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EQUIPMENT SEISMIC DESIGN:FUTURE DIRECTIONS

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SUMMARY

Presented in this paper is a study of the seismic behaviour of tuned equipment-structure systems. The equipment-structure system is represented by a coupled elasto-plastic (or bilinear) two-degree-of-freedom spring mass model. If the system can be decoupled, the two-degree-of-freedom system can be divided into two uncoupled single degree of freedom systems. The response of both the coupled equipment-structure and the decoupled systems are obtained by solving the governing differential equations numerically using the Wilson-θ method. The displacement and acceleration response data of the coupled and decoupled systems, when subjected to a set of nomralized earthquakes, are averaged for each set of parameters considered. The important parameters studied are the tuned frequency of the system, the mass ratio, damping and yield levels for the structure and for the euqipment. Based on the numerical results obtained, future directions of improvements for code provisions of equipment seismic design are proposed.

INTRODUCTION

Historically, building codes evolved to deal with the seismic design requirements of building structures. Until recently, very little attention was given to the seismic design of equipment, parts and portions housed inside the buildings. The equipment seismic design process is further complicated by the fact that equipment typically receives its seismic input from the structure. Therefore, accurate determination of equipment response depends to a great extent on our ability to accurately predict structural response of the building. Studies on equipment response and behaviour due to seismic events are still lacking. Therefore incorporating the relevent factors which may affect the equipment response in code design provisions is still lagging.

The dynamic interaction between the elastic structure and elastic equipment systems has been the subject of extensive investigations during recent years. (Refs. 1, 2, 3, 4, 5). Designing the equipment-structure systems based on elastic behaviour may result in over conservative designs if the equipment or the structure are expected to behave inelastically in the case of a major seismic event. Studies dealing with the dynamic interaction between inelastic structures and inelastic equipment have been somewhat limited (Refs. 6, 7, 8).

The objective of the current investigation is to study the seismic response of equipment-structure systems when the frequencies of free vibrations of the elastic uncoupled systems coincide. This is considered to be the most important case in practice since it leads to a quasi-resonance behaviour. In the analysis, one or both of the system components may behave inelastically. The characteristics of the inelastic behaviour of the system will depend on the degree of ductility incorporated into the design and construction.

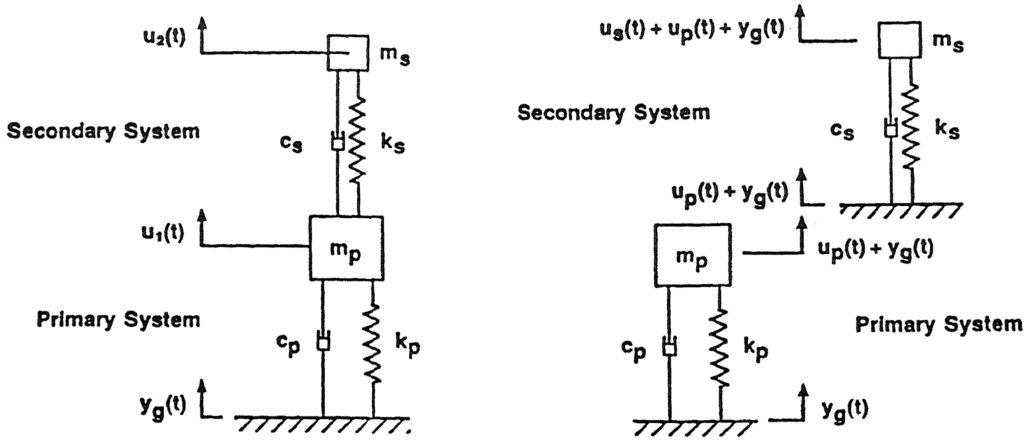

Fig. 1 Schematic of (a) coupled and (b) decoupled systems

SYSTEM MODELLING

The equipment-structure system is represented by a two-degree-of-freedom spring mass model. The two-degree-of-freedom model is shown in Fig. 1(a). If the system can be decoupled, the two-degree-of-freedom system can be divided into two uncoupled single degrees of freedom systems as illustrated in Fig. 1(b).

