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PARAMETRIC STUDY OF A TWO DEGREE OF FREEDOM SYSTEM WITH RESONANT MASSES

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ABSTRACT

The analytical study of a two degree of freedom system was carried out. The first story represents the building and the second one the tuned mass damper. The system was subjected to an harmonic load and three seismic records of the 1985 Mexico Earthquake corresponding to hard, intermediate and soft soils of Mexico City. In the elastic range, important response reductions resulted. The inelastic analysis was carried out for structural ductility demands of two and four; these are common values used to design buildings in Mexico. Two possible mass damper models were incorporated in the inelastic structure: one with elastic behavior and the other inelastic, with maximum ductility of six.

Results show that the best structural behavior was obtained when the mass damper and the structure remain in the elastic range; however, lateral displacement demands of the damper are too large. For these displacements the damper could be seriously damaged resulting impractical. If the structure becomes inelastic, with low ductility demands, while the damper does not exceed the elastic range, the structural response is reduced showing the efficiency of the tuned mass; in this case the tuned mass displacements are strongly reduced, as compared with the elastic behavior of the structure.

KEYWORDS

Energy dissipating devices; inelastic behavior of tuned mass damper; passive control; seismic response; mass ratio of tuned mass damper; frequency ratio of tuned massdamper-structure.

INTRODUCTION

Tuned mass dampers bases its application on the existence of inertia forces on additional masses opposite the movement of the structure. To know the applicability in the reduction of damage produced by seismic events, experimental and analytical studies have been carried out in different research institutions all over the world.

The greater part of the studies have been accomplished with seismic excitement of dynamic characteristics different from the quakes registered in the Mexican Republic, considering structures with elastic behavior; to date no conclusive results exist with respect to the influence of non-linear behavior on the response of these systems.

Election of the structural system

Given the great number of parameters that intervene in the inelastic response of structures of several degrees of freedom system, it is necessary to appeal to simplest systems that permit the obtention of general results. Complex structures of several degrees of freedom can be idealized as one degree of freedom system as long as the frequencies of vibration are well separated. For this reason, it was decided to study a one degree of freedom system adding a resonant mass as the second degree of freedom.

Excitation of the system

To excite the structure a harmonic signal was applied in the base of the structure, with amplitude Po and frequency such that the relationship of frequencies of the excitation to that of the structure "g" varied between 0.6 and 1.4. This first analysis had as purpose the notation of the application range of the different parameters involved in response. The accelerograms registered in the stations of SCT-EW, TACUBAYA-EW and VIVEROS-EW of the 1985 Michoacán earthquake were also used, corresponding to soft, hard and transition soil, respectively.

ELASTIC RESPONSE

The dynamic equations for the first and second level respectively, are:

$$m_1\ddot{x}_1 + k_1 x_1 + c_1\dot{x}_1 - k_2(x_2 - x_1) - c_2(\dot{x}_2 - \dot{x}_1) = -m_1\ddot{x}_g$$

$$m_2\ddot{x}_2 + k_2(x_2 - x_1) + c_2(\dot{x}_2 - \dot{x}_1) = -m_2\ddot{x}_g$$

considering $x = A\, e^{i\Omega t}$, the result is:

$$\frac{A}{x_{st}} = \sqrt{\frac{\left[g^2 - f^2(1+\mu)\right]^2 + \left[2g\xi_c(-1-\mu)\right]^2}{\left[-\mu f^2 g^2 + (g^2-1)(g^2-f^2) - 4g^2\xi_1\xi_c\right]^2 + 4g^2\left[\xi_c(-g^2-\mu g^2+1) + \xi_1(f^2-g^2)\right]^2}}$$

According to the previous results, the variables that determine response are:

- The relationship between the first mass level and the second one (μ)
- The relationship between the excitation frequency and the vibration frequency of the structure (g)
- The relationship between the vibration frequencies of the first and second level (f)
- The damping of the first and second level ξ_1 and ξ_2

RESULTS OF ELASTIC BEHAVIOR

The maximum displacement of the system without oscillator was used as source of comparison of the complete system response (structure with tuned mass damper). Parameters were varied in the intervals that are shown in table 1.

For the results that will be commented in the following paragraphs, the value of f (relationship of frequencies between the two degrees of freedom) was considered equal to the unit, due to the fact that in the variation interval of the other parameters this value provides minimal response. Upon considering f=1, ξ_c represents the damping ratio of the second level.

