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Time Domain Calculation of Equipment Response by Dynamic Coupled Analysis of Equipment and Structure

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1. Introduction

Floor response spectrum (FRS) for seismic analysis and earthquake resistant design of nuclear power plant has been calculated without considering dynamic interaction between main structure and its subsystems such as mechanical equipments or piping systems. This FRS tends to have high peak value in a narrow band near natural frequency of the main structure and sometimes causes excessive conservativeness for design of the subsystems. So several methods to reduce the conservativeness by considering equipment-structure interaction (ESI) have been suggested. However, most of them are based on dynamic analysis in frequency domain [1-3] or don't have established procedure to get FRS efficiently in time domain. Herein, a method to generate FRS in time domain by mode superposition is described and the result applied to the containment building model of Shin-Kori Nuclear Power Plant 3&4 (SKN3&4) is presented.

2. Method and Result

2.1 Methodology

The FRS including ESI effect in time domain can be obtained by general dynamic analysis for appropriate structural model in series. The model is composed of a main structure and a single degree of freedom (SDOF) system reflecting properties of the FRS. That is, the properties of the SDOF system such as mass, damping and stiffness are determined according to the equipment mass ratios, control frequencies and damping ratios at each selected location of the structure. Then the SDOF system is attached to the main structure and the maximum response value is calculated by the mode superposition method as described below.

The equation of motion of the total system is defined by the following equation:

$$M\ddot{Y} + C\dot{Y} + KY = P(t) \tag{1}$$

$$V = \Phi Y \tag{2}$$

where M , C , and K are respectively mass, damping, and stiffness matrix of the entire structure, and Y is the displacement vector of the system. By using mode vector Φ which is described in equation (2), and multiplying the equation (1) by Φ^T , we can rewrite the motion of equation as follows.

$$\Phi^T M\Phi \ddot{Y} + \Phi^T C\Phi \dot{Y} + \Phi^T K\Phi Y = \Phi^T P(t) \tag{3}$$

While typical structural system has damping matrix whose non-diagonal elements are all 0's, this system consisting of the main structure and the attached SDOF system has damping matrix with non-zero diagonal terms. This is not only because the damping ratio of the SDOF system is generally different from that of the main system but also because it must vary into several values. In order to solve with the non-classical damping system, theoretically we have to convert the problem into frequency domain or apply direct integration method. But the former doesn't relate with the purpose of this paper and the latter needs too much time to get solution.

Since the mass of the SDOF system is relatively small compared with that of the main structure, i.e., equipment-floor mass ratio is low, and the SDOF system has definite frequency trait, it can be supposed that the effect of the non-proportional damping behavior is negligible and the entire system has proportional damping characteristics. Therefore, the equation (1) can be expressed by mode separation as follows:

$$m_i\ddot{y}_i(t) + c_i\dot{y}_i(t) + k_i y_i(t) = p_i(t) \tag{4}$$

where subscript *i* means mode numbers ($i = 1, \cdots, e, \cdots, n$) and *e* is the mode number corresponding to the natural frequency of the SDOF system. The equation (4) can be rewritten by using natural frequency ω_i and damping ratio ξ_i as follows.

$$\ddot{y}_i(t) + 2\xi_i\omega_i\dot{y}_i(t) + \omega_i^2 y_i(t) = \frac{p_i(t)}{m_i} \tag{5}$$

$$\xi_i = \frac{c_i}{2\omega_i m_i} \tag{6}$$

Development of recent computer technology makes it possible to get the FRS at the selected locations by calculating and collecting the maximum response values of the SDOF system whose properties change in succession. Specific procedure for generation of FRS considering ESI effect in time domain is shown in Figure 1.

2.2 Application Result

For verification of the methodology described above, a containment building model of SKN3&4 is employed. The model is composed of three-dimensional beam-stick and lumped-mass elements with fixed base as shown in Figure 2. An earthquake ground motion having total duration of 20.48 seconds and strong motion of 7.5 seconds was generated by artificial synthesis method at intervals of 0.005 seconds. Peak ground acceleration of the motion is anchored to 0.3g and the shapes of time history and response spectrum are shown in Figure 3(a) and 3(b).

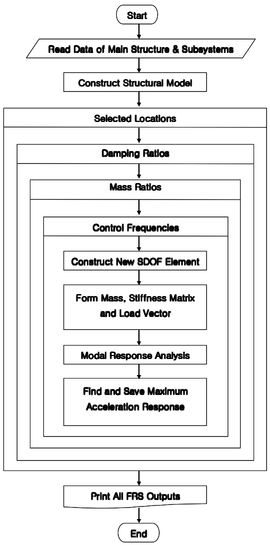
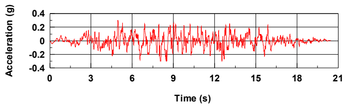
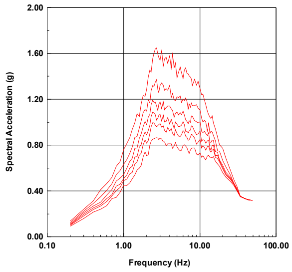


Figure 1. Procedure for generation of FRS considering ESI effect in time domain

Figure 2. Containment building model of SKN3&4



(a) Time history of input motion

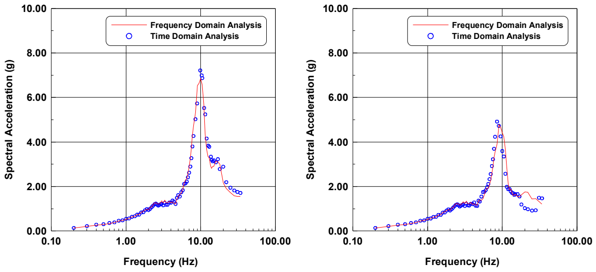


(b) Response spectrum of input motion (Damping ratio: 1%, 2%, 3%, 4%, 5%, and 7%)

Figure 3. Input ground motion

As the SDOF system attached to the containment building has minor equipment-floor mass ratio and apparent control frequency value, the assumptions mentioned in the previous section are acceptable and the analysis procedure can be applied to this model.

The analysis results are shown in Figure 4(a) and 4(b), respectively representing the FRS of two selected locations; top point of primary shield wall and top point of secondary shield wall. For both cases, damping ratio of the FRS is 4% and equipment-floor mass ratio is 2% and control frequency range is 0.2~34Hz. Enveloping and widening work is not performed yet.



(a) FRS at top point of primary shield wall

(b) FRS at top point of secondary shield wall

Figure 4. Analysis results of containment building

The figures also show the analysis results of frequency domain in the same graphs. As the results of time domain analysis are not different from those of frequency domain analysis, the methodology described in Section 2.1 is appropriate to get FRS of structures that satisfy the assumptions mentioned in the same section.

3. Conclusion

To reduce excessive conservativeness due to FRS without considering dynamic interaction between main structure and its subsystems, seismic analysis reflecting ESI effect can be performed in both frequency and time domain. In this paper, an efficient procedure to generate FRS in time domain by mode superposition was proposed and its validity was investigated by applying to the containment building of SKN3&4. This method can be useful tool for earthquake resistant design for structures having subsystems whose masses are relatively small compared with those of the main structure like nuclear power plants.

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