ON THE DECOUPLING OF SECONDARY SYSTEMS FOR SEISMIC ANALYSIS

by

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SYNOPSIS

The coupled analysis of primary (supporting) and secondary (supported) systems may not always be feasible or desirable. Decoupling of secondary systems from primary systems from the viewpoint of acceptable errors in frequency and response is studied. It is concluded that the presently used criteria for decoupling are both arbitrary and conservative. Due to the difficulties of interpreting the results of studies of simple systems for use in multi-degree-of-freedom models, the concept of mass ratio is generalized to reflect the modal masses of the subsystems. The impact of the location of the secondary system is also reviewed. A more general and rational criteria for decoupling is suggested.

INTRODUCTION

The coupled dynamic analysis of primary (supporting) and secondary (supported) systems may not always be feasible or desirable. The number of supported elements may be such that a coupled analysis would create computational difficulties. Also the adequacy of data regarding the secondary system at the time of the analysis of the primary system would not justify a coupled analysis. Additionally cost and scheduling considerations would usually rule out a coupled analysis. These and other considerations are the basis why, for example in nuclear power plants, a coupled analysis of structures, equipment and piping is rarely attempted. The objective of the present paper is to explore the conditions under which an uncoupled analysis is justified.

Any uncoupling criteria should consider the effects of the uncoupling on both the primary and secondary systems from a safety and economy points of view. Fig. 1 depicts these choices. Since the response of supported systems is dependent in a significant way on the frequencies of the supporting structure (1), it is imperative that the uncoupled frequencies of the latter are reasonably close to the system frequencies. Also from a safety point of view the uncoupled frequencies of the supported system should be reasonably close to the respective system frequencies so that resonance conditions are not inadvertently avoided. From a response point of view, safety requires that the uncoupled response is always larger than the coupled response for both primary and secondary systems, although some underdesign can always be tolerated. For nuclear power plant structures using broadband response spectra as the design basis, significant variations of response of primary systems are not possible and thus no economic issues are expected. For the secondary system however, excessive overdesign is a possibility if erroneous resonance conditions are predicted.

EXISTING CRITERIA

Although uncoupling of systems have been studied for other applications (2), it is with the advent of nuclear power plants that criteria for uncoupling for seismic analysis have been reported (3, 4, 5, 6). Some of these recommendations are shown in Fig. 2, which divide the region shown into two subregions where coupling is or is not required. Although all three criteria have similar shapes, the actual boundaries are significantly different,

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indicating indirectly the need for a more consistent criteria. One important feature of all three recommendations requires a definite revision: Dynamic systems are not as arbitrary as these lines suggest. For example, depending on whether the frequency ratio, f_e/f_s, is slightly larger or smaller than 0.8, the mass ratio, m_e/m_s, that would allow an uncoupled analysis, can be an order of magnitude different. f_e and f_s represent the uncoupled frequencies of the supported and supporting systems respectively and m_e and m_s the respective masses, (see Figure 3). More smooth transitions should be introduced into the development of these boundaries as shown by the solid lines (present recommendations). The above discussed criteria were derived by considering three types of uncoupled models (5, 6): a) mass of supported system rigidly lumped into the mass of the supporting system, b) the stiffness characteristics of the supported system restraining the response of the supporting system and c) neither stiffness nor mass of the supported system included in the supporting system model.

Although model 'a' is commonly used, the use of model 'b' should be discontinued since it distorts, in an unrealistic fashion, the stiffness characteristics of the total system. This becomes obvious when one considers a very stiff mounted system. Physically the total system should approach model 'a' as the supported system becomes incapable of relative distortions. Yet reported results (5, 6) indicate that the errors in the natural frequencies are in opposite directions between models 'a' and 'b'. Model 'b' is an unnatural model and does not relate to reality in any meaningful way. Thus the choice is between models 'a' and 'c'. Published results indicate that the errors in the natural frequencies using model 'a' are less than those of model 'c' for supported systems having frequencies greater than the supporting system. This is expected since as the relative distortion of the supported system decreases the mass of the supported system acts as if rigidly lumped with the supporting system. Model 'c', also referred to as the "cascading" model, would be more appropriate for supported systems that are relatively flexible.

TWO-DEGREE-OF-FREEDOM SYSTEMS

The logical place to start any study of uncoupling is a two-degree spring-mass system as shown in Fig. 3. Mass m_s could represent the primary (supporting) system and m_e the secondary (supported) system. Both frequency and response characteristics will be reviewed.

