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Numerical Study of Nonlinear Energy Sinks for Seismic Response Reduction

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ABSTRACT

This paper investigates the use of passive nonlinear energy sinks (NESs) for the response reduction of building structures under seismic loading. First, the building structure used in the numerical simulations for this investigationand the design input loading are described. Then, an optimization study is performed and the ideal parameters of the NES are determined. For this optimization study, physical measures that relate to the damage of the structure are used. With the optimized nonlinear energy sink, the sensitivity to the amplitude of the loading and the natural frequency of the building structure is investigated and compared with the sensitivity of the traditional tuned mass damper (TMD).The results of this study demonstrate that, for this loading, the TMD had superior performance when the natural frequency of the building structure was unchanged; however, when the natural frequency was changed, and thus the TMD detuned, the NES showed superior performance in controlling the response of the structure.

INTRODUCTION

Tuned mass dampers (TMDs) have long been explored as a means of reducing the dynamic response of civil structures. These devices have been implemented in structures worldwide, and are primarily used in tall buildings and towers to mitigate the response due to wind loading of the building's first mode [1]. In their simplest form, a TMD consist of a relatively small mass, generally less than 10% of the total mass of the structure [2], that is coupled to a building with linear spring and damping elements.

When the spring element is adjusted such that the natural period of the TMD is tuned close to a natural period of the building structure, the response of that mode of the building is reduced (see Figure 1a for an exampletransfer function representation of this phenomenon for a single degree-of-freedom (SDOF) structure). This reduction occurs due to the energy of this mode being directed to the TMD.

One of the shortcomings of these devices is that they must be tuned to a structural natural frequency; thus, their effectiveness is sensitive to errors in the initial estimate of the natural frequency and to changes in the natural frequency, known as detuning. An example of thisphenomenon is illustrated in Figure 1b, which shows the transfer function for a SDOF structure where the structure's natural frequency has decreased since the initial tuning of the TMD. Becausechanges in the natural frequency of a structure are expected due to common processes such as settlement, creep, and temperature effects, detuning is a concern in any structure employing a TMD. Moreover, the sensitivity of TMDs to detuning is one the factors that has prevented their widespread use formitigating the effects of seismic events; significant changes in natural frequency are expected during a major event due to the designed inelastic deformations of the structure. Several methods have beenexamined to help reduce the sensitivity of TMDs to detuning. Most of these include using two or more TMDs together to increase the effective bandwidth[3][4] or using an active tuned mass system[5]; however, little progress has been made to counteract the effects of detuning in simple systems employing only one completely passive TMD.

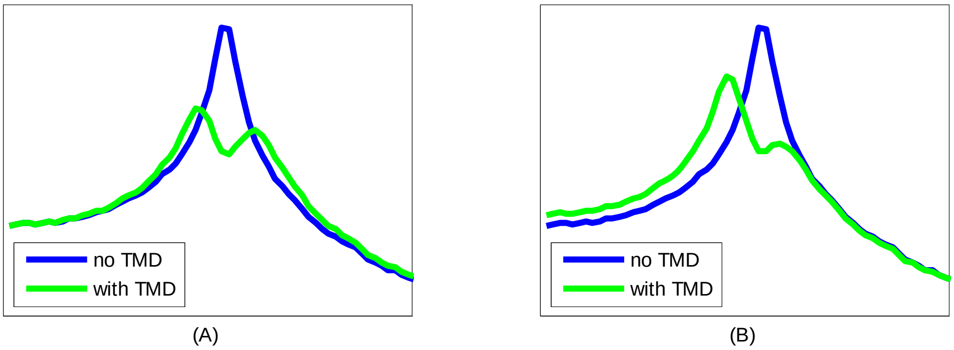


Figure 1: Example frequency response (a) Tuned TMD (b) Detuned TMD

In recent years, the response reduction of structures employing nonlinear energy sinks (NESs) has been explored, particularly for impulsive loading[6]. These devices are similar to TMDs in that they consist of relatively small masses coupled to a building structure with spring and damping elements; however, in the case of the NES, the spring element is essentially nonlinear, meaning that there is no linear stiffness component, rendering the system nonlinearizable. Without the linear stiffness component the NES has no preferred natural frequency and can resonate with any mode of the primary structure, during which time energy flows freely to the NES where it is dissipated. Unlike TMDs, the nonlinear nature of NESs makes them load dependent; thus, their performance is sensitive to the level of input.Additionally, with these devices the linear modes of the building structure become coupled, and energy is transferred from the lower modes of the structure to higher modes where it is dissipated more efficiently.