The equations of motion of the coupled system can be written as:

$$\begin{bmatrix} m_p & 0 \\ 0 & m_s \end{bmatrix}\begin{Bmatrix}\ddot{u}_1\\ \ddot{u}_2\end{Bmatrix} + \begin{bmatrix} c_p+c_s & -c_s \\ -c_s & c_s\end{bmatrix}\begin{Bmatrix}\dot{u}_1\\ \dot{u}_2\end{Bmatrix} + \begin{bmatrix}k_p+k_s & -k_s\\ -k_s & k_s\end{bmatrix}\begin{Bmatrix}u_1\\ u_2\end{Bmatrix} = -\begin{Bmatrix}m_p\\ m_s\end{Bmatrix}\ddot{y}_g \tag{1}$$

The dots denote time derivatives and $\ddot{y}_g$ represents the ground motion. The displacement of the structure is u_1 while that of the equipment is denoted u_2. Damping coefficients for the structure and equipment systems are denoted c_p and c_s respectively.

For the uncoupled equipment structure system:

$$\begin{aligned} m_p\ddot{u}_p + c_p\dot{u}_p + k_p u_p &= -m_p\ddot{y}_g \\ m_s\ddot{u}_s + c_s\dot{u}_s + k_s u_s &= -m_s\ddot{x}_p \end{aligned} \tag{2}$$

where $\ddot{x}_p$ is the absolute acceleration of the primary system.

The input ground motion used in the equipment-structure system analysis is taken as actual strong motion earthquake records normalized to a spectral acceleration of 1.0 g at the period of tuned equipment-structure system. Various strong motion records are used in order to account for the variations in the actual earthquake characteristics. The ground motions used in the current study are El Centro (1940) S90W, Parkfield (1966) N6SW and San Fernando (1971) S74W. This represents a wide range of earthquake intensity, distance from fault and duration.

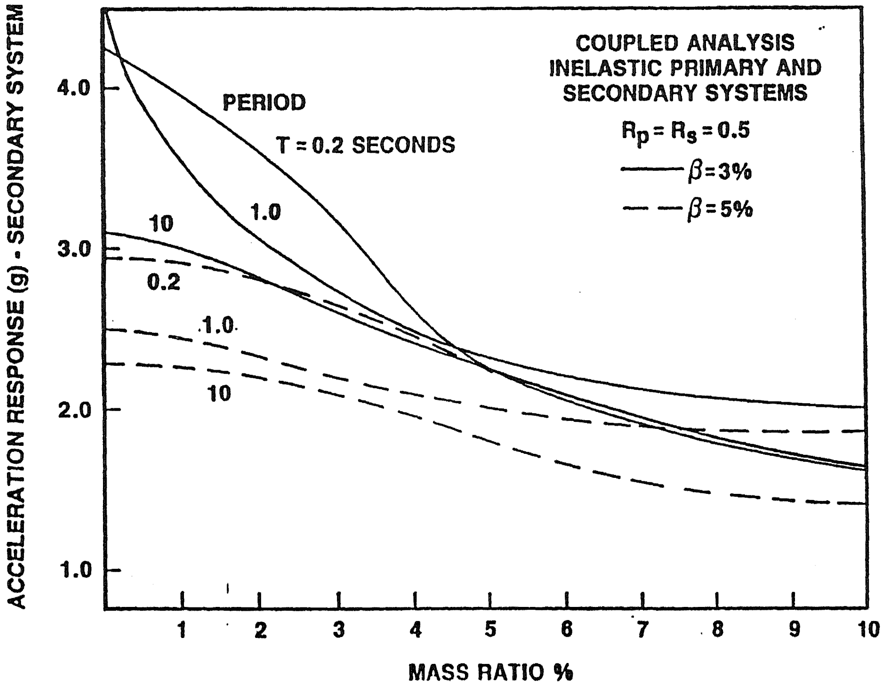

Fig. 2 Effect of damping and system period on the response of secondary system (Equipment)

