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MULTIPLE PASSIVE TUNED MASS DAMPERS FOR REDUCING EARTHQUAKE INDUCED BUILDING MOTION

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SUMMARY

This paper discusses a methodology for designing multiple tuned mass damper (TMD) systems for reducing building response motion. The technique is based on extending the classic work of Den Hartog from a single degree of freedom to multiple degrees of freedom. Conclusions of earlier workers on the effectiveness of a single first mode TMD are verified and multiple TMD systems are evaluated. Simplified, linear mathematical models were excited with the El Centro 1940 N-S earthquake record. Significant motion reduction was achieved using the design technique.

INTRODUCTION

Recently there has been active research on base isolation, active mass dampers, and active tendon systems for reducing earthquake induced building motion. Each of these techniques has its limitations and practical implementation problems, however. The purpose of this paper is to re-examine the use of passive tuned mass dampers.

In 1979 Petersen (Ref. 1) reported on the successful design, construction and installation of a large scale tuned mass damper to reduce first mode motion. The system was for the Citicorp Center Building, Manhatten, New York, U.S.A. Sladek and Klinger (Ref. 2) reported in 1980 that such a system, while effective for reducing wind response motion, was not recommended for reducing seismic response of tall buildings.

This paper agrees with that conclusion for a single passive tuned mass damper. However, if multiple tuned mass dampers are applied to the tall structure significant motion reduction results.

SINGLE DEGREE OF FREEDOM TMD DESIGN

The design approach developed here applies the single degree of freedom analysis of Den Hartog (Ref. 3) to each of the major contributing modes of the tall structure. A brief example of Den Hartog's results will be useful.

Den Hartog's work applied to designing a TMD for an undamped spring mass system. The author has found that for low damping there is negligible effect for the purposes here. Figure 1a. shows the system subjected to an externally applied force F. By changing coordinates we can achieve a mathematically similar form for the case of base excitation by earthquake acceleration $\ddot{x}_g$, Figure 1b. Therefore, the optimum Den Hartog TMD design of Figure 1c that reduces y in Figure 1a will correspondingly reduce u in Figure 1b.

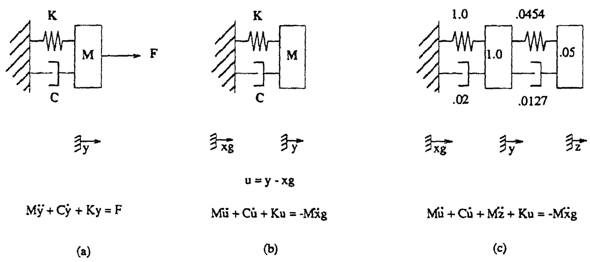

Figure 1. Single Degree of Freedom System with TMD

Den Hartog (Ref. 4), by clever mathematical analysis and reasoning, developed formulas for choosing the optimum damping and stiffness for the TMD, given the mass. Let us assume 5% of the main structure mass, M, is allowable for the TMD. For main structure parameters of unity mass, M, and unity stiffness, K, the optimum values of TMD stiffness and damping are shown in Figure 1c. A value of 1% damping for the main structure was assumed.

Figure 2 compares the frequency response magnitude function of $\ddot{u}$ due to $\ddot{x}_g$ without and with the optimum TMD.

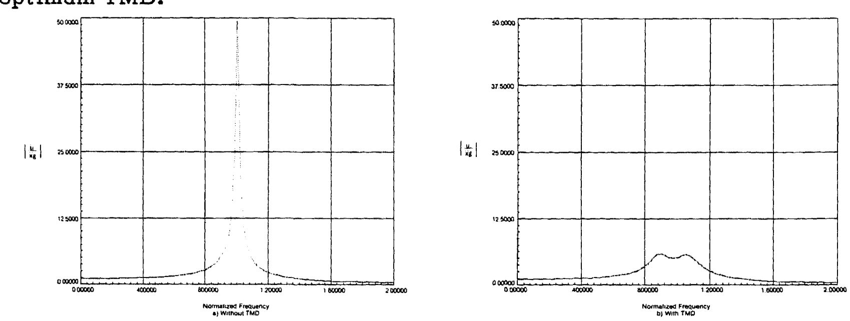

Figure 2. SDOF Frequency Response Functions

Single Degree of Freedom El Centro Earthquake Response. The earthquake transient response of the design was studied by simulation using the El Centro N-S 1940 record as the input. A natural frequency of 1 Hz, midrange in the response spectrum content of El Centro, was chosen for the main system. Figure 3 shows the comparison between the system without and with the 5% mass TMD design. Note the peak acceleration response is reduced 40% using the TMD.

The general conclusion from the lowly damped single degree of freedom analysis is that we can significantly reduce random and transient input system response using the Den Hartog optimum designed TMD.

