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EFFECT OF MODELING ON SEISMIC RESPONSE OF SECONDARY SYSTEMS

Armen Der Kiureghian

Department of Civil Engineering
University of California
Berkeley, California, U.S.A.

SUMMARY

In the seismic analysis of secondary subsystems, such as equipment and piping in nuclear power plants, highly idealized models are used to represent complex primary structures. Most frequently, a simple lumped-mass, stick model is used and the effect of local vibrations of structural and nonstructural elements are ignored. In this paper, through a parametric study on floor response spectra for two example structures, the influences of various modeling idealizations on the secondary response are examined. It is shown that model idealization can have significant influence on the predicted response of high-frequency secondary subsystems. In particular, the neglect of the local vibration of structural elements may result in an underestimation and the neglect of the local vibrations of nonstructural elements may result in an overestimation of the secondary response. Insight and guidelines for proper modeling of the primary structure are provided throughout the paper.

INTRODUCTION

Secondary subsystems supported on primary structures, such as equipment and piping attached to the containment structure in a nuclear power plant, play important roles in maintaining the safety or operation of industrial facilities, particularly in the event of severe earthquakes. Such subsystems often comprise a large portion of the design and construction cost of facilities. Hence, accurate methods for predicting their responses to earthquake excitations are of great interest.

In recent years, based on methods of random vibrations and perturbation theory, accurate analytical methods for predicting the seismic response of secondary subsystems directly in terms of the ground response spectrum have been developed (Refs. 4,5). These techniques are capable of accounting for such phenomena as tuning (i.e., the coincidence of the frequencies of the two subsystems, which gives rise to resonant responses of the secondary subsystem), interaction, non-classical damping, and cross-modal and cross-support correlations, which are special characteristics of composite primary-secondary systems. Comparisons with "exact" results obtained by time history analyses of the composite system have verified the accuracy of these analytical methods.

The experience with these analytical methods, however, has revealed a curious phenomenon. Namely, theoretically estimated responses for tuned secondary subsystems are much larger than responses observed for similar subsystems in experiments or in real earthquakes. For example, it is not unusual to theoretically predict an amplification of 20 in the peak response of a tuned secondary subsystem, e.g., a peak acceleration of 20g from an earthquake of 1g peak ground acceleration. However, such large amplifications have never been observed or measured for secondary subsystems, even in carefully conducted experiments (Ref. 2). This phenomenon is even more pronounced if one attempts to predict the response of tuned tertiary subsystems, such as a light valve attached to a piping system. In a recent theoretical study, peak tertiary accelerations of order 100g from an earthquake of 0.5g peak ground acceleration were predicted (Ref. 8). Such estimates surely are not in concurrence with our engineering intuition.

It is shown in this paper that a main cause for the overestimation of the response of tuned secondary subsystems lies in the idealization of the primary structure in the theoretical modeling of the system. In the current practice, usually a lumped-mass model of the primary structure describing its global features is used to generate floor response spectra (FRS). (An FRS represents the peak response of an oscillator attached to a specified point in the primary structure, plotted as a function of the frequency and damping of the oscillator.) The peaks of the FRS at tuning frequencies are broadened to account for the effect of uncertainty in the primary modal frequencies; the peak-broadened FRS are then used to estimate the secondary responses (see Ref. 1). Such models neglect the effect of local vibrations of structural elements and of the various nonstructural elements attached to the structure. Whereas the adequacy of such idealized models for predicting the response of primary structures has been established by a long history of experiments and measurements, their validity for predicting the response of secondary subsystems remains to be investigated. This paper demonstrates that the conventional modeling approach which neglects the local vibrations of structural and nonstructural elements may lead to erroneous estimates of the secondary response. In particular, it is shown that neglecting the effect of structural elements may result in underestimation of the response of high-frequency secondary subsystems, and neglecting the effect of nonstructural elements may result in a gross overestimation of the response of tuned secondary subsystems.

EFFECT OF MODELING OF THE PRIMARY STRUCTURE

A visit to a nuclear power plant is an enlightening experience for any structural engineer interested in the dynamic response of structures and secondary subsystems. At each floor of the structure one observes an enormous number of nonstructural attachments, such as equipment items, pipes of all sizes running in all directions, valves, hangers, cabinets, ducts, etc., as well as structural elements, such as beams, columns, walls, and slabs. Although virtually all such elements participate in the dynamic response of the system, for pragmatic reasons it is virtually impossible to account for every detail. In practice, most typically a lumped-mass model (usually a simple stick) is used, where the entire mass of a floor or a segment of a floor together with its attachments is lumped at a nodal point. In this approach no account is made of the local vibrations of structural or nonstructural elements.