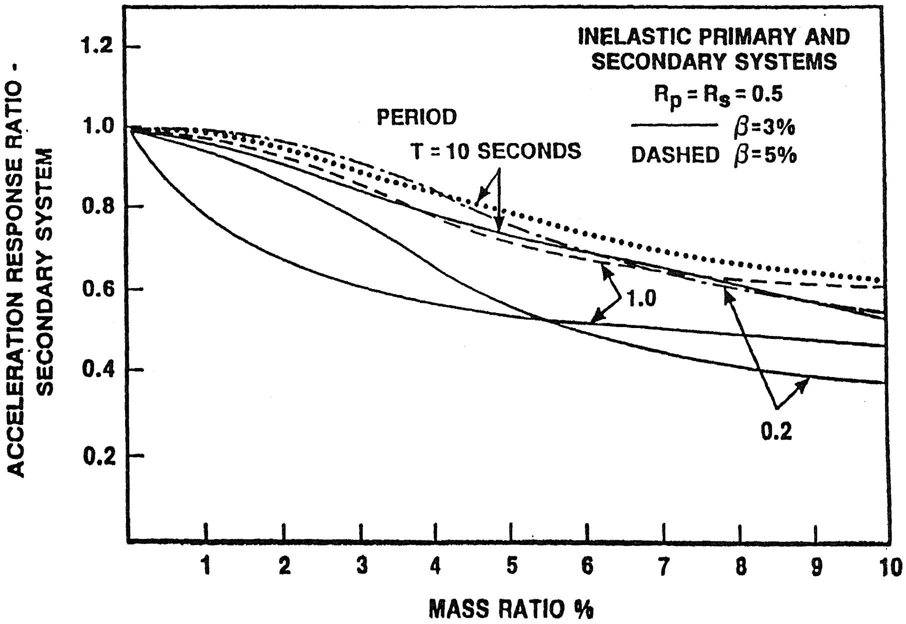

Fig. 3 Effect of damping and system period on the secondary system acceleration response ratio (Equipment)

The response of the coupled equipment-structure system is obtained by solving Eq. (1). The load displacement relationship of the spring is taken as elastoplastic. The response of the decoupled system is obtained in a similar manner by solving Eq. (2). The peak displacement and acceleration response data of the coupled and decoupled systems when subjected to the three different normalized earthquakes are averaged for each set of parameters considered.

SYSTEM RESPONSE RESULTS

The damped, tuned two-degree-of-freedom model is defined by the period T, mass ratio μ, damping ratio β, and the yield levels R_p and R_s for the primary and secondary systems. For simplicity, damping in the equipment and structure system is taken to be the same and represent an average damping for the combined system. The periods of free vibration of the primary and secondary systems are set to be equal which represents the case of a tuned system. The yield level forces in the primary and secondary springs are determined by multiplying the maximum elastic spring force by the yield factors R_p and R_s respectively. The maximum elastic spring force is obtained from the elastic analysis for each specific case using an uncoupled analysis.

The range of values of the parameters under study are chosen to represent practical cases. The range of fundamental periods encountered in structural and equipment design is found to be from 0.1 to 10.0 seconds. Five representative mass ratios are selected for the numerical calculations with the values of 0.1, 1.0, 2.0, 5.0 and 10%. Damping ratios of 3% and 5% are selected to correspond to steel and concrete structures respectively. The values of the yield level factors R_p and R_s representing the primary and secondary systems respectively are taken as 1.00, 0.75, 0.50 and 0.25.

Typical cases of the system behaviour are illustrated in Figs. 2 and 3. In each figure, two sets of curves for different tuned periods of 0.2, 1.0 and 10 seconds are shown which represent the acceleration response of the secondary system for the case of 3% and 5% damping ratios.

Acceleration response ratios, defined as the ratio of the response acceleration obtained by a coupled analysis to the response acceleration obtained by a decoupled analysis, were calculated for each analysis case for the primary and secondary systems. Table I gives the acceleration response ratios for the secondary system for various yield levels and tuning periods.

PRACTICAL IMPLICATIONS

Table I which gives the acceleration response ratio for the secondary system for various yield levels and periods can prove very useful for equipment designers. The designer can assess quickly the beneficial effects of the mass ratio or force ductility on reducing the secondary system response.

Table I can be translated to actual accelerations and forces on equipment V_p, once the input acceleration to the primary system is known. These forces can then be related to building codes design levels. It can be observed from the table that the present Building Codes such as the NBCC and ATC-3 do not recognize the important parameters such as mass ratio, damping, period and ductility on equipment response. Future directions for such codes should attempt to account for these parameters.