Figure 1 shows the first level lateral displacement (structure) of the two degrees of freedom system for damping ratio of the structure and mass relationship of 1%. It is observed that for μ=1% the behavior is strongly dependent upon varying the damping of the structure from 1% to 6%, with respect to applicability of the oscillator to reduce response. It is clear that when increasing the damping of the structure, the advantage of using the oscillator is reduced to a small interval in the zone near the resonance, or it can even cause increase to the response. This conclusion is maintained in the subsequent figures.

Table 1. Parameter used in the analysis of the system

Parámetro	Valor
μ	1%, 2%, 4%, 6%, 9%, 11%, 16%
g	between 0.6 y 1.4
f	1
ξ_1	1%, 2%, 4%, 6%, 9%, 11%, 16%
ξ_c	1%, 2%, 4%, 6%, 9%, 11%, 16%

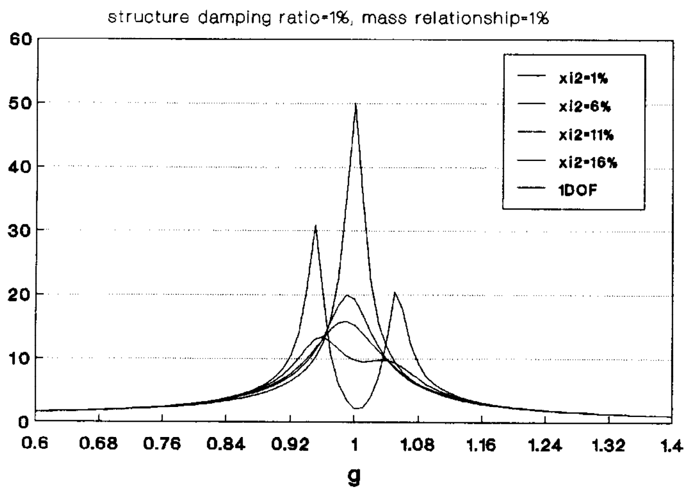

Figure 1 Response of the structure under harmonic load

Upon increasing the mass relationship to 4%, the interval of "g" wich are presents maximum response values with oscillator, increases with respect to g=1 (resonance); at the same time the maximum displacement is reduced. However, this originates greater displacements, in a frequency ratio range, as compared with the one degree of freedom system displacement. This trend continues with the greater mass relationships.

The set of previous parameters shows that the increase of the structure damping reduces the response of the system that causes that the oscillator lose efectiveness. Increasing the mass relationship, the interval of application increases and for oscillator damping ratios smaller than 6%. its utilization is not safe.

The influence of the mass relationship in the behavior is shown in figs 2 to 4, for various damping ratios. Increasing the mass relationship, the response curve of the complete system crosses the corresponding curve of the one degree of freedom system in increasingly removed points from the value of g=1, which widens the interval of application.

Upon increasing the damping of the oscillator, response improves considerably in the zones outside of the resonance threshold. For structural dampings greater than 6% and small oscillator dampings, the changes in response are not very meaningful. The greater difference of behavior upon varying the mass relationship is presented in the zone near the resonance. In zones outside of this interval the curves are much more nearer each other.