This paper explores the potential of NESs to mitigate the response of building structures to seismic excitation using numerical studies of a 2 DOF structure. Optimal parameters for the NES are determined with the structure subjected to a scaled band-limited white noise(BLWN) ground motion. These optimized results are then used for natural frequency and input level sensitivity simulations.Comparisons are made with the identical structure employing a TMD.

MODEL BUILDING STRUCTURE AND DAMPERS

In this paper, a two-degree-of-freedom linear model of a shear building is used as the example structure (Figure 2). This model is based onone built fora physical experiment conducted in the Smart Structures Technology Laboratoryat the University of Illinois at Urbana-Champaign, and is designed to have natural frequencies similar to those of a typical midrise steel structure [7]. The mass and stiffness matrices for this model in relative coordinates are shown given by

$$\mathbf{M}=\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix}=\begin{bmatrix} 24.3 & 0 \\ 0 & 24.2 \end{bmatrix}\text{ kg} \qquad \mathbf{K}=\begin{bmatrix} k_1+k_2 & -k_2 \\ -k_2 & k_2 \end{bmatrix}=\begin{bmatrix} 15040 & -8220 \\ -8220 & 8220 \end{bmatrix}\text{ N/m} \tag{1}$$

resulting in first and second natural frequencies of 1.63 and 4.56 Hz,, respectively. The damping in the model is set at 2% in each mode, which is again similar to that of a typical midrise steel structure [8].

Figure 2 also shows representations of the model structure implemented with the TMD and NES. For both the TMD and the NES,the mass ratio, μ, has been set to 5% of the total mass of the building structure, $m_{tot}=m_1+m_2$. For the TMD, the optimal values of k_{TMD} and c_{TMD} to reducethe displacement response of a structure undergoing random base acceleration was studied using numerical analysisin [9], and a set of empirical equations for the optimized parameters were developed. These optimized parameters and the equations used to calculate them are given by

$$\begin{gathered}\alpha_{opt}=\frac{(1-\mu/2)^{1/2}}{1+\mu}=0.94 \\ \zeta_{opt}=\sqrt{\frac{\mu(1-\mu/4)}{4(1+\mu)(1-\mu/2)}}=0.110 \\ \omega_{TMD}=\alpha_{opt}\omega_1=0.94(1.63)2\pi=9.63\,{}^{rad}\!/_{\sec} \\ k_{TMD}=\omega_{TMD}^2\mu m_{tot}=(9.63)^2(0.05)(24.3+24.2)=224.89\,{}^{N}\!/_{m} \\ c_{TMD}=2\zeta_{opt}\sqrt{\mu m_{tot}k_{TMD}}=5.14\,{}^{Ns}\!/_{m}\end{gathered} \tag{2}$$

where ω_{TMD} is the natural frequency of the TMD, ω_1 is the first natural frequency of the structure, ζ_{opt} is the optimal damping ratio of the TMD, α_{opt} is the optimal ratio of the natural frequency of ω_{TMD} to ω_1, k_{TMD} is the optimal linear stiffness coefficient of the TMD, and c_{TMD} is the optimal linear damping coefficient of the TMD.