Four factors in the modeling of the primary structure are relevant to an accurate prediction of the secondary response: (a) the level of refinement in the model describing the global features of the primary structure, (b) the effect of local vibrations of structural elements, (c) the effect of local vibrations of nonstructural elements, and (d) the effect of uncertainty in the properties of the primary structure. In this paper, the effects of the first three factors are evaluated by examining the floor response spectra for two example structures: a cantilever column representing the containment vessel of a nuclear power plant, and a four-story frame structure representing an auxiliary building. The two structures with their properties are depicted in Fig. 1. In all cases, the floor response spectra are computed with a zero mass of the oscillator (i.e., neglecting the effect of oscillator-structure interaction) and for 2 percent damping of the oscillator. The NRC RG-160 recommended ground response spectra for the horizontal and vertical directions with 1.0g and 0.5g peak ground accelerations, respectively, are employed for this analysis. The effect of the fourth factor is studied elsewhere (6,7).

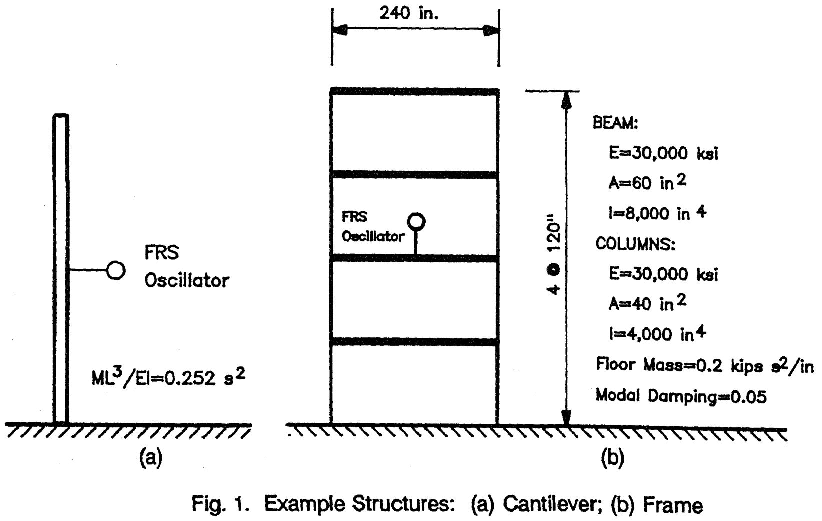

Fig. 1. Example Structures: (a) Cantilever; (b) Frame

Effect of Model Refinement A measure of refinement of the primary structure model is the level of mass discretization. To examine this effect, the cantilever column is represented by a lumped mass stick model with in turn 4, 8, and 16 nodal masses. In each case, the rotational moments of inertia of the nodal masses are ignored. The resulting floor response spectra for an oscillator attached at the midheight of the cantilever are shown in Fig. 2a. The following observations can be made: (a) Refinement in the mass discretization tends to shift the peaks of FRS towards higher frequencies without appreciably changing their amplitudes. This is due to a shift in the modal frequencies of the primary structure as the mass distribution is refined. (b) The shift in the peaks is increasingly more pronounced at higher frequencies and for a coarser mass discretization. (c) For the 4-DOF model, the FRS exhibits a fourth peak which is due to the largely shifted fourth mode of the primary model. Obviously, this model is inadequate for predicting the FRS at high frequencies.

The main conclusion from these observations is that the level of mass discretization in the primary model should be such that all primary modal frequencies that are within the range of FRS frequencies are accurately represented. Otherwise, spurious peaks from shifted modal frequencies may appear in the FRS. Since secondary subsystems often have high-frequency modes, the needed level of model refinement can be greater than that needed for predicting the response of the primary structure itself. From the preceding observations, it is also clear that, provided the proper level of model refinement is used, shifts in the peaks of FRS due to further model refinement would be sufficiently small so as to be absorbed by the peak broadening mentioned above.

Effect of Local Vibration of Structural Elements The FRS for an oscillator attached at the middle of the second-floor beam of the frame structure is considered. Curves 1 in Fig. 2b depict the horizontal and vertical FRS based on a model of the primary structure in which the mass at each floor level is lumped at the two end points (i.e., neglecting the local vibrations of the beam), mass rotational moments of inertia are neglected, and axial deformations of all members are included. Curve 2 depicts the horizontal FRS for the same model but ignoring the effect of axial deformations. Curves 3 depict the horizontal and vertical FRS including the effect of the local vibration of the attachment floor. For this purpose, the floor mass is discretized at eight points along the beam. The following observations can be made: (a) The effect of axial deformations on the horizontal FRS is negligible. (b) The refinement in the mass discretization results in shifts in the peaks of the horizontal FRS similar to those observed in the preceding example. (c) For the vertical FRS, in addition to the shift in the peaks, a new peak is observed at 42.6 Hz. This peak is due to the local vibration mode of the floor beam in the vertical direction.