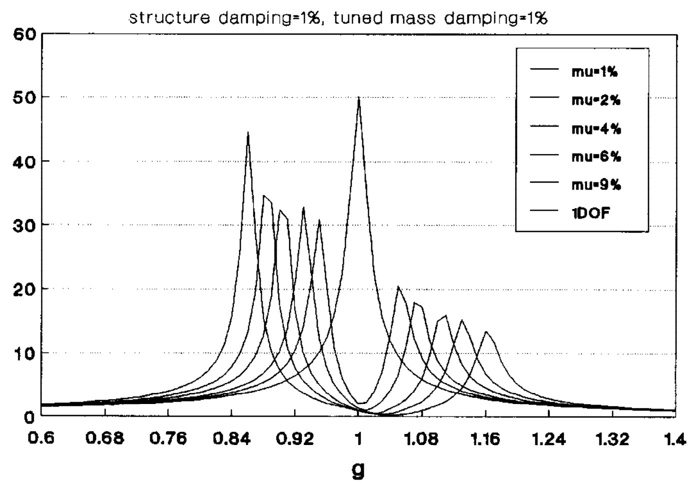

Figure 2 Reponse of the structure under harmonic load

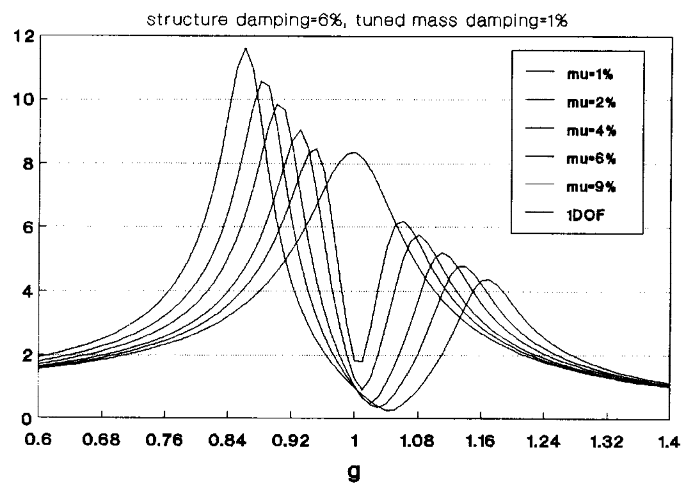

Figure 3 Response of the structure under harmonic load

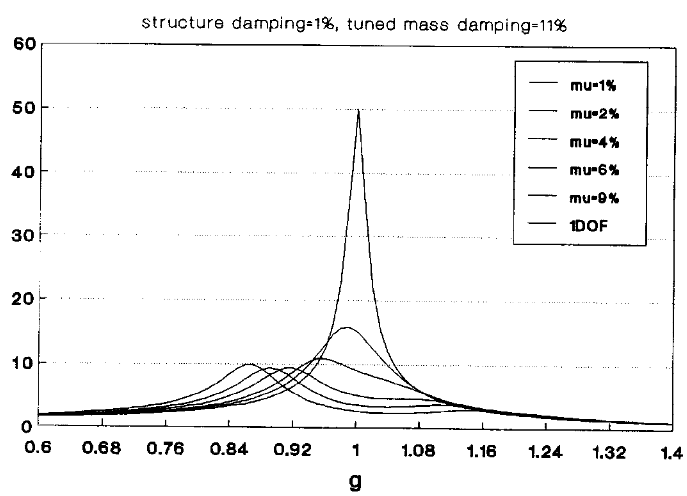

Figure 4 Response of the structure under harmonic load

Response under earthquake records

Structural response for seismic records was obtained using DRAIN-2DX program (Prakash and cabbage, 1992) that solves the dynamic equations with the step by step method. For the study of the structure subjected to real quakes, it was considered m_1=500 (kg-s^2 /cm), and the other parameters (μ, g, f, ξ_1, ξ_c) were obtained based on the m_1 value. ξ_1 is the damping ratio of the first mode of vibration and ξ_c the damping ratio of the second mode of vibration (ξ_c = ξ_2 when f=1).

Structures with periods from 0.1 sec to 4 sec, with $\xi_1=\xi_2$ of 1%, 6% and 11% and mass relationships - μ- of 1%, 2%, 4%, 6% and 9% were considered. The previous structures were subjected to the records of SCT, TACUBAYA and VIVEROS of the 1985 earthquake of Michoacan.

Elastic response of the structure with tuned mass damper for mass relationships of 1% to the 9%, damping ratio of 1% and under the excitation of the east-west component of the SCT record, is shown in fig 5. The graph, as expected, is considerably different from the one obtained upon applying harmonic load. Although the advantages of incorporating the oscillator are cleary reduced, as compared with the previous case, for all the mass relationships, there are response reductions in the resonant amplification zones of the one degree of freedom system (structure without oscillator). The most efficient mass relationship is found between 2% and 4%, since in this case important reductions of response in resonant amplification zones and small increases for the remaining periods exist. For large mass relationships (greater than 6%) the response increases (with respect to the one degree of freedom system) for several periods, reducing the applicability of the resonant mass.

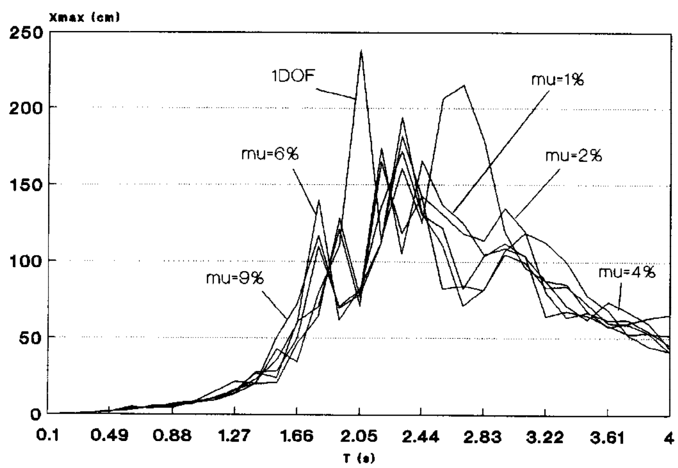

Figure 5 Response of the structure under SCT-EW record

The response of the system under Tacubaya record, is shown in fig 6. The best response is obtained for a mass relationship of 4%, that reduces displacements for periods located between 2.5 sec and 3.4 sec, with small increases outside of this zone; for Viveros record, the conclusions are similar. Though response of the system is satisfactory for the Tacubaya and Viveros records, it is important note that structural responses are lower than those corresponding to the SCT record, which very probably means that the oscillator will be unnecessary in these cases.

