01, 14% for the frequency ratio of 2.0 and 12% for the frequency ratio of 2.67. The mass ratio is also a dominant factor in the response error. The peak error is 331%, 173%, and 146% for the same frequency ratios when the mass ratio is 0.1. The response error of the uncoupled model may become very large due to the resonance of the structure and equipment even in the case that the mass ratio and the frequency ratio satisfy the criteria for decoupling.

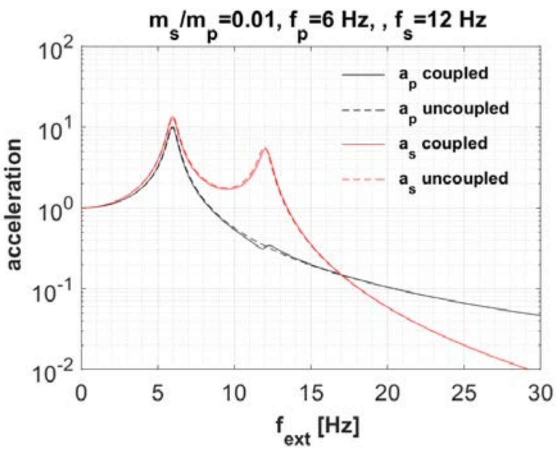

Fig. 1. Response accelerations of structure and equipment for coupled and uncoupled models as function of excitation frequency for the system with mass ratio, 0.01 and frequency ratio, 2.0.

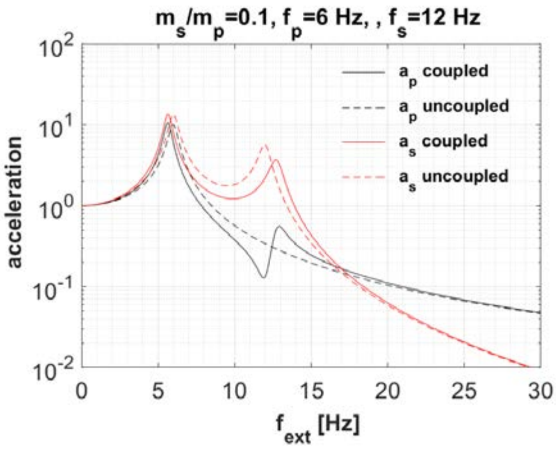

Fig. 2. Response accelerations of structure and equipment for coupled and uncoupled models as function of excitation frequency for the system with mass ratio, 0.1 and frequency ratio, 2.0.

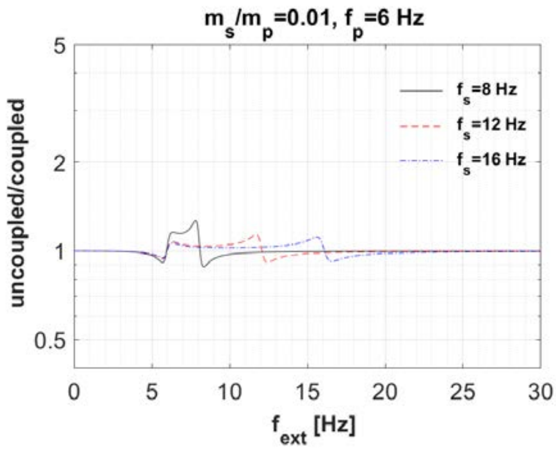

Fig. 3. Error level in the response acceleration of uncoupled model compared to the coupled model as function of excitation frequency for the system with mass ratio, 0.01 and frequency ratio, 1.33, 2.0, and 2.67.

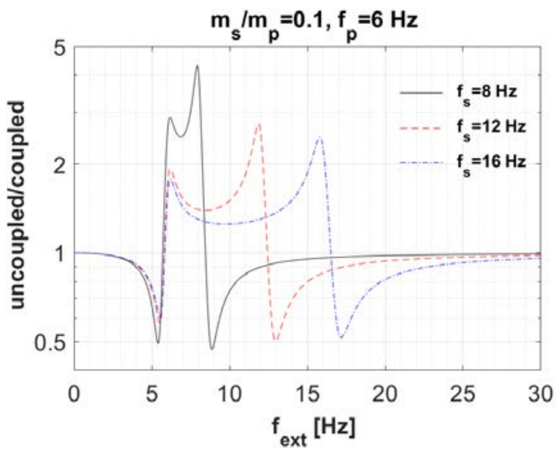

Fig. 4. Error level in the response acceleration of uncoupled model compared to the coupled model as function of excitation frequency for the system with mass ratio, 0.1 and frequency ratio, 1.33, 2.0, and 2.67.

2.2 Seismic Input with Different A/V Ratios

Responses of the structure and equipment are calculated for the coupled and uncoupled models. Earthquakes with different peak ground acceleration to velocity (A/V) ratios [6] are used as input ground motion to investigate the effect of input frequency on the seismic response. Ten earthquakes each according to the low, moderate and high A/V ratios are selected, using a total of 30 earthquakes. The high A/V group has more high-frequency components than other groups. The seismic responses of the structure and equipment are calculated by using the Newmark method. [3] The peak amplitude is chosen from response results of time integration and its average value over 10 different inputs is taken as the response for each A/V group.

Mean errors in the response acceleration of the uncoupled model compared to the coupled model are computed. Figures 5 and 6 show the mean error in the system with the mass ratio of 0.01 and the frequency ratios of 1.33, 2.0, and 2.67. The uncoupled model reproduces the response of the structure with error less than 3% for the given condition. The mean error increases from zero to 3% for the structure with the frequency ratio of 1.33 as the A/V ratio changes from low or moderate ratio to high ratio. The errors in equipment response are less than 7% for the given condition. The mean error increases from 2% to 7% for equipment with the frequency ratio of 1.33 as the A/V ratio changes from low or moderate ratio to high ratio.

