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COMBINED CONTROL STRATEGY BASE ISOLATION AND TUNED MASS DAMPER: AN EFFECTIVENESS ANALYSIS OF ITS APPLICATION TO NON-LINEAR BENCHMARK BASE ISOLATED STRUCTURE

M. De Iuliis[1], Petti L.[2], Palazzo B.[3]

[1] *Research Assistant, Dept. of Civil Engineering , University of Salerno, Italy*
[2] *Assistant Professor, Dept. of Civil Engineering, University of Salerno, Italy*
[3] *Full Professor, Dept. of Civil Engineering, University of Salerno, Italy*
Email: mdeiuliis@unisa.it, petti@unisa.it, palazzo@unisa.it

ABSTRACT :

Base isolation is nowadays widely considered as an effective strategy to protect structures subject to seismic excitations. However, it has been shown that, in the case of seismic excitations with high energy content at low frequencies, i.e. a near-fault event or a seismic wave propagating itself through alluvial soil, isolation bearings may undergo gross deformations. Observing that the response of base-isolated (BI) systems is dominated by the first-modal contribution and that Tuned Mass Damping (TMD) is able to reduce the fundamental vibration mode, a new idea of combining both properties into a unique system (BI&TMD) was proposed and investigated by Palazzo and Petti.
A benchmark structure in which the non-linear response of isolation devices (elastomeric and friction pendulum) is explicitly considered has been recently defined. By using this model, this paper aims to investigate the non-linear behaviour of the benchmark isolated structure when a mass damping system is applied on the isolation layer, in order to study the effectiveness of this strategy in reducing the seismic response of the isolation layer.

KEYWORDS: Base Isolation, Tuned Mass Damping, Hybrid control strategy

1. INTRODUCTION

The control of seismic structural response has been widely investigated in the last decade, research efforts have led to notable progress both in theoretical and technological knowledge with the introduction of new materials and devices having high effectiveness and reliability. Among the several proposed control strategies, the Base Isolated systems (BI) has to be considered nowadays an effective strategy to protect civil structures against seismic excitations. Numerous real applications confirm this statement. Its effectiveness depends on the low-pass filtering capacity of the range of frequencies where the earthquake energy is strongest and closest to the superstructure's fundamental natural vibration period. The filtering capacity mainly influences the superstructure's inter-storey drifts by concentrating large deformations onto the isolation bearings. Therefore, the central problem of the base isolation strategy is that, under certain excitations, having high energy content at a low frequency [Spencer et al., 2000], the system may suffer from excessive displacements at the base. The control of such displacements is generally achieved by using high-damping isolation devices. Nevertheless this strategy worsens the whole system's performance with a significant increase in absolute accelerations and displacements at the superstructure [Palazzo and Petti, 1997].
By observing that well isolated system responses are dominated by the first-modal contribution and that Tuned Mass Dampers are able to reduce the fundamental vibration mode, a new idea of combining both properties into a unique system was proposed and investigated by Palazzo and Petti [Palazzo and Petti, 1994]. The objective of the proposed combined system is to control the system response by only reducing the fundamental modal contribution which is dominant in such systems. This positive behaviour is due to the appropriate combination of three fundamental properties of the original systems: the reduction in the ground motion transmission to the superstructure, the dynamic behaviour modification due to the BI and the first vibration mode reduction by means of the TMD at this frequency. By considering the BI structure as a single-degree-of-freedom it could be proved that TMD acts as a closed loop control applied to the isolation layer. Such a combined system BI&TMD has been positively tested when applied to both plan and tri-dimensional frame systems, in the case of recorded seismic events and synthetic

excitations produced through stochastic approaches in the case of linear behaviour by the isolation bearings. No studies are available in technical literature regarding the effectiveness of the proposed approach in mitigating the seismic non- linear response.
The present paper presents the results concerning the control of a benchmark base-isolated structure by using the BI&TMD strategy. There is first a brief review concerning the potentiality of the proposed approach in the case of linear seismic response and subsequently a discussion on significant results regarding the effectiveness of the strategy when frictional isolation devices are considered.