Table I: Acceleration response ratio* of secondary system for various yield levels and periods (Average of 3 normalized earthquakes – Case of $\beta = 3\%$)

Yield level of primary system R_p	Mass Ratio μ %	Elastic Secondary System $R_s = 1$			$R_s = 0.75$			$R_s = 0.50$			$R_s = 0.25$		
		T=0.2	1.0	10.0	T=0.2	1.0	10.0	T=0.2	1.0	10.0	T=0.2	1.0	10.0
1.00	10	.257	.322	.376	.324	.420	.484	.480	.623	.710	.906	.938	.915
	5	.337	.392	.526	.425	.511	.678	.629	.758	.904	.959	.981	.974
	2	.542	.516	.734	.687	.672	.928	.943	.878	.988	.974	.989	.981
	1	.691	.580	.851	.875	.755	.985	.980	.944	.991	.979	.991	.984
	.1	.929	.903	.979	.985	.995	.995	.986	.994	.994	.983	.994	.986
0.75	10	.309	.371	.464	.326	.398	.488	.480	.589	.714	.907	.913	.923
	5	.386	.438	.605	.407	.470	.638	.599	.697	.896	.963	.981	.979
	2	.657	.518	.806	.695	.547	.853	.948	.810	.990	.982	.991	.985
	1	.804	.597	.899	.848	.641	.953	.985	.910	.993	.986	.994	.986
	.1	.960	.923	.985	.947	.978	.996	.988	.995	.995	.987	.995	.986
0.50	10	.318	.411	.506	.318	.411	.506	.376	.461	.523	.734	.864	.895
	5	.460	.470	.681	.460	.470	.681	.550	.527	.726	.955	.917	.895
	2	.745	.594	.847	.745	.594	.847	.868	.661	.905	.988	.991	.990
	1.	.829	.701	.923	.829	.701	.923	.942	.778	.971	.990	.995	.991
	.1	.956	.944	.985	.956	.944	.985	.987	.987	.994	.991	.995	.992
0.25	10	.397	.474	.538	.397	.474	.538	.397	.474	.538	.531	.527	.555
	5	.614	.557	.701	.614	.557	.701	.614	.557	.701	.821	.619	.727
	2	.785	.724	.852	.785	.724	.852	.785	.724	.852	.973	.803	.885
	1	.825	.833	.921	.825	.833	.921	.825	.833	.921	.988	.916	.948
	.1	.931	.968	.979	.931	.968	.979	.931	.968	.979	.992	.997	.989

* Acceleration response ratio is the ratio of the response acceleration obtained by a coupled analysis to that obtained by a decoupled analysis.

CONCLUSIONS

The most important parameters which have a significant effect on equipment response are the mass ratio, yield levels of the system components, system damping and the tuned frequency.

Uncoupled analysis always overestimates the coupled secondary system response. Numerical design charts such as those of Table I, are most useful to the designer to assess the merits of undertaking a nonlinear coupled analysis. Such charts are also essential as a first step for codifying equipment seismic design.

The future direction for equipment seismic design should account for the different physical parameters as those identified in this study. At present, the lack of such quantification makes equipment design largely empirical.

REFERENCES

1. Aziz, T.S. and Duff, C.G., "Decoupling Criteria for Seismic Analysis of Nuclear Power Plant Systems", Joint ASME/CSME Pressure Vessels and Piping Conference, Montreal, Canada, June 1978.
2. Aziz, T.S. and Duff, C.G., "Mass Coupling Effects in the Dynamic Analysis of Nuclear Power Plant Systems", Joint ASME/CSME Pressure Vessels and Piping Conference, Montreal, Canada, June 1978.

3. Hadjian, A.H., "On the Decoupling of Secondary Systems for Seismic Analysis", 6th World Conference on Earthquake Engineering, India, 1977.
4. Hernried, A.G. and Sackman, J.L., "Response of Secondary Systems in Structures Subjected to Transient Excitation", Earthquake Engineering and Structural Dynamics, Vol. 12, March 1984.
5. Igusa, T. and Kiureghian, A.D., "Dynamic Characteristics of Two-Degree-of-Freedom Equipment-Structure Systems", Journal of Engineering Mechanics, January 1985.
6. Kawaktsu, T. and Kitade, K., "Floor Response Spectra Considering Elasto-plastic Behaviour of Nuclear Power Facilities", Transaction of the 5th International Conference on Structural Mechanics in Reactor Technology, Volume K(b), Paper K9/4, Berlin, West Germany, August 1979.
7. Ghobarah, A., Aziz, T. and Nguyen, C.X., "Inelastic Response of Tuned Systems", Fifth Canadian Conference on Earthquake Engineering, Ottawa, July 1987, pp. 571-576.
8. Ghobarah, A. and Aziz, T., "Seismic Response of Tuned Systems", Canadian Journal of Civil Engineering, Vol. 14, No. 6, December 1987, pp. 780-787.