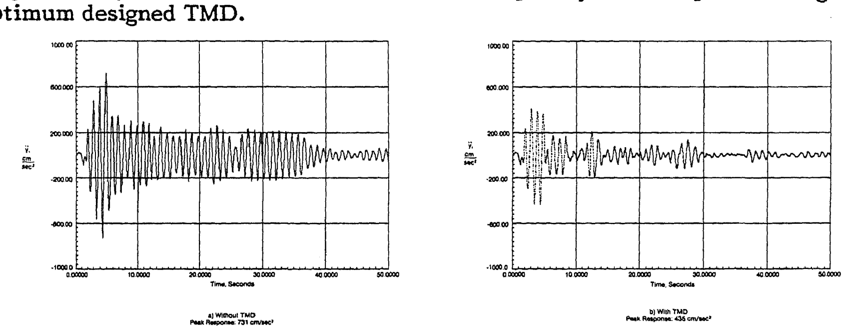

Figure 3. SDOF El Centro Acceleration Response

MULTIPLE DEGREE OF FREEDOM DESIGN

However, real buildings have multiple degrees of freedom and modes of vibration that are all responsive to broad band earthquake excitation. For the case of tall buildings, many of these modes are closely packed in the earthquake excitation frequency range. By noting two factors, the previous single degree of freedom analysis can be applied, however. First, it is well known that modal analysis will convert the coupled multiple degree of freedom system to uncoupled single degree of freedom systems in modal coordinates. Second, it is assumed that the low mass TMD's will only have an effect on the system response at the tuned frequency. These two factors allow using Den Hartog's results for multiple degree of freedom systems.

A particular example will demonstrate the general procedure. Consider a hypothetical tall building modeled as a shear building with 8 identical floor masses, M, and interstory stiffness, K. Figure 4 is a schematic diagram of the model. For simplicity of analysis, the inherent building damping was assumed zero. The multiple tuned mass damper system is shown located at floor masses, 3, 5, 6, and 8. These locations were chosen based on the reasoning given below.

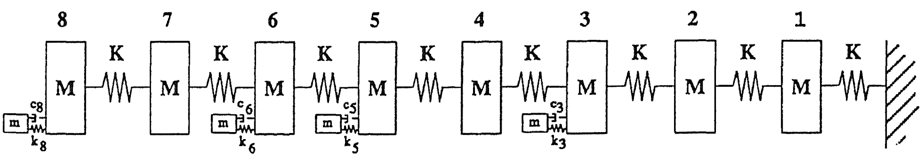

Figure 4. Hypothetical Tall Shear Building, 8 Degrees of Freedom

Let us assume the total weight of the building is 40,000 tons and the lowest natural frequency is .27 Hz. Then the individual floor weight is 5000 ton and the interstory stiffness is 424 ton/cm. A model analysis was performed on this building model and the result is given in Table 1 (below).

Mode No.:	1	2	3	4	5	6	7	8	Physical
Nat. Freq. Hz:	.27	.80	1.3	1.8	2.2	2.5	2.7	2.9	Location
$[\Phi]$ =	.09	.26	.39	.47	.48	.43	.33	.18	1
	.18	.43	.47	.26	-.09	-.39	-.48	-.33	2
	.26	.48	.18	-.33	-.47	-.09	.39	.43	3
	.33	.39	-.26	.43	.18	.47	-.09	-.48	4
	.39	.18	-.48	.09	.43	-.33	-.26	.47	5
	.43	-.09	-.33	.48	-.26	-.17	.47	-.39	6
	.47	-.33	.09	.17	-.39	.48	-.43	.26	7
	.48	-.47	.43	-.39	.33	-.26	.18	-.09	8
Participation Factor, β :	2.63	.85	.49	.32	.21	.14	.11	.05	

Table 1: Modal Analysis Data of 8 DOF Building Model

Let us consider the basic single degree of freedom motion equation with TMD. It may be written:

$$\ddot{u} + 2\xi\omega\dot{u} + \frac{m}{M}\ddot{z} + \omega^2 u = -\ddot{x}_g$$

where conventional symbols have been written for the damping ratio, ξ and the natural frequency, ω. Now after modal analysis, the modal coordinates q_i, are related to the physical coordinates, u_i, by the modal shape matrix, ϕ.

$$\underline{u} = [\phi]\,\underline{q}$$

Then a similar SDOF equation may be written for each modal coordinate, assuming non-interaction of individual tuned mass dampers with other modes:

$$\ddot{q}_i + 2\xi_i\omega_i\dot{q}_i + \alpha_i\frac{m_i}{M_i}\ddot{z}_i + \omega^2{}_i q_i = -\beta_i\ddot{x}_g$$

Note the similarity with the single degree of freedom case. The coefficients α_i ; and β_i are determined from knowledge of the mode shape matrix. β_i is known as the modal participation factor, and let α_i be known as the effective TMD modal mass coefficient.

For the simple example we chose to analyze, the generalized modal mass M_i is equal to the physical story mass M_i, and the β_i is the simple sum of the mode shape physical coordinates. To determine the α_i we choose the maximum antinode amplitude location for each mode. For the first 4 modes, these are at physical locations 8, 3, 5, and 6 respectively. Note this is the location of the TMD's shown in Figure 5. The first design rule is to place the TMD's at the antinode locations of the individual mode shapes. How many modes need to be considered? This question is answered by examining the mode shape matrix, the participation factors, the earthquake design response spectrum, and the natural frequencies of the structure. For this example, the first four modes contribute about 95% of the motion at the top of the building. Therefore, four TMD's are designed.