2. THE BASE ISOLATED BENCHMARK STRUCTURE

The benchmark structure [Narasimhan et al., 2006] is a base-isolated eight-storey, steel-braced frame building, 82.4 meters high and 54.3 meters wide, and it is representative of existing buildings in Los Angeles, California. The floor plan is L-shaped (figure 1). The superstructure is modelled as a three-dimensional linear elastic system, and both the superstructure and the base are modelled by using three master degrees of freedom (DOF) per floor. The combined model of the superstructure (24 DOF) and isolation system (3 DOF) consists of 27 degrees of freedom. All twenty four modes in the fixed base case are used in modelling the superstructure for which a 5% damping ratio is assumed.
The base isolation system for the aforementioned superstructure is not strictly assigned as it can be modified depending on the dynamic response analysis to be carried out. Generally, it is possible to arrange three device types into 92 default configurations: linear elastometric isolation system with low damping, non-linear friction isolation (pendulum devices), and the bilinear elastometric isolation system (lead-rubber devices). In this study, numerical analyses have been carried out by considering an isolation system constituted by both elastomeric and frictional devices (Figure 1).

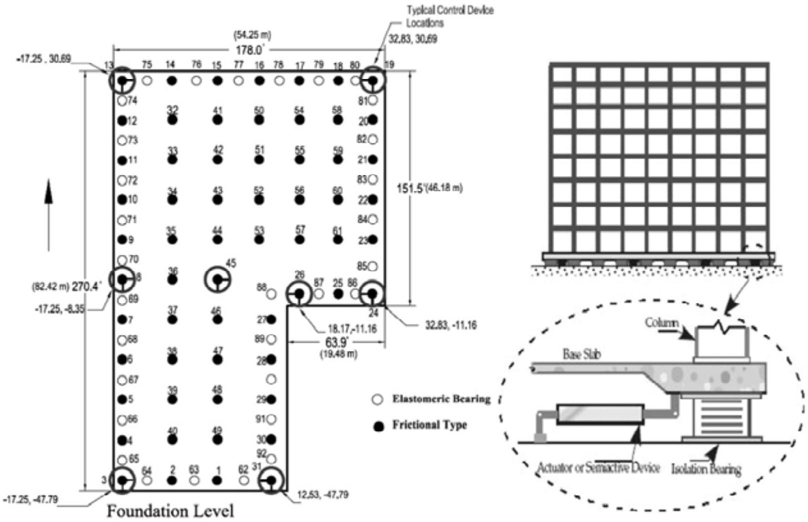

Figure 1: Benchmark structure - Isolation level plan

The numerical model of the benchmark problem has been developed by its authors by using the Simulink tool in Matlab software [Narasimhan et al., 2006], this model has been modified to take into account the passive actions applied by the Tuned Mass damping systems. In particular two TMD system configurations are herein investigated (Figure 2 - Configuration A and Configuration B) consisting of two satellite masses located at the edge of the isolation level to control both translational and rotational components of motion. The masses' positions are defined by means of the following coordinates: $x_1^A = 28.83m$, $x_2^A = 13.25m$, $x_1^B = 26.69m$, $x_2^B = 43.49m$ and their optimal tuning, in the case of the linear response, have been evaluated by classical frequency analysis. Results of tuning optimization are listed in table 2.1.

Table 2.1 Optimal mass dampers stiffness and damping

Mass ratio	Frequency and damping	Configuration A	Configuration B
$\mu = 0.05$	$(\omega^{x}_{TMD}, \xi^{x}_{TMD})$	$(1.84\ rad/\sec, 0.132)$	$(1.86\ rad/\sec, 0.132)$
	$(\omega^{y}_{TMD}, \xi^{y}_{TMD})$	$(1.78\ rad/\sec, 0.131)$	$(1.76\ rad/\sec, 0.131)$
$\mu = 0.10$	$(\omega^{x}_{TMD}, \xi^{x}_{TMD})$	$(1.77\ rad/\sec, 0.181)$	$(1.77\ rad/\sec, 0.181)$
	$(\omega^{y}_{TMD}, \xi^{y}_{TMD})$	$(1.72\ rad/\sec, 0.181)$	$(1.67\ rad/\sec, 0.181)$

