Generation of Equipment Response Spectrum Considering Equipment-Structure Interaction

Sang-Hoon Lee, Kwang-Hoon Yoo
Korea Power Engineering Company, Inc., 360-9 Mabuk-ri, Guseong-eup, Yongin-shi, Gyeonggi-do
shljrl@kopec.co.kr, yh@kopec.co.kr

1. Introduction

Floor response spectra for dynamic response of subsystem such as equipment, or piping in nuclear power plant are usually generated without considering dynamic interaction between main structure and subsystem. Since the dynamic structural response generally has the narrow-banded shapes, the resulting floor response spectra developed for various locations in the structure usually have high spectral peak amplitudes in the narrow frequency bands corresponding to the natural frequencies of the structural system. The application of such spectra for design of subsystems often leads to excessive design conservatisms, especially when the equipment frequency and structure are at resonance condition. Thus, in order to provide a rational and realistic design input for dynamic analysis and design of equipment, dynamic equipment-structure interaction (ESI) should be considered in developing equipment response spectrum which is particularly important for equipment at the resonance condition.

Many analytical methods have been proposed in the past for developing equipment response spectra considering ESI. However, most of these methods have not been adapted to the practical applications because of either the complexities or the lack of rigorousness of the methods. At one hand, mass ratio among the equipment and structure was used as an important parameter to obtain equipment response spectra. Similarly, Tseng has also proposed the analytical method for developing equipment response spectra using mass ratio in the frequency domain[2]. This method is analytically rigorous and can be easily validated. It is based on the dynamic substructuring method as applied to the dynamic soil-structure interaction (SSI) analysis, and can relatively easily be implemented for practical applications without to change the current dynamic analysis and design practice for subsystems. The equipment response spectra derived in this study are also based on Tseng's proposed method.

2. Theoretical background

Using the dynamic substructuring technique, the problem of determining equipment response spectra including ESI can be defined into a form similar to the seismic SSI system problem in which the equipment represents the structure of the SSI system and the structural system represents the soil foundation of the SSI system. Base on such an analogy, the dynamic interaction between the equipment and the supporting structural system can be characterized using the equipment support impedance function which represents the dynamic force-displacement relation of the supporting structural system at the equipment support location.

The equation of motion for the single-degree-of-freedom system subjected to the floor acceleration time history excitation $\ddot{Z}(\omega)$ in the frequency domain can be expressed as

$$\ddot{U}_e(\omega) = H_e(\omega)\cdot\ddot{Z}(\omega) = \frac{1+i(2\beta_e\Omega_e)}{(1-\Omega_e^2)+i(2\beta_e\Omega_e)}\ddot{Z}(\omega) \quad (1)$$

where $\ddot{U}_e(\omega)$ is the Fourier Transforms of absolute acceleration of equipment, $\ddot{u}_e(t)$; $H_e(\omega)$ is the transfer function of the SDOF system; β_e is equipment damping ratio; ω is circular frequency; Ω_e is the ratio of circular frequency to the equipment frequency. Using the solution of Eq. (1), the equipment response spectral value, $R_f(\omega_e,\beta_e)$, is given by

$$R_f(\omega_e,\beta_e) = \left|\ddot{u}_e(t)\right|_{\max} = \left|\int_{-\infty}^{\infty} H_e\ddot{Z}(\omega)e^{i\omega t}d\omega\right|_{\max} \quad (2)$$

In order to develop the equipment response spectrum considering ESI, the equation of motion for the equipment and supporting structure subjected to the floor acceleration $\ddot{Z}(\omega)$ can be written in the frequency domain as[2]

$$\left[-\omega^2 m_e + \frac{i\omega c_e + k_e}{1+\kappa}\right]X_e(\omega) = -m_e\ddot{Z}(\omega) \quad (3)$$

where m_e , c_e , k_e are mass, damping coefficient, and stiffness of the equipment, respectively; $X_e(\omega)$ is the Fourier Transform of the relative displacement of the equipment; κ is the equipment-to-structure impedance ratio. The solution to Eq. (3) in the frequency domain can be expressed as[2]

$$\ddot{U}_e(\omega) = H'_e(\omega)\cdot\ddot{Z}(\omega) = \frac{1+i(2\beta_e\Omega_e)}{\{1-(1+\kappa)\Omega_e^2\}+i(2\beta_e\Omega_e)}\ddot{Z}(\omega) \quad (4)$$

where $H'_e(\omega)$ is the transfer function of the SDOF system including ESI. The equipment response spectral value, defined by as $R_e(\omega_e,\beta_e,m_e)$, is thus given by

$$R_e(\omega_e,\beta_e,m_e) = \left|\ddot{u}_e(t)\right|_{\max} = \left|\int_{-\infty}^{\infty} H'_e\ddot{Z}(\omega)e^{i\omega t}d\omega\right|_{\max} \quad (5)$$

