DAMPING AND THE SEISMIC RESPONSE OF TERTIARY EQUIPMENT

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SUMMARY

Some preliminary work is reported from a research program aimed at achieving an improved modelling of damping in simplified seismic design procedures. Three present methods of handling damping are studied and compared with results from "exact" analyses. The exact analyses use direct integration of the coupled equations of motion and complex modal analysis. It is concluded that an improved damping model is required to improve the simplified analysis of secondary and tertiary equipment within major structures.

INTRODUCTION

Major engineering structures, such a nuclear power plants, can often be envisioned as being composed of up to three levels of systems. This concept of a three level system is illustrated in simple schematic in Figure 1. These three levels within such a structure will be referred to as being primary, secondary or tertiary. The primary system refers to the main structure, which supports most or all of the equipment, piping, components, etc., contained within the building. The secondary systems normally consist of the large components and pieces of equipment and any large diameter piping. Finally, the tertiary systems would consist of the small equipment and any small diameter piping.

Any major structure must be designed to resist a design level of seismic activity. In order to carry out that design, the engineer must be able to determine the response of the structure to the expected ground motion.

In recent years, several studies have been done concerning the modelling of the seismic response of two-level (primary and secondary) structures, including studies by Villaverde and Newmark (Ref. 1) and Ruzicka and Robinson, (Ref. 3). However, no studies, except one done by A.C. Heidebrecht (Ref. 4), have been done dealing with a three-level system. From a safety point of view, especially in nuclear power plants, it is important that design engineers have a solid understanding of how tertiary systems respond seismically so that they can design these systems in an appropriate manner.

In the past, especially for tertiary systems, it was most common to consider the different levels of a system as being uncoupled. In other words, it was assumed that each system was not affected by any higher level systems. In reality, however, all systems within a structure are coupled and their response is dependent on the responses of all the other systems, to a greater or lesser extent. As a result, a good model must account for this interaction between the different levels of a structure.

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This paper will deal with some preliminary work that has been done with respect to the adequacy of present simplified methods of handling the damping in a coupled three-level system. With high amplification of ground motion present in many tertiary systems, a proper modelling of the damping is critical since the maximum structural response will be limited by the damping that is present within the structure.

The objective of this paper is to evaluate three simplified methods of combining the damping ratios of up to three uncoupled systems into coupled damping ratios for a coupled structure composed of the uncoupled systems.

PRESENT RESEARCH RESULTS

One of the problems that must be addressed when analyzing three-level systems is that of how to define the damping of the coupled structural system when only the uncoupled damping ratios are known. The two major possibilities that present themselves are to attempt to define a coupled model damping ratio, which may or may not actually exist, or to use an explicit damping matrix and attempt to arrive at the same conclusions through its use. Some effort has been spent in the investigation of three possible simplified methods of calculating coupled damping ratios and attempting to determine which, if any, would yield satisfactory results.

Initially, a numerical comparison of the three simplified methods of calculating coupled damping ratios was carried out using a coupled two degree of freedom system. The damping ratios of the coupled system were determined by (1) directly assigning the uncoupled damped ratios, (2) proportioning of the uncoupled damping ratios according to the strain energy, and (3) calculating the coupled damping ratios based on the assumptions that the normal modes of the system will uncouple the damping matrix.

The three methods may be represented by the following equations for calculating the coupled damping ratios.

$$(\beta_i)_{DIRECT} = \zeta_p, \zeta_s \qquad (1)$$

where β_i = coupled damping ratio
ζ_p = primary damping ratio
ζ_s = secondary damping ratio

$$(\beta_i)_{STRAIN} = \frac{\lambda_p^2 \zeta_p + \mu\theta(\lambda_s - \lambda_p)^2 \zeta_s}{\lambda_p^2 + \mu\theta(\lambda_s - \lambda_p)^2} \qquad (2)$$

where λ_p, λ_s = components of the mode shape corresponding to primary and secondary system
μ = mass ratio
θ = square of uncoupled frequency ratio

$$(\beta_i)_{UNCOUPLE} = \frac{\lambda_p^2 \zeta_p + \mu\sqrt{\theta}\,(\lambda_s - \lambda_p)^2 \zeta_s}{\frac{\omega_i^*}{\omega_p}(\lambda_p^2 + \mu\lambda_s^2)} \qquad (3)$$

where ω_i^* = coupled natural frequency of system
ω_p = uncoupled primary frequency

The study assumed that the primary and secondary uncoupled damping ratios were 0.05 and 0.02, respectively, and the primary system was assigned a natural frequency of 1 Hz. The study involved varying both the mass and squared frequency ratios and then determining the predicted modal damping ratios (coupled), based on the three, previously described methods and the resulting coupled frequencies and mode shapes. Typical results of the study (numerical) are described in Figure 2.