The main conclusion from the above observations is that the local vibration of an attached structural element can have a significant influence on the FRS if the modal frequency of the structural element is within the frequency range of interest. Since structural elements usually have high-frequency modes, their effect is significant only for secondary subsystems with high-frequency characteristics.

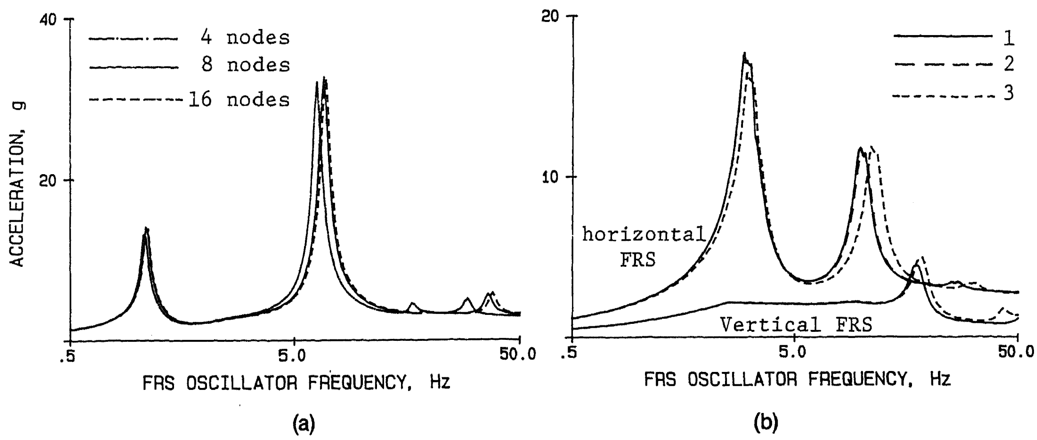

Fig. 2. Effect of Modeling on FRS: (a) cantilever Structure; (b) Frame Structure

Effect of Local Vibration of Nonstructural Elements A nonstructural element attached to the primary structure is modeled herein as an oscillator of frequency ω_0, damping ratio z_0, and mass m_0, the latter being a small fraction of the attached floor mass, m. Each such attached oscillator tends to affect the modes of the primary structure. This influence is greatest when the oscillator mass is large and when its frequency is near a modal frequency of the primary structure. In that case the modal frequencies of the primary structure are shifted and closely spaced modes appear in the combined oscillator-structure system (Ref. 4). Such closely spaced modes are known to result in a "dispersion" of vibratory energy and, hence, reduced resonance peaks in the FRS (Ref. 3).

To investigate this effect, consider a nonstructural element attached in the second floor (same floor as the FRS oscillator) of the frame structure with a frequency equal to the first mode of the primary structure and a damping ratio z_0 = 0.05. The horizontal FRS (excluding the local vibration of the beam element) for three values of the mass ratio m_0/m = 0., 0.01, 0.05 are shown in Fig. 3. Observe that the effect of the local vibration of the nonstructural element is to reduce the peak of the FRS corresponding to the first mode of the primary structure. This is due to two effects: dispersion of the vibratory energy in the primary structure and, hence, reduced sharpness in the resonance, and the added energy dissipation due to the damping in the nonstructural element. Also observe that the nonstructural element does not have a significant influence on the FRS at frequencies beyond the immediate neighborhood of its natural frequency.

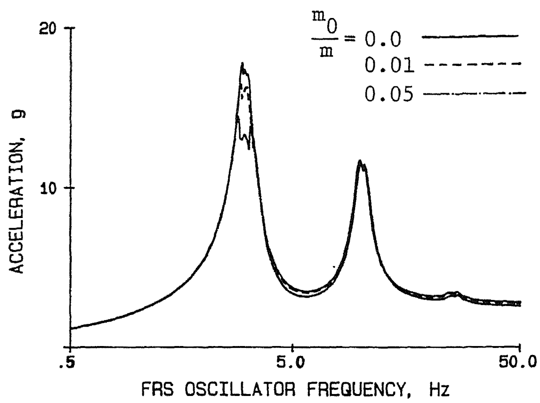

Fig. 3. Effect of a Nonstructural Element on FRS of the Frame Structure

To further investigate the above effect, a parametric study of the FRS of the 8-DOF cantilever column is performed. The results, taken from Ref. 3, are summarized in Fig. 4. These results show the second peak in the FRS in Fig. 2a (shown as a dashed curve in Fig. 4) as affected by the local vibrations of nonstructural elements with varying mass, frequency, and point of attachment. In all cases z_0 = 0.02 is assumed. Fig. 4a shows the influence of the mass of the nonstructural element which is attached to the DOF 4 and has a frequency equal to that of the second primary mode. The reduction in the peak is significant even for small values of the oscillator mass. Fig. 4b shows the influence of the frequency of the oscillator for a mass ratio of 0.05. The reduction in the peak becomes less significant with increasing distance between the frequency of the oscillator and the primary modal frequency. Fig. 4c shows the influence of the location of the nonstructural element; it is found that the influence on the FRS is greater when the element is attached at DOF's where the second primary mode has a large displacement.