3. Application examples

The equipment response spectrum generated by the above scheme was compared with the one obtained from full structure model with equipment model to identify the effectiveness of the described technique through numerical analyses.

3.1 Validation

The problem considered[3] is a typical pressurized water reactor building with the equipment subjected to an input motion, 1940 El Centro earthquake (north-south direction with 10 sec duration digitized by 0.005seconds). The equipment weighing 23.1kips is located at the top level of the building, and its damping coefficient is 2%. The response spectral values to the full structure model at the frequency range of 0.2Hz through 25Hz were calculated using SASSI, dynamic soil-structure interaction analysis program in frequency domain[4]. The equipment response spectrum with ESI was also calculated by the above scheme, and the two spectral curves were plotted as the Figure 1 for comparison. Since both approaches to obtain equipment response spectra are based on linear dynamic analysis, two spectral curves should give the same values as the results of the Figure 1.

3.2 Effect of equipment mass

In this step, spectral peak reduction is shown through the application of this scheme for generating equipment response spectra with a variety of equipment mass. The reactor building, equipment location and the input excitation considered in the numerical analyses were given to the same condition as the previous example. The three equipment mass types, 0.2kips, 0.5kips, 1.0kips, were selected additionally. As shown in Figure 2, the spectral peak reduction appeared evidently around 5.1Hz and in the frequency range of 15.7Hz to 16.1Hz, and became more significant as the equipment mass increased. The spectral peak value was reduced to maximum 23.8% in this example.

4. Conclusions

An analytical scheme for generating equipment response spectra taking into account ESI has been reviewed. The effectiveness and the applicability of the scheme were also investigated through numerical example analyses using a typical pressurized water reactor building. The equipment response spectra developed in this technique, even though requiring additional calculation efforts, offer the following definitive advantages:

(1) The equipment response spectra developed by this technique have lower response spectral amplitudes theoretically than those of the conventionally defined floor response spectrum at the corresponding location and for the same damping. The reduction is especially significant at the spectral peak and is proportional to the equipment mass.

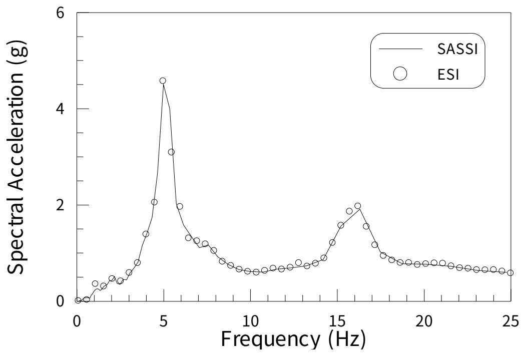

Figure 1. Comparisons of equipment spectral accelerations considering ESI effects with those from conventional dynamic response analysis using SASSI.

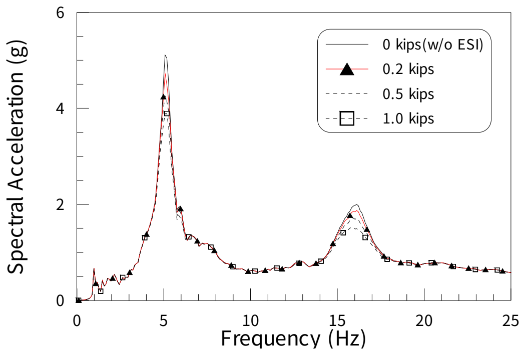

Figure 2. Effect of equipment mass in generating equipment response spectrum taking into account ESI.

(2) The equipment spectra as defined can be directly applied for subsystem analysis and design in the almost same manner as are the conventional floor response spectra without having to change the current design practice.

The method reviewed in this study only available in the frequency domain analysis shall be extended into the time domain analysis in the further study.

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