The A/V ratio is dominant in the response error of the uncoupled model when the mass ratio becomes 0.1. The mean error in the structure response increases by 28%, 15%, 13% for each frequency ratio as the A/V ratio changes from low ratio to high ratio as shown in Fig. 7. The error in the equipment response increases by 38%, 19%, 19% for each frequency ratio as shown in Fig. 8. The uncoupled model overestimates the response with error of 26% and 58% for the structure and equipment with the mass ratio of 0.1 and the frequency ratio of 1.33 when the A/V ratio is high. The high-frequency components in the earthquakes with high A/V ratio are assumed to increase the response error of the uncoupled model.

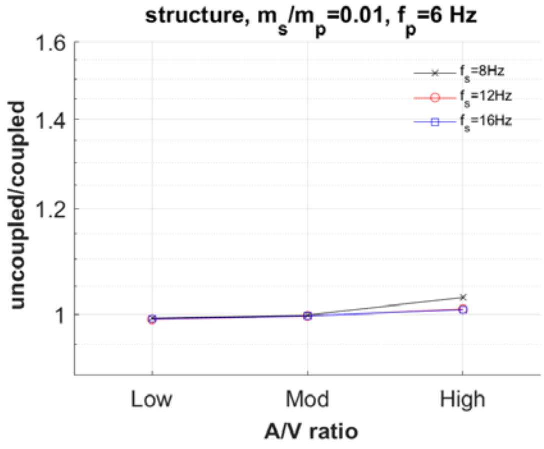

Fig. 5. Mean error in the response acceleration of the structure in the uncoupled model compared to the coupled model as function of A/V ratio for the system with mass ratio of 0.01 and frequency ratios of 1.33, 2.0 and 2.67.

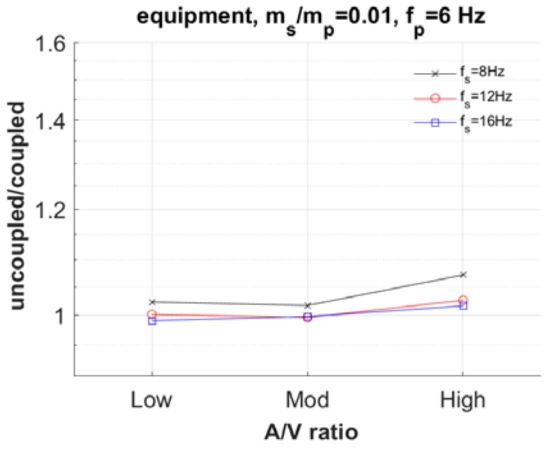

Fig. 6. Mean error in the response acceleration of equipment in the uncoupled model compared to the coupled model as function of A/V ratio for the system with mass ratio of 0.01 and frequency ratios of 1.33, 2.0 and 2.67.

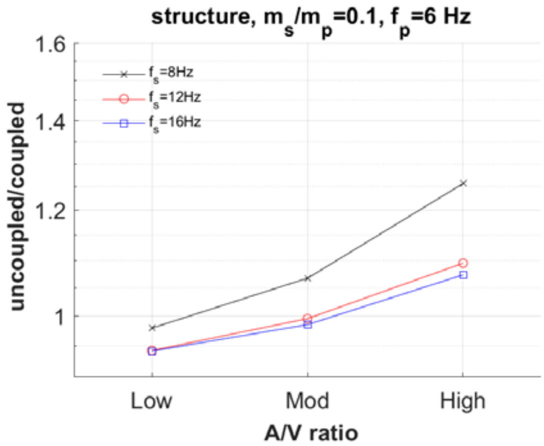

Fig. 7. Mean error in the response acceleration of the structure in the uncoupled model compared to the coupled model as function of A/V ratio for the system with mass ratio of 0.1 and frequency ratios of 1.33, 2.0 and 2.67.

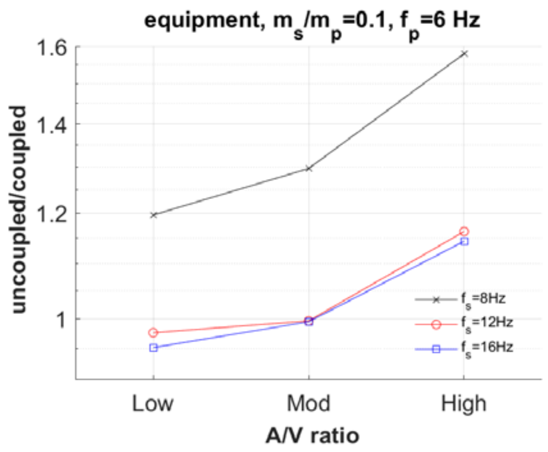

Fig. 8. Mean error in the response acceleration of equipment in the uncoupled model compared to the coupled model as function of A/V ratio for the system with mass ratio of 0.1 and frequency ratios of 1.33, 2.0 and 2.67.

3. Conclusions

Seismic responses of a structure-equipment system are analyzed with various input. A simple harmonic excitation and earthquakes with different A/V ratios are considered as input ground motion. The response error of the uncoupled model is affected by the resonance of the structure and equipment. The response error increases as the A/V ratio changes from low ratio to high ratio. The high-frequency components in the earthquakes with high A/V ratio are assumed to increase the response error of the uncoupled model. Under the high A/V condition, the uncoupled model may overestimate the response even in the cases that satisfy the decoupling criteria.

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