Upon increasing the damping ratio to 6%, the response of the system subjected to the SCT record, changes radically. The Response for the periods near to 2.5 sec is reduced considerably when then oscillator is incorporated, but its maximum response amplitude (in other periods) is only 20% less than the amplitude corresponding to the one degree of freedom system. Given the inherent uncertainties to the earthquakes and to the dynamic properties of the structures, the possible utilization of the oscillator, from an economic point of view, must consider only 20% of response reduction.

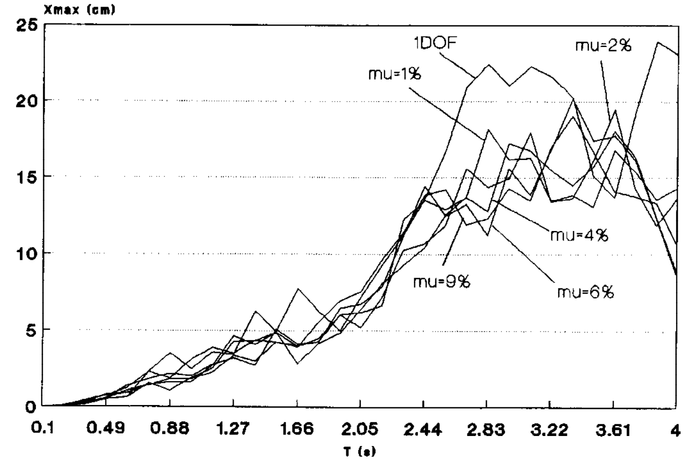

Figure 6 Respnse of the structure under Tacubaya record

<u>Response of the second level</u>

Graph 7 presents a typical response of the second level for different mass relationships and damping ratios of the structure of 1%, corresponding to the elastic analysis of the system subjected to the SCT-EW record. As a source of comparison with all the previous results, the figure also have the response of the one degree of freedom system.

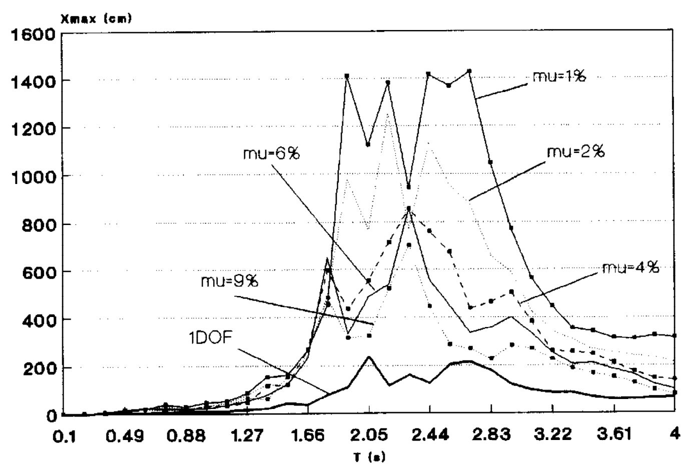

Figura 7 Response of the tuned mass damper under SCT record

The curves show that with the increase of the mass relationship and the damping ratio, the response is reduced. For a damping ratio of 1%, the maximum lateral displacement of the oscillator is extraordinarily large for a wide interval of periods. With the highest studied damping ratio (11%) and the largest mass relationship, the displacement of the oscillator continues to bei unacceptable from a practical point of view.

With the materials that currently we use, it is practically impossible to build an oscillator that, with elastic behavior, permits the maximum displacement of the previous figures. For this reason, the oscillator and the structure would have the previous behavior, provided that the excitation not make the system enter the inelastic interval. This means that we could expect reductions of response as mentioned, only under moderate seismic excitation.

RESULTS OF INELASTIC BEHAVIOR

Since excitation such as the SCT record would originate invariably inelastic behavior in structures (as those which currently are designed) with dynamic properties that locate them in the resonance threshold and due to the fact that this type of structures are the most viable to incorporate a resonant oscillator, it was decided to study the seismic response of these systems when they enter the inelastic range.