It was observed that for squared frequency ratios greater than 5.0 and less than 2.0, all three methods yielded basically the same results.

It was seen that the three methods do not yield close results except for the small mass ratios and very small or large squared frequency ratios. Unfortunately, pseudo-resonance, which occurs when uncoupled frequencies of different system levels are equal, of third-level systems must be covered. For mass ratios of up to even 0.10, these methods yield substantially different results. As a result, these results must be checked in another manner to see if any of them are considered to be accurate.

Two methods which yield "exact" results for any symmetric damping matrix can be used for comparison with the proportioning methods. This comparison, however, is not a direct comparison of damping ratios, but rather a comparison of maximum predicted response.

These two methods use complex modal analysis (Ref. 1) and direct integration (Ref. 2) of the coupled equations of motion and do not yield the usual uncoupled equations of motion. The use of complex modal analysis will yield uncoupled complex equations of motion, but at the same time, turns an NxN eigenvalue problem into a 2Nx2N eigenvalue problem. Direct integration does not worry about uncoupling the equations of motion, but rather deals with the response of the entire system as a whole. Neither method requires a diagonal damping matrix in order ot be used.

Complex modal analysis uncouples the equations of motion in the complex plane. The equations of motion are rearranged such that

$$\begin{bmatrix} [O] & [M] \\ [M] & [C] \end{bmatrix} \{\dot{q}_p\} + \begin{bmatrix} -[M] & [O] \\ [O] & [K] \end{bmatrix} \{q_p\} = \{F(t)\} \tag{4}$$

where

$$\{q_p\} = \begin{Bmatrix} \{\dot{x}_p\} \\ \{x_p\} \end{Bmatrix}, \{F(t)\} = \begin{Bmatrix} \{0\} \\ \{R(t)_p\} \end{Bmatrix},$$

$\{x_p\}$ = system displacements

and $\{R(t)_p\}$ = applied forcing function.

The complex eigenvalues and eigenvectors can now be obtained from free vibrations and the eigenvectors can be used to uncouple the equations of motion. From this, then, the system displacements or other responses can also be obtained.

The direct integration method was used to determine maximum responses for a variety of mass and frequency ratios. These results were then compared with the maximum responses obtained from a modal superposition program which used three different proportioning methods to determine its modal damping ratios. A set of sample results are illustrated in Figure 3.

The worst results were obtained by the method of direct assignment with a maximum error of over 25%. The results for the other two methods were fairly consistent with each other and exhibited a maximum error of almost 12.5%. In general, large errors were exhibited at or near pseudo-resonance of systems and errors tended to increase as the mass ratio decreased.

As a result of the comparison based on a direct integration "exact" result, it can be concluded that direct assignment of uncoupled damping ratios is not appropriate as a general method of determining coupled damping ratios. The remaining methods, although not exact, do maintain similar orders of their error and almost always keep the error to less than 10%.

Following this, it was decided that complex modal analysis should also be used. The results of this analysis would supply a check on the direct integration analysis and ensure that no errors were made in either analysis procedure. Initially, an expression derived by Villaverde and Newmark was used to calculate modal damping ratios from the solution of the complex eigenvalue-eigenvector problem. These damping ratios were then compared with those obtained from the simplified procedures. A sample of the data is supplied in Table 1 and shows that significant differences occur around a squared frequency ratio of unity.

As a final step, a computer program was written which used complex modal analysis to solve for dynamic structural response. This would provide one more check on the results obtained when comparing the simplified procedures with the direct integration procedure. The resulting complex modal analysis yielded the same responses as the direct integration of the coupled equations of motion, and therefore, leads to the same conclusions with respect to the simplified methods of handling damping.

It would appear that all major time domain methods of addressing this type of coupled system damping problem have been attempted. Other studies into this type of problem, for two levels, have used frequency domain analysis (Ref. 3) (not attempted or considered here).

Studies using frequency domain analysis or complex modal anlaysis both came to the conclusion that widely spaced modes would exhibit one of the uncoupled damping ratios, while pseudo-resonant modes would exhibit modal damping equal to the arithmetic average of the uncoupled damping ratios. This appears to be borne out in the numerical comparison of the three methods of proportioning damping and the complex modal damping. Unfortunately, however, modal analysis using the simplified coupled damping ratios does not give the same maximum response as the "exact" complex pseudo-resonance between the uncoupled systems.