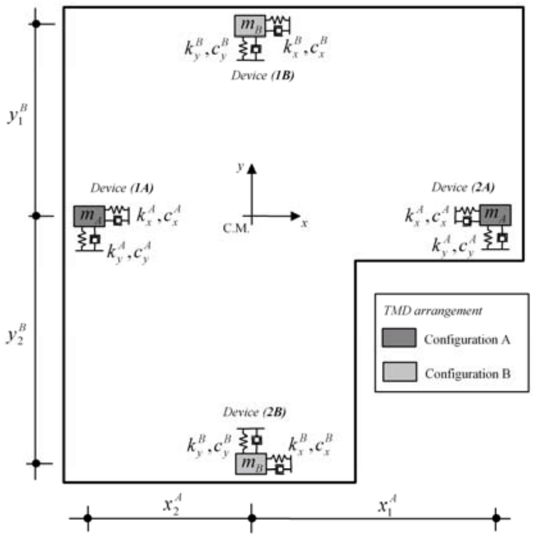

Figure 2: TMD systems configuration

3. EFFECTIVENESS OF BI&TMD SYSTEM – SEISMIC LINEAR RESPONSE

Wide-ranging numerical experimentation on the dynamic linear response of base-isolated benchmark structures equipped with Tuned Mass Dampers has been carried out in order to verify the effectiveness of the proposed control strategy. The benchmark's authors [Narasimhan et al., 2006] suggest both a set of seven bi-directional recorded seismic inputs (Newhall, Sylmar, El Centro, Rinaldi, Kobe, Jiji, Erzinkan) to study the spatial dynamic behaviour of the structure, and a set of performance indexes to describe the effect of the control system on the isolated benchmark. In this study seven indexes have been considered (Table 3.1).

Table 3.1: Optimal mass dampers stiffness and damping

Index	Description
J_1	Peak base shear (isolation-level) in the controlled structure normalized by the corresponding shear in the uncontrolled structure
J_2	Peak structure shear (at first-storey level) in the controlled structure normalized by the corresponding shear in the uncontrolled structure
J_3	Peak base displacement or isolator deformation in the controlled structure normalized by the corresponding displacement in the uncontrolled structure
J_4	Peak inter-storey drift in the controlled structure normalized by the corresponding drift in the uncontrolled structure
J_5	Peak absolute floor acceleration in the controlled structure normalized by the corresponding acceleration in the uncontrolled structure
J_7	RMS base displacement in the controlled structure normalized by the corresponding RMS base displacement in the uncontrolled structure
J_8	RMS absolute floor acceleration in the controlled structure normalized by the corresponding RMS acceleration in the uncontrolled structure

The results of numerical analysis are fully described by Palazzo et al. [Palazzo et al., 2006], they allow for the following considerations about the control system's effectiveness:

- Well-designed TMD on BI improves the seismic behaviour of the benchmark isolated structure in relation to all considered performance indexes and recorded seismic events;
- Indexes J_3 (peak base displacement) and J_7 (RMS base displacement), concerning the control of the base level motion, presents lower values when compared to the others. This is consistent with the design target to minimize the isolation bearings displacements. Moreover, the superstructure absolute acceleration, in terms of root mean square (J_8 index), is also strongly reduced;
- The proposed strategy presents different effectiveness levels in reducing isolator displacement on varying the dynamic characteristics of the seismic event. High performances are obtained for the El-Centro earthquake, more than 50% reduction in J_7 index (figure 3), whilst for the Jiji earthquake slightly less than 10% reduction has been observed (figure 3).
- TMD on BI appears to be very effective in reducing the RMS seismic response of the isolators. Its effectiveness is reduced if referred to the isolators peak displacement control;