The analysis was accomplished with the same parameters mentioned for the elastic analysis, when the structures were subjected to quake records. For this study the computer program DRAIN-2DX (Prakash and cabbage, 1992) was used again. The material behavior was considered elastoplastic. One degree of freedom systems with ductility demand of the oscilator of 6 under the SCT record, and ductility demand of 4 and 2 for the structure were analyzed. The study was done in two parts: a) when the oscillator behaves inelastically and the structure is maintained elastic, and b) when the oscillator is maintained elastic and the structure behaves inelastically.

Inelastic oscillator

The following parameters were adopted for this analysis: $\xi_2=0.01$, $\mu=0.01$ and $\xi_1=0.01$. Based on these values, The response of the system with material properties that causes inelastic behavior of the oscillator was analyzed.

The incorporation of the oscillator hardly modifies the seismic response. Drawing the time response of the oscillator, it was observed that for the interval of the one which presents the greater amplitudes of the record, the oscillator behaves inelastic. Based on the results of the elastic analysis, the best response is obtained when the period of the structure and that of the oscillator coincide. Since the post yield stiffness used was of 1% of the elastic, it was decided to calculate the response again, modifying the dynamic properties so that the periodos of the two levels would be equal when the oscillator is in the inelastic range. The obtained response was, in general terms, the same as that for the previous case. These results suggest rejeening the utilization of oscillators with inelastic behavior as a possible system for the reduction of seismic response.

With the oscillator properties such that the elastic periods are equal, the behavior of the second level presents a large displacement for periods of high quake energy. On the other side, reducing the tuned mass damper stiffness, the oscillator is so flexible that the structure is moved as if the resonant massdid not exist and therefore the displacement of the oscillator is very small.

Inelastic structural behavior

Below, the response of the structure with the oscillator was analyzed, considering elastoplastic behavior of the structure and elastic behavior of the oscillator. The yield properties were determined so that the ductility demand of the first level (structure), when subjected to the SCT record, was two for all the periods.

The response of the structure (Q=2) with and without oscillator for 1% of damping ratio, varing the other parameters was obtained. Response with the oscillator is, for some periods, lower than that of the structure and for others this behavior is interchanged. In general, the utilization of the oscillator results unfavorable.

Thereinafter, the yield properties of the structure without an oscillator were modified so that for all the periods studied, the ductility demand was Q=4, when the systems were subjected to the SCT record. Increasing the damping ratio and the mass relationship to 4% and 6% tuned mass damper reduces the displacement of the structure considerably, with reductions between 25% and 40% in the zones of maximum responses. With a damping ratio of 1% and mass relationships of 4% and 6%, the previous response does not improve, which allows us to conclude that the most convenient response is obtained when the mass relationship and the damping ratio have equal values between 4% and 6%.

The displacements of the second level (oscillator) for the structure with Q=2, continue to be very high. For Q=4, the behavior of the additional mass improves considerably with the increase of the damping ratio. Other parameter combinations produce inadmissible displacement, from a practical point of view.

Since the response of the structure does not improve when the oscillator is in the inelastic interval, it was decided to seek the causes that originated this behavior. The two degree of freedom system was again subjected to an harmonic record to determine the time of the load application necessary to reach the maximum reduction of the first level (structure). It is observed that at around 10 sec the response reaches 65% of the maximum reduction. the response history of the oscillator that showed the short intervals of the inelastic resonant mass behavior (smaller to 4 sec) was also obtained, explaining the reduction of system efficiency.

CONCLUSIONS

1. Results showed that for moderate quakes, where the structure and the oscillator remain in the elastic range, the resonant mass can indeed be useful to reduce the response, avoiding the inelastic behavior of the structure, associated with possible damages. For greater intensity events, the large displacement of the oscillator would make it enter in the inelastic range, reducing, at the same time, its applicability.
2. When the structure behaves inelastically, with a mass relationship of 6% and a damping ratio of around 6%, the addition of a tuned mass damper reduces the structural response, with reasonable displacement demands of the oscillator.
3. For countries such as Mexico, the use of oscillators as devices of passive control, would be a relatively economic option in structures with dynamic properties that make them vulnerable to the resonance phenomenon.
4. The main disadvantage of the resonant mass is found in the strong dependency of its efficiency on the dynamic characteristics of the structure and with the characteristics of the seismic record. For this reason, it is recomendable that structural safety with oscillators of passive control not depend totally on this system.
5. In structures already built whose dynamic characteristics make them vulnerable to future seismic events, tuned mass dampers could contribute to an important reduction of response.

REFERENCES

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