Frequency Evaluation

The frequency equation of the system shown in Fig. 3 can be generalized for any frequency ratio, f_e/f_s. From plots of the dimensionless system frequencies vs. mass ratio, m_e/m_s, the solid lines of Fig. 2 can be derived to reflect any level of acceptable error of system frequencies. The error in both supporting and supported frequencies are considered. Three curves are shown that divide the region into two subregions where 5%, 10% and a 15% error in the system frequencies can be tolerated. A 15% error in frequency is deemed tolerable. Errors in modeling of complicated systems do not justify more restrictive uncoupling criteria. These curves differ from the existing criteria in a few important characteristics: first the untenable situation of minute frequency ratio (f_e/f_s) variations requiring an order of magnitude different mass ratios is eliminated; for frequency ratios of 0.5 and less, practically no restrictions exist on the mass ratio (this is as it would be expected from an intuitive interpretation of the problem); and finally, acceptable levels of error in system frequencies, which could vary from one case to another, could be adopted.

Response Evalution

Extensive studies have been conducted on the response of coupled and uncoupled two degree-of-freedom systems subjected to ideal white noise base excitations (2). Four mean square responses have been examined: two spring distortions and two absolute accelerations. Except for the relative displacement of the primary (supporting) system, the remaining three responses result in overestimates because of uncoupling. The results shown in Figure 4 are obtained from data given in Figures 2.20, 2.21, 2.22 and 2.23 of Reference 2. The presentation has been rearranged to suit the intentions of the present discussion. These results do not justify modifications of the recommended decoupling criteria depicted in Figure 2.

MULTI-DEGREE-OF-FREEDOM SYSTEMS

The evaluation of the frequency and response changes due to uncoupling of secondary systems from primary systems of multi-degree-of-freedom models is a difficult task: the myriad possibilities make the study almost untractable. Under these circumstances the extension of the results obtained from the two-degree-of-freedom system seems almost the only rational approach. In studies related to uncoupling, two definitions have been used to describe the mass ratio: a) mass of equipment to support mass only, and b) mass of equipment to total mass of supporting system. The first case would be more appropriate for example to an equipment on a flexible slab excited in the vertical direction. The meaningful mass ratio for this case would then be the mass of the equipment to the mass of the slab rather than to the total structure mass. The results from a sample problem is depicted in Figure 5. However, with this definition the mass ratio will not be unique and will depend on the crudeness or refinement of the primary system model. In fact, mass ratios would increase as more refined models are used for the same supporting system (7). To overcome these difficulties and to obtain a unique concept of mass ratio the modal mass associated with each system frequency has been suggested (7). The modal mass is nothing more than the mass of the equivalent simple oscillators of a multi-degree-of-freedom system (8). This concept overcomes the problem cited earlier of the vertical response of the slab and the dependence of the answer on the refinement or crudeness of the system model.

Although the use of the modal mass eliminates a few problems associated with multi-degree-of-freedom systems there are other parameters that also must be considered. One of these is the location of the attachment point of the secondary system to the primary system. For a given model and frequency ratio, the location of the secondary system impacts on the system frequencies in some complicated function of the mode shape of the tuned frequency. Thus for the equipment tuned to the fundamental mode of the supporting system, the impact on the system frequency is a maximum when the equipment is attached at the top of the primary system, and a minimum when attached at the bottom (7). At this time no definite criteria is formulated to exploit the level of location of the secondary system. The criteria will be based on the worst location, namely at the top of the primary system. Many examples indicate that when the equipment is located at the top of the primary system, the criteria developed for the two-degree-of-freedom system shown in Figure 2 is essentially applicable to the multi-degree system by simply redefining m_s as the modal mass of the supporting system. A simple example shown in Figure 6 is studied for this purpose. Defining m_s as the modal mass for the primary system, the ratio of the coupled frequency to the uncoupled fundamental frequency of the primary system is plotted as a function of the modal mass ratio in Figure 7. Results are shown for three

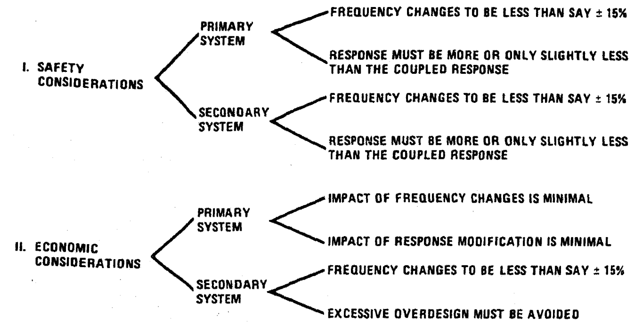


FIGURE 1. SPECIFICATIONS FOR UNCOUPLING.