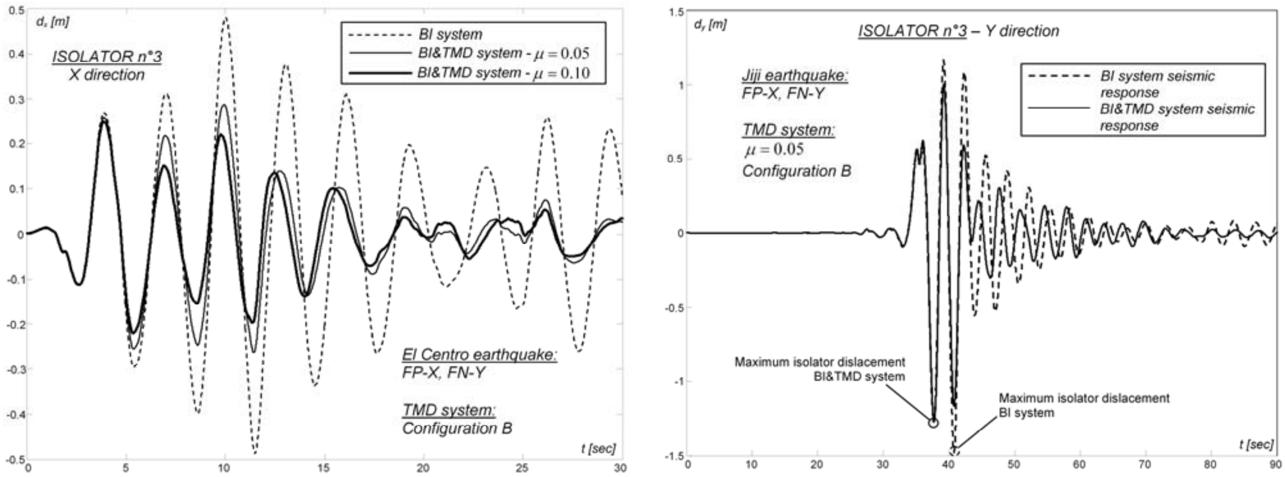

Figure 3: TMD effectiveness in reducing base isolators relative displacement

Finally, TMD on BI appears to be very effective in reducing the RMS seismic response of the isolators. However BI&TMD control strategy reduces its effectiveness if peak displacement control of isolation devices is pursued, because of the inertia of TMDs, which does not allow devices to be effective in the application of the control actions at once.

4. EFFECTIVENESS OF BI&TMD SYSTEM – SEISMIC NON-LINEAR RESPONSE

In order to investigate the effectiveness of a Tuned Mass Damping system to improve the seismic performance of a non-linear Base Isolated System, a mixed solution for the isolation layer has been considered in which 31 elastomeric devices and 61 frictional devices are adopted. The devices' hysteretic behaviour has been modelled by using the well-known Bouc-Wen model [Wen, 1976], and their force-displacement responses are represented in figure 4. A parametric analysis has been carried out by varying the mechanical characteristics of the satellite masses to evaluate the non-linear seismic response of the benchmark structure to the seismic events under consideration. In particular, the performance indexes, for the non-linear benchmark structure equipped with a TMD system, are evaluated on varying the mechanical parameters (ω_x, ω_y, ξ) of the satellite masses within the following ranges:

$$0.5\omega^{lin}_{x,opt} \le \omega_x \le 1.5\omega^{lin}_{x,opt}\,,\;\; 0.5\omega^{lin}_{y,opt} \le \omega_x \le 1.5\omega^{lin}_{x,opt}\,,\;\; 0.5\xi^{lin}_{x,opt} \le \xi \le 1.5\xi^{lin}_{x,opt} \tag{4.1}$$

Both Configuration A and configuration B for the satellite masses are taken into account in the parametrical analysis.

The results of such an analysis for the Erzinkan earthquake, with reference to the J_3 and J_7 performance indexes, which are those related to the isolation layer relative displacement seismic response, are plotted in figure 5. In particular, a contour line plot has been adopted to show the effect on varying the tuning frequencies in both *x* and *y* directions on the TMD system's seismic performance. Moreover, the optimal progress of these two variables has been represented, pinpointing the optimal tuning of the mass damping devices as the intersection of such progress.