EVALUATION OF PRESENT STATE OF RESEARCH

This paper has dealt with the evaluation of some simplified methods of determining coupled damping ratios from uncoupled damping ratios. When these methods are combined with normal modal superposition time history technique, it was found that the simplified methods introduced significant errors in the maximum structural response, especially near pseudo-resonance. Since this damping model must be incorporated into a complete simplified coupled structural model, it would be preferable to minimize the error being introduced by the damping model. Therefore, another method of defining coupled damping characteristics is required, at least for the case of closely spaced, uncoupled natural frquncies.

Presently, experimental research is being carried out with the purpose of determining how the coupled damping ratios of a system are related to the uncoupled damping ratios of the components of the system. It is expected that this work will lead to a better model for combining uncoupled modal damping ratios and, as a result, a better estimation of seismic response for structures containing two or more levels of systems.

REFERENCE

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Table 1. Modal Damping Ratios

Mass Ratio	$(F_s/F_p)^2$	Mode	Complex	Strain Energy	Ignore Off Diagonal Terms
0.001	0.3	1	.0200	.0200	.0200
		2	.0500	.0500	.0500
	0.9	1	.0210	.0222	.0219
		2	.0490	.0478	.0481
	1.0	1	.0258	.0352	.0347
		2	.0444	.0348	.0353
	1.1	1	.0486	.0476	.0472
		2	.0214	.0224	.0228
	3.0	1	.0499	.0500	.0499
		2	.0201	.0200	.0200
0.010	0.3	1	.0200	.0202	.0200
		2	.0500	.0498	.0500
	0.9	1	.0263	.0285	.0270
		2	.0437	.0415	.0430
	1.0	1	.0339	.0357	.0340
		2	.0362	.0343	.0360
	1.1	1	.0410	.0420	.0404
		2	.0290	.0280	.0296
	3.0	1	.0494	.0498	.0484
		2	.0206	.0202	.0206

F_p: Primary system uncoupled frequency (Hz)
F_s: Secondary system uncoupled frequency (Hz)

