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Significance of non-classical damping in seismic qualification of equipment and piping

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HIGHLIGHTS

- Damping in coupled building-piping or building-equipment systems is nonlclassical.
- Significance of nonclassical damping is illustrated.
- Classical damping assumption can over predict or under predict response.
- Significance of nonclassical damping increases for very light secondary systems.
- Composite modal damping is another form of classical damping.

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ABSTRACT

This paper presents a discussion on the significance of non-classical damping in coupled primary-secondary systems such as building-equipment or building-piping. Closed-form expressions are used to illustrate that the effect of non-classical damping is significant in systems with tuned or nearly tuned uncoupled modes when the mass-interaction is sufficiently small. Further, simple primary-secondary systems are used to illustrate that composite modal damping is another form of classical damping for which the transformed damping matrix, obtained after pre- and post-multiplication of the damping matrix with the modal matrix, contains only diagonal terms. Both the composite and the classical damping give almost identical results that can be much different from the corresponding results for non-classical damping. Finally, it is shown that consideration of classical damping (ignoring the off-diagonal terms) can give excessively conservative results in nearly tuned primary-secondary systems. For perfectly tuned primary-secondary systems, however, classical damping can give responses that are much lower than what they should be.

1. Introduction

Following the events at Fukushima-Daiichi nuclear power plant, "Recommendation 2.1" of the near term task force required all licensees to the re-evaluate seismic hazard at their sites (EPRI, 2012). The subsequent effort undertaken by the nuclear industry has highlighted that the seismic hazard-consistent ground motions for various sites in central and eastern US contain significant high frequency motion. In many cases, floor spectra are higher than the licensed design basis. Therefore, the industry is in the midst of a large undertaking to address the seismic qualification of equipment and piping subjected to these higher than design basis spectral accelerations especially in the high frequency region (EPRI, 2012; Cho et al., 2011; Huang et al., 2011a,b; Rydell et al., 2014).

The nuclear industry has initiated cost-intensive shake table testing of some equipment such as electrical cabinets and relays (EPRI, 2014, 2015). In other cases, large scale simulations of the soil-foundation-building systems are being used to generate floor motions which are then used as input in the seismic qualification of secondary systems such as equipment and piping (EPRI, 2013). Owners of several nuclear power plants and other facilities are faced with a critical decision to demonstrate that the plant continues to be safe and will remain safe during the newly established seismic hazard. In fact, technologies such as base isolation are being considered for improving the seismic resiliency of the equipment and piping in nuclear plants (Firoozabad et al., 2015). Several recent studies have emphasized the need to appropriately account for damping in the calculation of floor spectra for such systems (Kelly and Marsico, 2015; Firoozabad et al., 2015; Li et al., 2015).

Interestingly, the main reason for higher amplifications in the floor spectra can be attributed to the shortcomings of current prac-

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tice for calculating seismic response. The current practice follows the historic approach in which the primary systems (buildings) and the secondary systems (equipment and piping) are analyzed separately (uncoupled). The seismic response of a secondary system depends not only on its own dynamic characteristics but also on its interaction with the primary structure supporting it. An analysis of the coupled primary-secondary system can account for the effects of tuning between the frequencies of the two systems, non-classical damping, modal mass interaction, and phasing between the relative motion of various supports in a multiply supported system such as piping. Considerable effort has been made in the past to evaluate the response of non-classically damped coupled primary-secondary systems (Guo et al., 2013; Papagiannopoulos and Beskos, 2009; Gupta, 1992; Gupta and Gupta, 1998a,b; Burdisso and Singh, 1987; Igusa and Kiureghian, 1985). USNRC together with Brookhaven National Laboratory conducted a benchmark study for performing the coupled analysis (Xu and DeGrassi, 2000). A seismic analysis of the coupled building-piping system gives responses that can be an order of magnitude less than those calculated from an uncoupled analysis (Gupta and Gupta, 1995). If the current practice of evaluating seismic response would have adopted a coupled system analysis, which is also benchmarked by USNRC (Xu and DeGrassi, 2000), then there is a strong likelihood that the industry would not need to allocate significant resources for addressing the problem of excessively high amplifications in the floor spectra.

One reason for differences in the traditional uncoupled and the coupled analysis is related to mass interaction between the primary and secondary systems. The mass ratios between the modes of actual building and piping systems in a nuclear power plant have been found to be on the order of 0.0001 or lower and often an uncoupled analysis is considered accurate due to negligible interaction between the two uncoupled systems. Since mass interaction is only one of the several aspects that play a significant role in a coupled analysis, negligible mass interaction between the two systems is not a sufficient criterion to conduct an uncoupled analysis. For example, multiply supported piping systems exhibit significant correlations between the input motions at piping supports which cannot be accounted for in an uncoupled analysis. Even for a singly connected secondary system, the effect of non-classical damping can be significant as shown in this manuscript. A coupled analysis therefore necessitates consideration of non-classical damping when the damping characteristics of the primary and secondary systems are different.