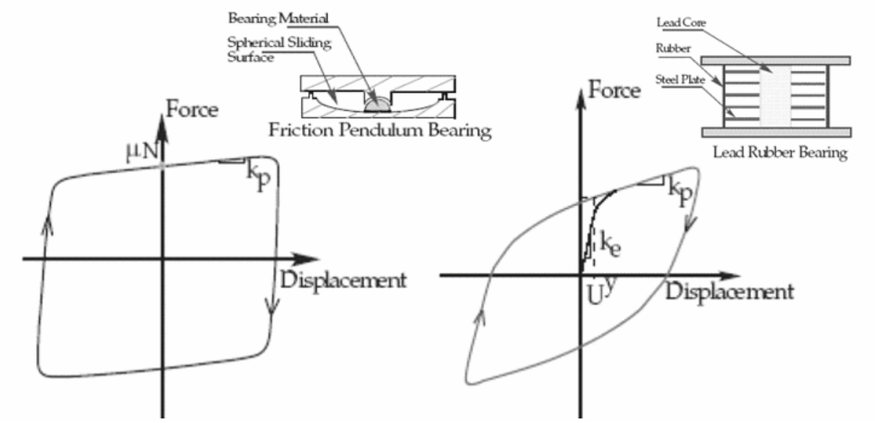

Figure 4: Non-linear isolation devices. Force-displacement response

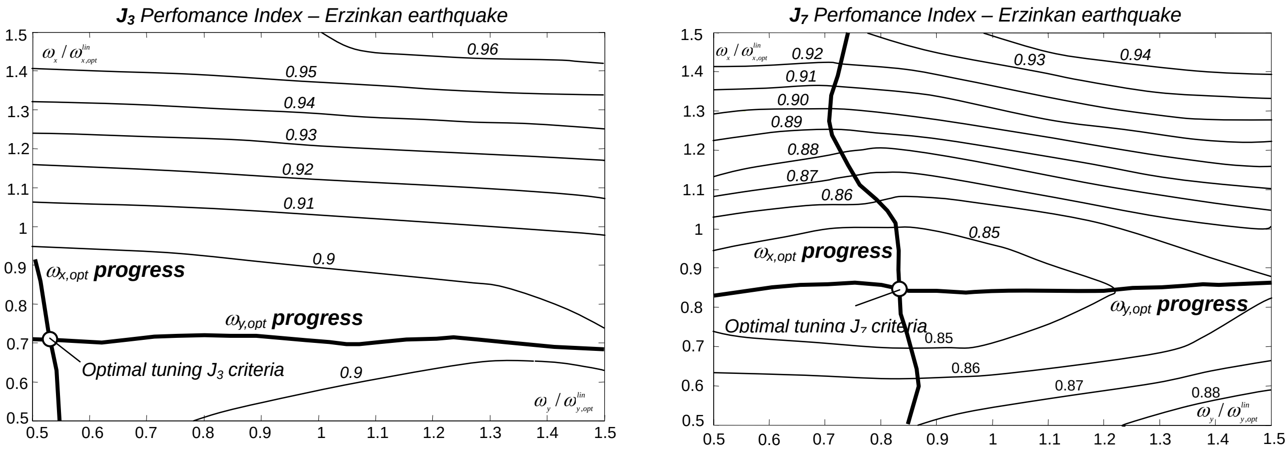

Figure 5: Isolation layer response on varying TMD system tuning ($\xi = \xi_{opt}^{lin}$)

By looking at figure 5, it is clear that the effectiveness of the mass damping system in reducing the seismic displacement demand is lower than in the case of linear behaviour: a 10% maximum reduction for the peak isolator displacement and a 15% maximum reduction for the RMS base displacement has been observed. In order to summarise the parametrical analysis results, in figures 6-7 the progress line for $\omega_{x,opt}$ and $\omega_{y,opt}$ are represented for all the seismic events under consideration. This allows for more consistent consideration regarding the non-linear dynamic behaviour of this BI&TMD system.