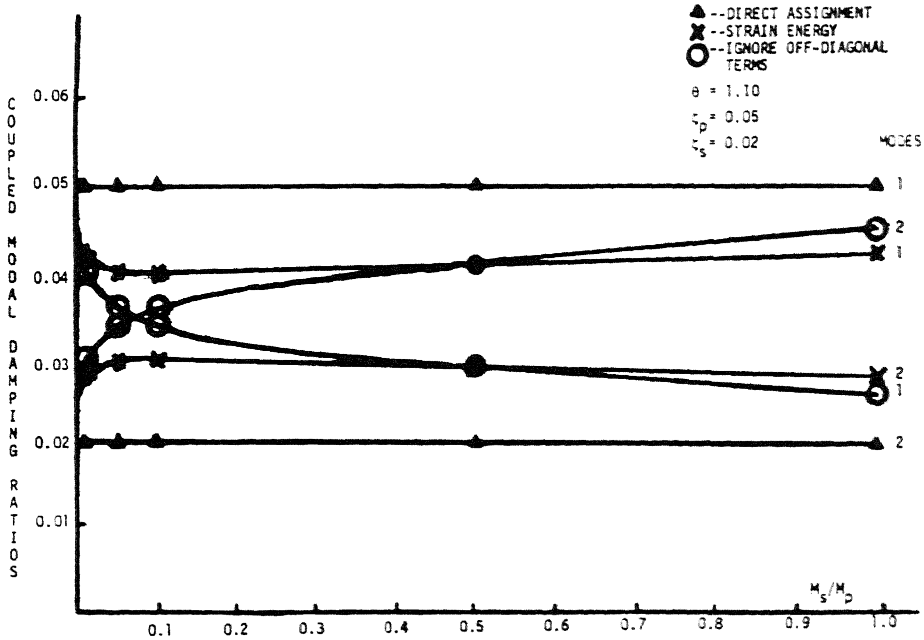

Figure 2. SIMPLIFIED COUPLED MODAL DAMPING RATIOS FOR 2DOF SYSTEM

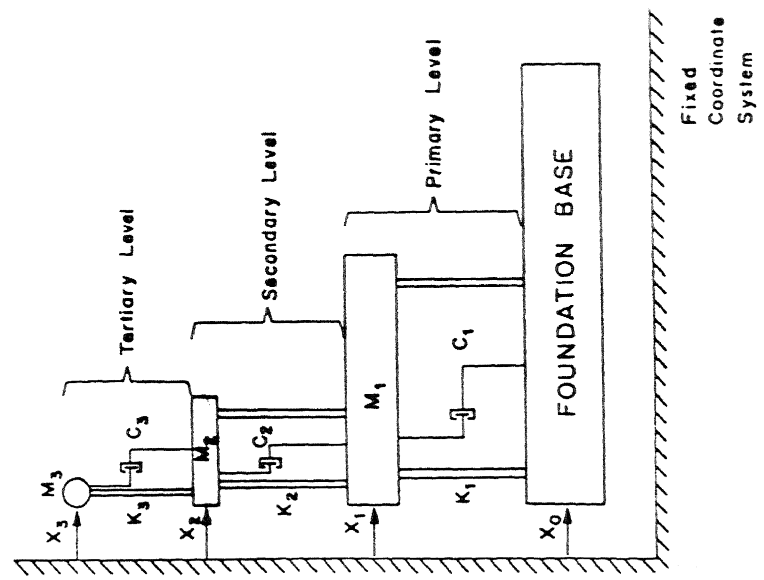

FIG.1 Idealized Three Level Model

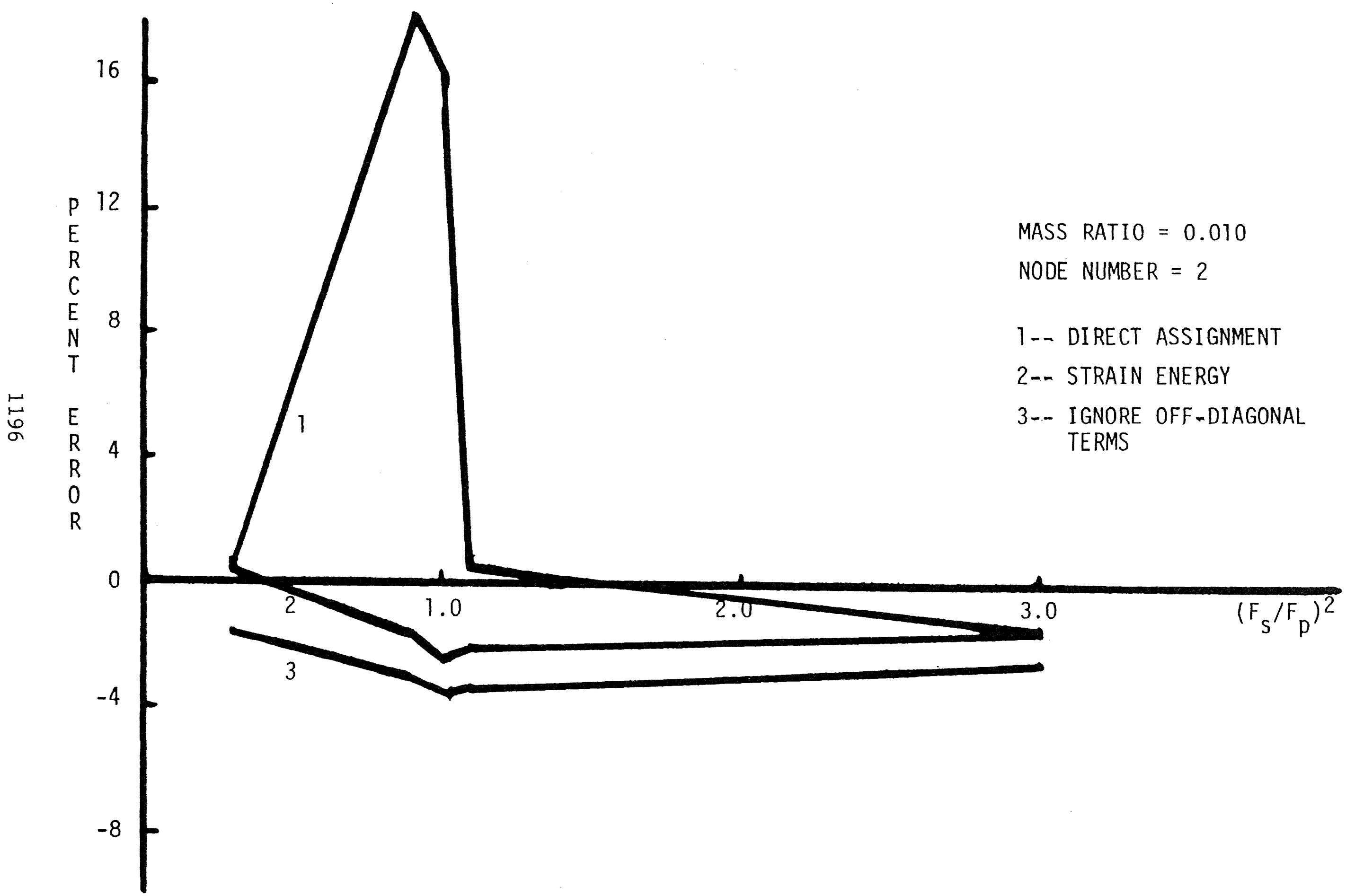

Figure 3. PER CENT ERROR IN MAXIMUM RESPONSE (Simplified vs "Exact")