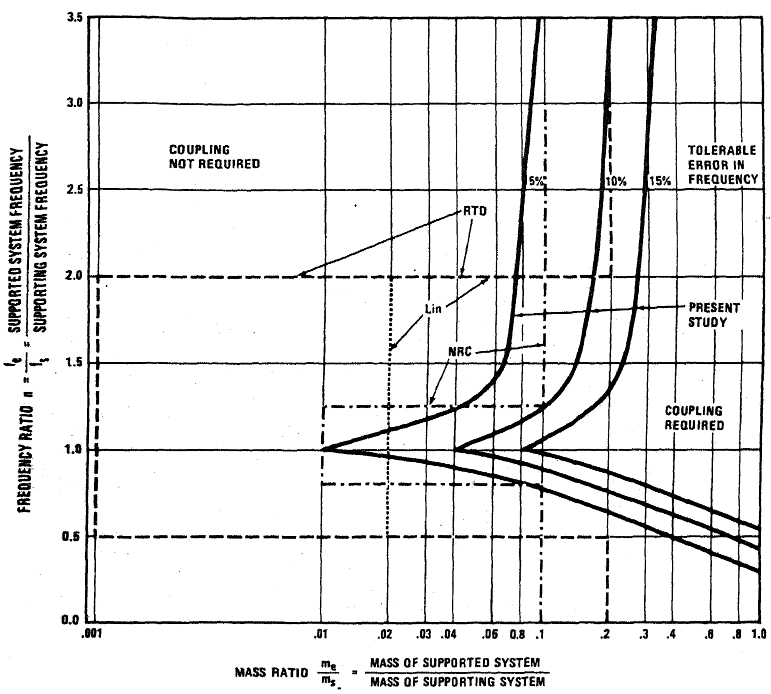


FIGURE 2. SCHEMATIC REPRESENTATION OF DECOUPLING CRITERIA

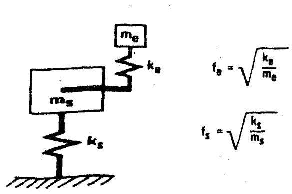


FIGURE 3. SIMPLEST MODEL OF SUPPORTED AND SUPPORTING SYSTEM

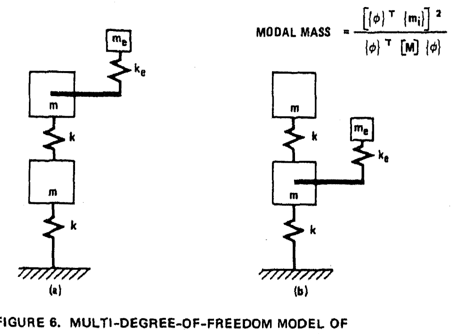


FIGURE 6. MULTI-DEGREE-OF-FREEDOM MODEL OF SUPPORTED AND SUPPORTING SYSTEM.

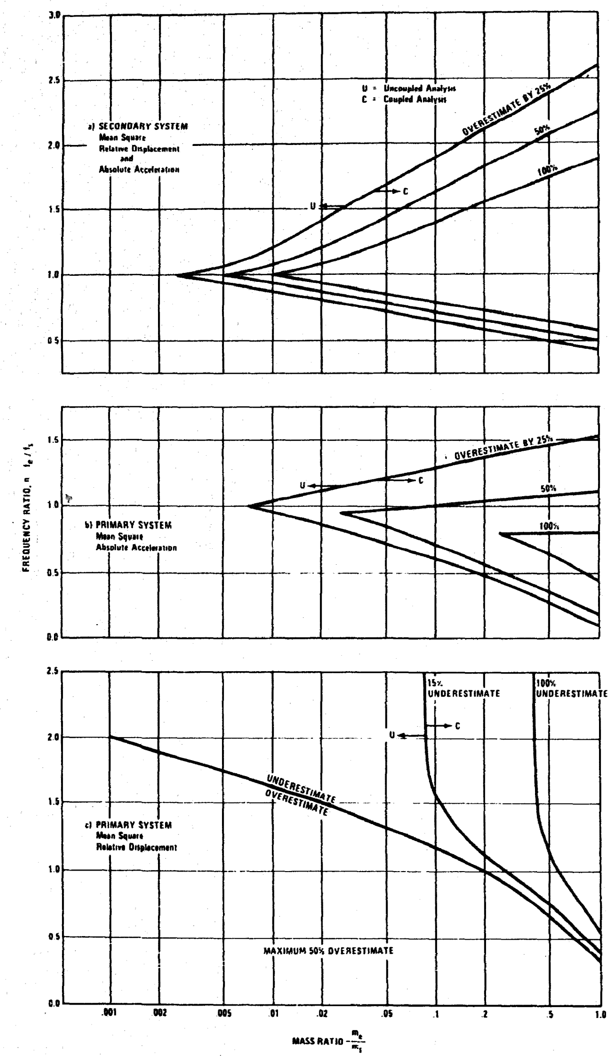
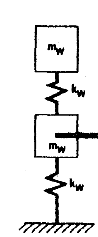