Seismic input event characteristics significantly affect the optimal tuning of the mass damper system, in particular three zones can be recognized for both the J_3 and J_7 indexes. The first zone is characterized by high values for the optimal frequency of TMD system in *y* direction, nevertheless different *x* direction optimal frequency values are observed for controlling base isolators' peak displacement and RMS displacement time-history. However, TMD systems' effectiveness for seismic events in this case appears to be low. The same effectiveness level results in zone two, in which high optimal tuning values are observed for both TMD acting in *x* and *y* directions. The mass damper appears instead to be most effective for the Sylmar and Erzinkan recorded seismic input, zone 3, whereas tuning values close to 85% of the linear optimal ones for both translations in *x* and *y* directions allows us to obtain the maximum reduction in terms of RMS for the relative displacement time-history, whereas the frequency in the *y* direction, set to 70% value of the linear optimal, seems to control the peak response.

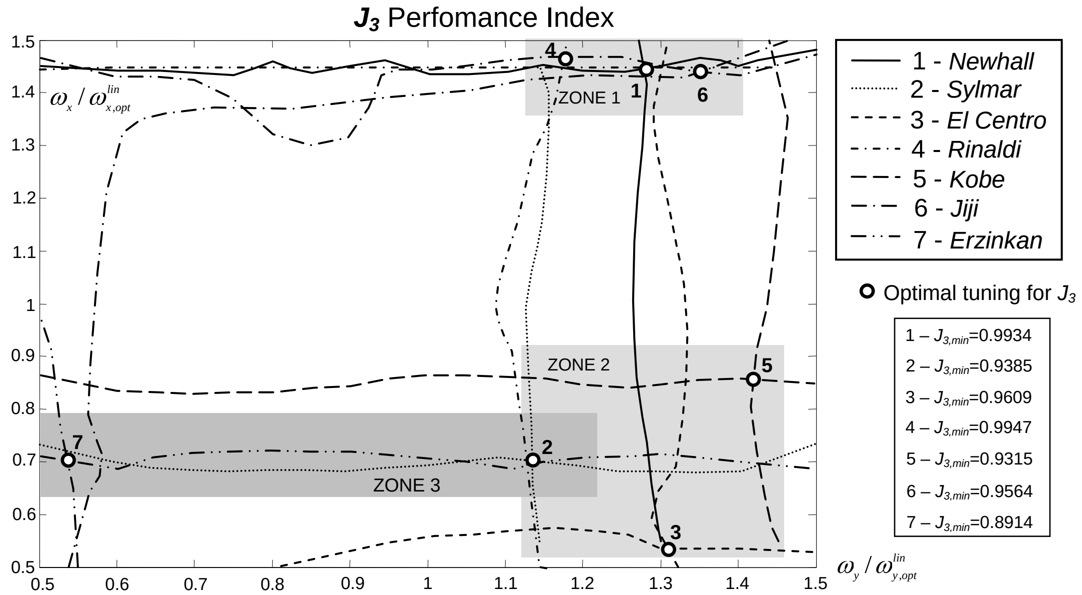

Figure 6: Superposition of optimal tuning progress for different seismic events

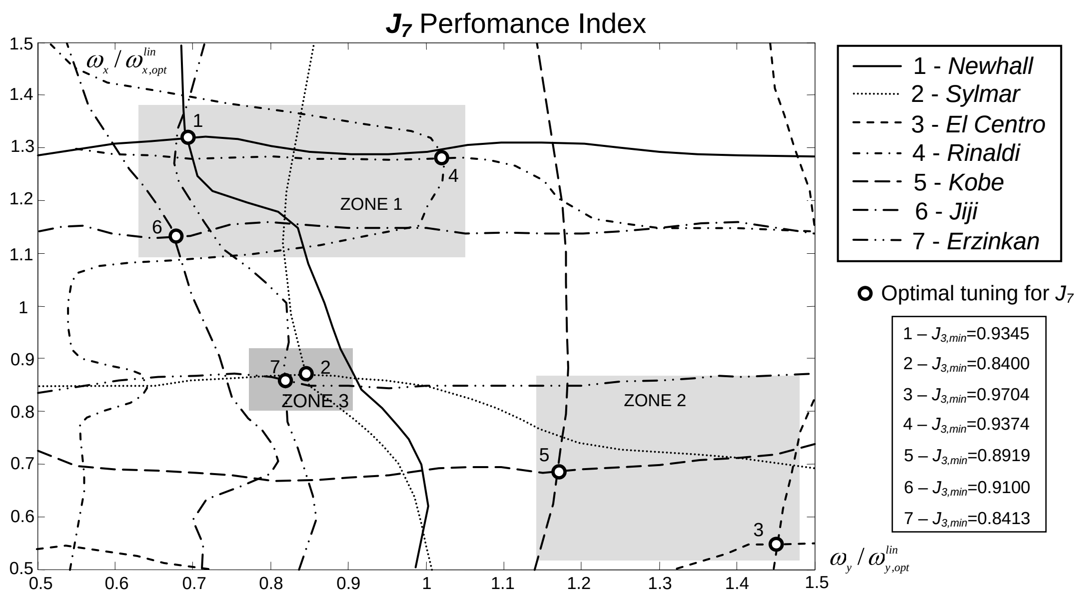

Figure 7: Superposition of optimal tuning progress for different seismic events