The effective TMD modal mass coefficient, α_i, is the antinode mode shape value. For all the modes of our chosen example this is .48. Now the TMD design can proceed. First we determine the 5% TMD mass by:

$$\frac{\alpha_i m_i}{M_i} = .05;\ \alpha_i = .48;\ M_i = 5.097\ \frac{\text{ton}\cdot\text{s}^2}{\text{cm}}$$

Therefore, m_i is equal to $.527\ \frac{\text{ton}\cdot\text{s}^2}{\text{cm}}$ or a weight of 521 ton for each building damper TMD. The complete design then follows from knowlege of the modal natural frequencies and Den Hartog's design formulas. Table 2 shows the result.

TMD Location	Modal Freq. Hz	TMD Weight, tons	TMD Stiffness $\frac{\text{ton}}{\text{cm}}$	TMD Damping $\frac{\text{ton}\cdot\text{s}}{\text{cm}}$
Citicorp Center	.15	363	.57	.123
#8	.27	521	1.35	.276
#3	.80	521	11.9	.671
#5	1.30	521	31.5	1.09
#6	1.75	521	57.6	1.48

Table 2. Optimum TMD Design Parameters

Multiple Degree of Freedom El Centro Response. A simulation of the eight degree of freedom system with the four TMD system described above was performed with the El Centro acceleration as the input. Three responses are compared in Figure 5.

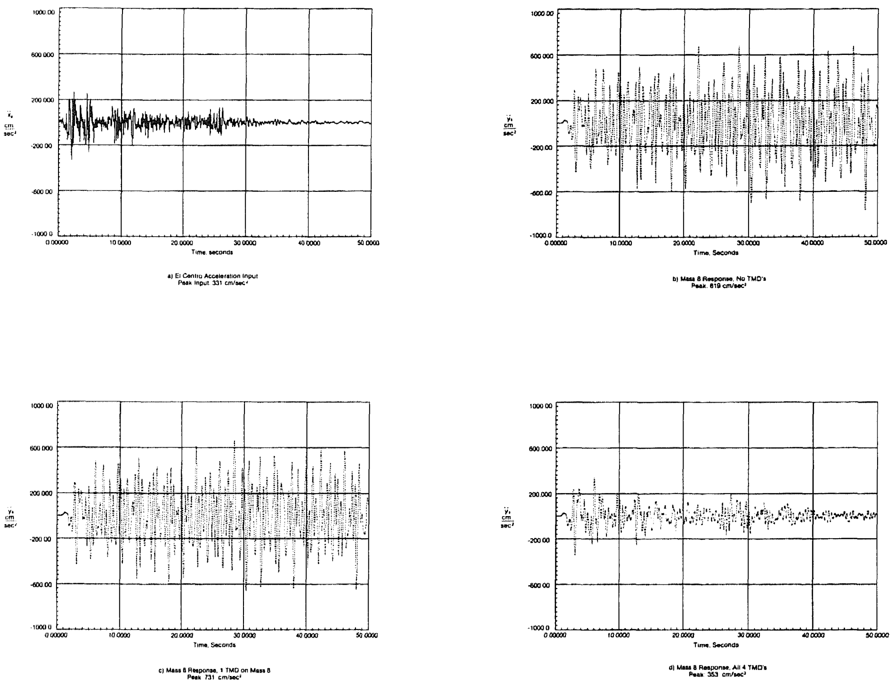

Figure 5. Multiple Degree of Freedom El Centro Responses

Note there is only an 11% reduction of the peak response with 1 TMD, but there is a 56% reduction with all four TMD's. If there was inherent building mode damping on the order of 1%, which is more realistic, we would expect about a 50% reduction.

During the simulation to determine the response to El Centro, the kinetic and kinematic parameters of the TMD's was monitored. The results are shown in Table 3. The average power absorbed by all four TMD's during the 50 seconds was 107 kW.

TMD Location	Damper Force, ton	Damper Piston Area cm^2	TMD Vel cm/sec	Damper Flow, lpm	TMD Stroke, cm	Damper Power, kW
Citicorp Center	21.3	83.9	172	865	± 114.0	359
#8	26.3	125	116	872	± 49.3	299
#3	50.8	241	76	1095	± 14.7	379
#5	72.5	343	66	1367	± 8.8	469
#6	81.6	387	55	1281	± 5.5	440

Table 3. TMD Physical Parameters Maximums

CONCLUSIONS

It has been shown with simple but representative mathematical models that:

1) Single degree of freedom tuned mass dampers are not effective in significantly reducing earthquake induced building motion.

2) Multiple passive tuned mass damper systems designed by modal and Den Hartog analysis give motion reductions between 40% and 60% for a 5% increase in the mass of the building.

3) The required physical parameters for such a multiple TMD system are similar to those of the system already installed in the Citicorp Center.

ACKNOWLEDGEMENTS

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