Some of the prior studies acknowledge the significant of non-classical damping due to non-zero off-diagonal terms in the transformed damping matrix (Xu and Igusa, 1991; Xu, 2004). Igusa et al. (1984) illustrates the differences between classical and non-classical damping by evaluating spectral moments in a perfectly tuned primary and secondary system oscillator. Xu and DeGrassi (2000) and Xu et al. (2004) present the details of a USNRC sponsored benchmark program that focused on evaluation and verification of various methods that are available to analyze the non-classically damped coupled primary-secondary systems. Interestingly, the benchmark study concluded that non-classical damping introduces only minor differences in the response of simple secondary systems which is contrary to the observations made in Igusa et al. (1984) even though the simple systems considered in both these studies are perfectly tuned primary–secondary systems and the modal mass ratios are also sufficiently small. Therefore, the conflicting conclusions in these studies make it difficult to understand the significance of non-classical damping.

Sometimes composite modal damping (ASCE, 1998; Gurbuz et al., 2011) is incorrectly identified as an alternative to non-classical damping. For example, an attempt was made in the benchmark study conducted by BNL (Igusa et al., 1984; Xu et al., 2004) to compare the results obtained by considering the non-classical nature of the damping matrix to those obtained by using composite modal damping for the coupled system. Comparison of results from response spectrum analyses of simple primary-secondary systems with the corresponding results from time history analyses was used to conclude that the non-classical and the composite modal damping give close results. For real-life like building-piping systems, large differences were observed between the results for the two methods of modeling damping characteristics but it was concluded that these were likely due to the incompatibilities among finite element models and not due to the differences in the nature of damping characterization. In the present paper, we provide a detailed discussion on the significance of non-classical damping in coupled primary-secondary systems and use simple systems to illustrate the differences between non-classical, classical, and composite modal damping.

2. Coupled system response

In the analysis of non-classically damped coupled primary-secondary systems, it is generally assumed that the uncoupled primary and the uncoupled secondary systems are classically damped, i.e. their individual damping matrices are diagonalized when they are pre- and post-multiplied by the respective undamped modal matrices. However, when the modal damping ratios of the two systems are unequal, the combined damping matrix $\boldsymbol{C}$ would be no longer diagonal when pre- and post-multiplied by the undamped modal matrix of the coupled system. The combined system, therefore, becomes non-classically damped. For non-classically damped systems, the free-vibration equation of motion gives complex eigenvalues and eigenvectors together with their conjugates. Let the complex eigenvalue in the i^{th} coupled mode be denoted by λ_i and its conjugate by $\bar{\lambda}_i$. Together, λ_i and $\bar{\lambda}_i$ give the coupled modal frequency ω_i and the damping ratio ζ_i. Each complex eigenvector and its conjugate give two real modal vectors, $\boldsymbol{\Psi}_i^d$ and $\boldsymbol{\Psi}_i^v$ (Gupta, 1992) . For an acceleration time history input, the coupled response can be calculated by direct integration of the coupled system equation of motion. Alternatively, a modal superposition may be used as follows

$$\boldsymbol{U} = \sum_{i=1}^{N} \boldsymbol{U}_i = \sum_{i=1}^{N} (\boldsymbol{U}_i^d - \boldsymbol{U}_i^v) = \sum_{i=1}^{N} (\boldsymbol{\Psi}_i^d z_i - \boldsymbol{\Psi}_i^v \dot{z}_i) \tag{1}$$

in which $\boldsymbol{U}$ is the displacement vector of the coupled system relative to the fixed primary system base; superscripts d and v denote responses corresponding to the relative displacement and relative velocity parts, respectively; and z_i is the relative displacement and $\dot{z}_i$ the relative velocity of an equivalent SDOF system.

For design purposes, earthquake input is defined in terms of a design response spectrum and not an acceleration time history. In response spectrum method of analysis, the modal responses are calculated as

$$\boldsymbol{U}_i^d = \boldsymbol{\Psi}_i^d S_{Di}^d; \quad \boldsymbol{U}_i^v = \omega_i \boldsymbol{\Psi}_i^v S_{Di}^v \tag{2}$$

where S_{Di}^d and S_{Di}^v are the spectral displacements in coupled mode i. Superscripts d and v denote that the spectral values correspond to the relative displacement and the relative velocity spectra, respectively.

3. Significance of velocity-based response

As discussed above, the complex eigenvalues and eigenvectors of non-classically damped systems can be used to represent the modal response in terms of two real vectors, one corresponding to the relative displacement spectrum and the other corresponding