From the above results, it is clear that a single nonstructural element with the proper frequency, mass, and location of attachment can significantly reduce the peak in the FRS. In reality, a primary structure has numerous nonstructural attachments with varying characteristics. Also, at the time of analysis or design of a secondary subsystem,. the characteristics of other attachments to the primary structure are largely unknown. Therefore, a statistical approach to the modeling of nonstructural elements is essential. In this paper, purely as a preliminary investigation, the combined effect of such multiple nonstructural elements is studied by the following means: At each DOF of the primary structure three oscillators of equal mass are attached; the oscillator frequencies are selected by random generation with a uniform distribution between 5 to 10 Hz; each oscillator is assumed to have 2 percent damping; the combined (8 + 3x8 =) 32-DOF system is considered as the primary structure for which the FRS are computed. The resulting FRS for two values of the oscillator/floor mass ratio are depicted in Fig. 4d. This figure shows that in a realistic structure with many attached nonstructural elements the peaks in the FRS can be significantly smaller than those predicted without considering the effect of the nonstructural elements.

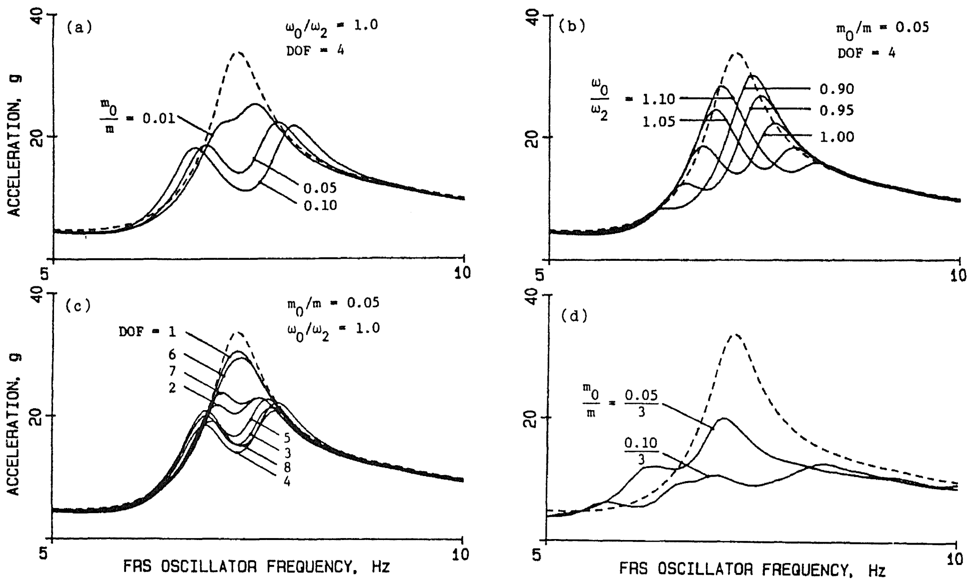

Fig. 4. Effect of Nonstructural Elements on FRS of the Cantilever Structure: (a) Effect of m_0; (b) Effect of ω_0; (c) Effect of Location; (d) Effect of Multiple Elements

Effect of Uncertainty in the Properties of the Primary Structure Uncertainty in the mass and stiffness properties of a primary structure result in uncertainty in its natural frequencies and, hence, in the positions of the peaks in the FRS. On the other hand, uncertainty in the damping characteristics results in uncertainty in the amplitude of FRS. Recent analytical studies using first and second-order reliability methods (Ref. 7) reveal that the uncertainty in the mass and stiffness characteristics can have a dominant influence on the secondary response, even if the associated uncertainty is smaller than that in the damping. This and an earlier study (Ref. 6) also reveal that the conventional peak-broadening procedure is a reasonable and practical approach to account for the effect of the uncertainty in the natural frequencies. More refined methods, such as those described in Ref. 7, are available for more careful investigations of this effect.

CONCLUSIONS

The main conclusions from this study can be summarized as follows: (a) The mass discretization in the primary model should be sufficiently fine such that all global modal frequencies of the primary structure within the frequency range of the FRS are accurately represented; (b) local vibrations of attached structural elements may introduce peaks in the FRS if the natural frequencies are within the range of interest; (c) local vibrations of attached nonstructural elements may significantly reduce the amplitudes of the peaks in the FRS; (d) uncertainties in the mass, stiffness and damping characteristics of the primary structure can have significant influence on the secondary response; (e) in general, a careful modeling of the primary structure is necessary for accurate prediction of the response of attached secondary subsystems. The level of refinement necessary might be greater than that required for predicting the response of the primary structure itself.

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