In order to physically understand the different efficiency of the control system, the seismic response for base-isolated benchmark structure without TMD system has been investigated. In particular, the Fourier transform of the base displacement time-history, both in x and y direction, has been evaluated for every considered seismic event. Results are plotted in figure 8, in which the magnitude of the Fourier transform versus the circular frequency ($\omega = 2\pi \cdot f$) is represented.

This figure clearly show the effect of non-linear behaviour of the isolation system: despite the system works as a SDOF system, different frequency peaks are generally observed in the isolators' drift time-history transform. These peaks depend on the input signal dynamic features and its effect on the system in terms of non-linear behaviour. In the analyzed case, where friction devices are considered, the overall stiffness of the isolation system mainly depends on the seismic displacement demand; such demand significantly varies during the event forcing the systems' dynamic response to present wide-ranging energy frequency content.

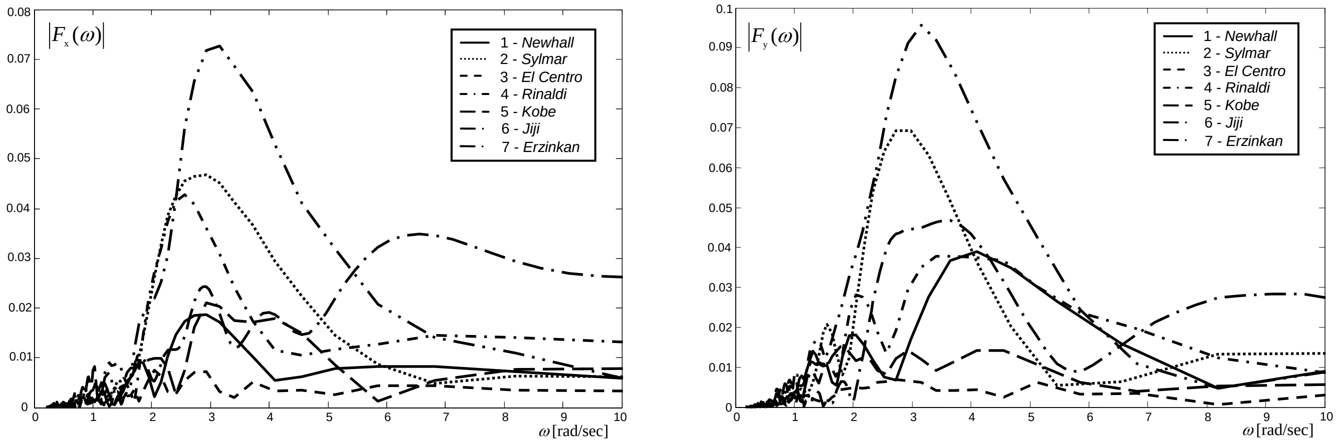

Figure 8: Base isolation drift - Non-linear seismic response Fourier transform

This effect can be observed for each of the considered seismic input, however some seismic response (El Centro, Newhall) presents a Fourier spectrum with energy distributed on a wide frequency range, whereas in other cases (Sylmar, Erzinkan) a single frequency response peak is still recognizable.