FIGURE 4. RESPONSE MODIFICATIONS DUE TO UNCOUPLING (ADAPTED FROM REF. 2)



$$\frac{\text{SECONDARY SYSTEM MASS}}{\text{PRIMARY SYSTEM TOTAL MASS}} = \frac{m_e}{m_s + 2m_w} = \frac{1}{2+48} = 0.02$$ (COUPLED ANALYSIS NOT REQUIRED)

$$\frac{\text{SECONDARY SYSTEM MASS}}{\text{SUPPORT MASS}} = \frac{m_e}{m_s} = \frac{1}{2} = 0.5$$ (COUPLED ANALYSIS REQUIRED)

$$\frac{\text{SECONDARY SYSTEM MASS}}{\text{MODAL MASS (1st MODE)}} = \frac{m_e}{m_m} = \frac{1}{2.02} = 0.5$$ (COUPLED ANALYSIS REQUIRED)

UNCOUPLED SYSTEM			COUPLED SYSTEM FREQUENCIES	ERROR
PRIMARY SYSTEM		SECONDARY SYSTEM FREQUENCY		
MODAL MASS	FREQUENCIES		1.35	29%*
2.01	1.91	1.91	2.70	41%*
45.45	23.61	—	23.61	—
2.53	61.81	—	61.82	—

*COUPLED ANALYSIS REQUIRED

FIGURE 5. MODEL EMPHASIZING THE SIGNIFICANCE OF MODAL MASS

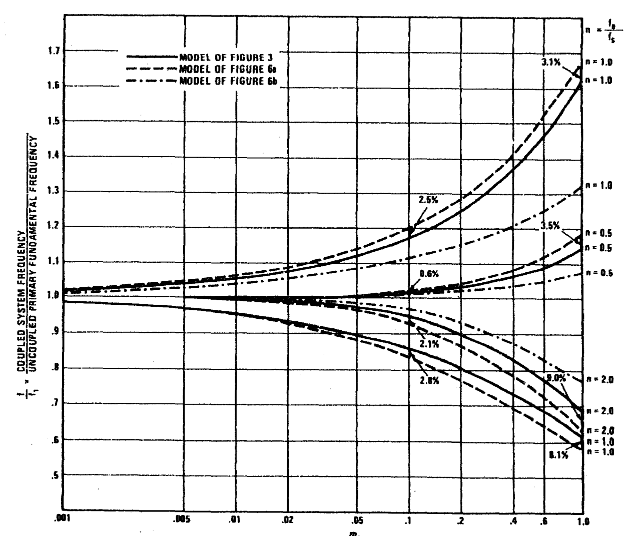


FIGURE 7. FREQUENCY STUDY OF MODEL IN FIGURE 6

frequency ratios, f_e/f_s of 1.0, 0.5 and 2.0. As expected the impact of coupling is largest when $f_e/f_s = 1.0$. Also the impact of the model of Figure 6b is less than that of Figure 6a. The more significant point to note though is the close relationship of the results from the models of Figure 3 and 6a. The differences between the two are shown as a percentage change at selected mass ratios. The insignificance of these differences, specially in the range of mass ratios where decoupling is usually considered, affirms the earlier statement that the criteria of Figure 2 is applicable to multi-degree-of-freedom systems by simply redefining m_s as the modal mass. These criteria would be conservative for all equipment not attached to the top of the primary system.

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