It's well known that a TMD system is able to reduce a single vibration frequency contribution to seismic response, it optimally works when dynamic response presents energy content concentrated on a well-defined single frequency. So, the frequency distribution of the energy content should be considered a suitable index to estimate the effectiveness of a TMD system.

With this in mind, in figure 9, a comparison between the transfer function of equivalent SDOF systems, which parameters are estimated to optimally fit the normalized Fourier transform progress for two different seismic events, and the same Fourier transform is carried out.

It's straightforward from this figure that an equivalent SDOF system represents a better model to describe the dynamic non-linear behaviour in the case of Erzinkan earthquake than for Newhall event, therefore a well-designed TMD is able to be more effective for Erzinkan and Sylmar (figure 8) recorded seismic inputs , which impose an output Fourier spectra having a well-defined single response peak.

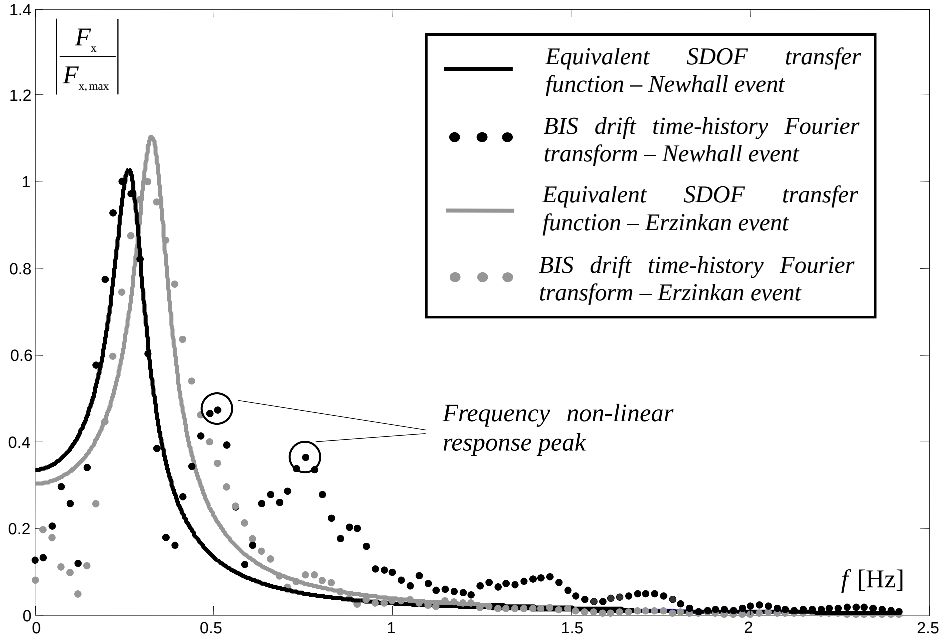

Figure 9: Equivalent SDOF to model the isolators' frequency non-linear response

5. CONCLUSION

In this paper, the seismic response of a base-isolated benchmark structure in which the non-linear response of isolation devices is explicitly considered has been considered. By using this model, this paper investigate the non-linear behaviour of this structure when a mass damping system is applied on the isolation layer, in order to study the effectiveness of this strategy in reducing the seismic response of the isolation layer. Results show that the seismic performance in reducing the seismic displacement demand is lower than in the case of linear behaviour: a 10% maximum reduction for the peak isolator displacement and a 15% maximum reduction for the RMS base displacement has been observed. Moreover, the efficiency of BI&TMD system noticeably varies depending on the dynamic characteristics of the input seismic event, in particular it's showed as well-designed TMD works properly in reducing peak and RMS displacement of base isolators when non-linear seismic response presents energy content laying on a narrow frequency band.
These results have to be considered as a first step in a more comprehensive framework in which detailed analysis are going to carried out to explore the possibility to adopt Mass Damping to improve the seismic non-linear response of structures.

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