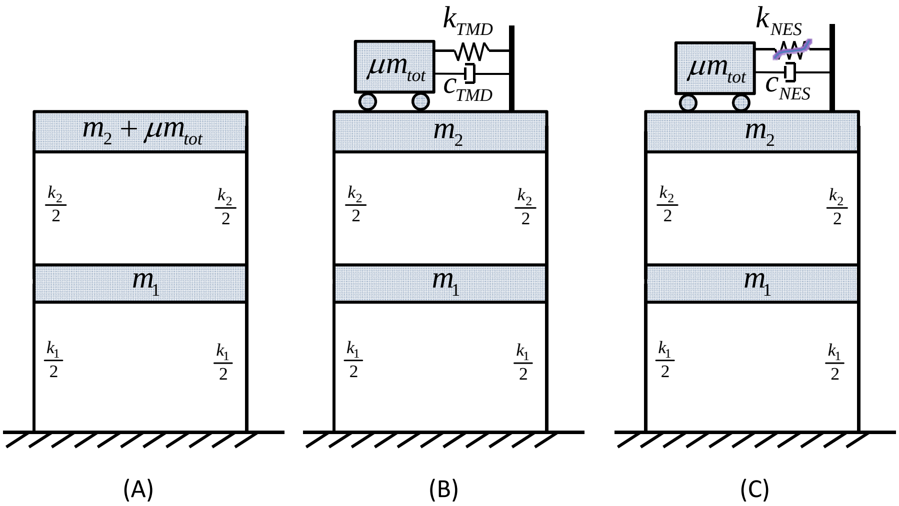


Figure 2: Structure model (a) building Structure, (b) structure with TMD, and (c) structure with NES

Similar to the TMD in this study, the NES is connected to the top floor of the building structure with nonlinear stiffness and linear damping elements; the stiffness element has a purely cubic nonlinearity

$$F_{NES-spring} = k_{NES} x^3 \tag{3}$$

This type of nonlinearity can be implemented in many ways; however, one of the most common has been to use elastic elements and geometric nonlinearities to do so [10]. Given the complex nature and amplitude sensitivity of structures with elements containing essential nonlinearities, no simple equations exist to calculate the optimized parameters for the NES. In asubsequent section, a study is performed to determine optimized values of k_{NES} and c_{NES} for the particular loading used in this study.

DESIGN GROUND MOTION

The ground acceleration record that was used as the design input for this study is shown in Figure 3. This record is a band-limited white noise that has been passed through an eight-pole elliptical filter with a cutoff frequency at 40 Hz. Additionally, this record was scaled such that the maximum displacement response of the building structure when subjected to this loading was 0.02 m (see Figure 4).

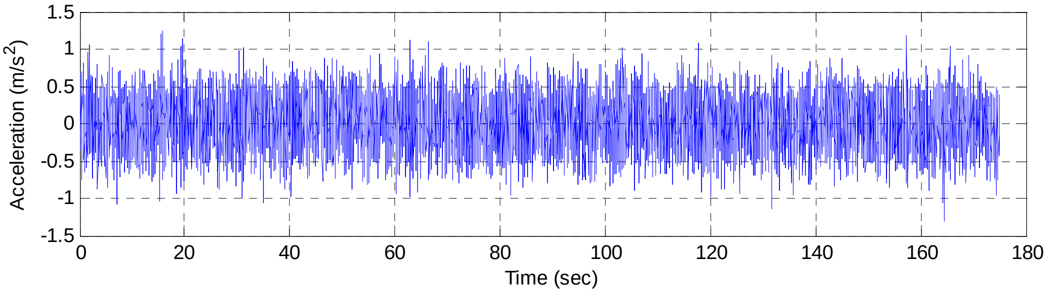


Figure 3: Design Input Ground Acceleration Record

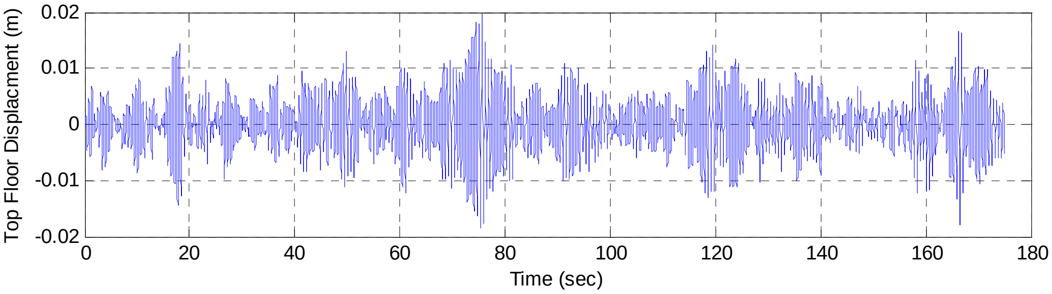


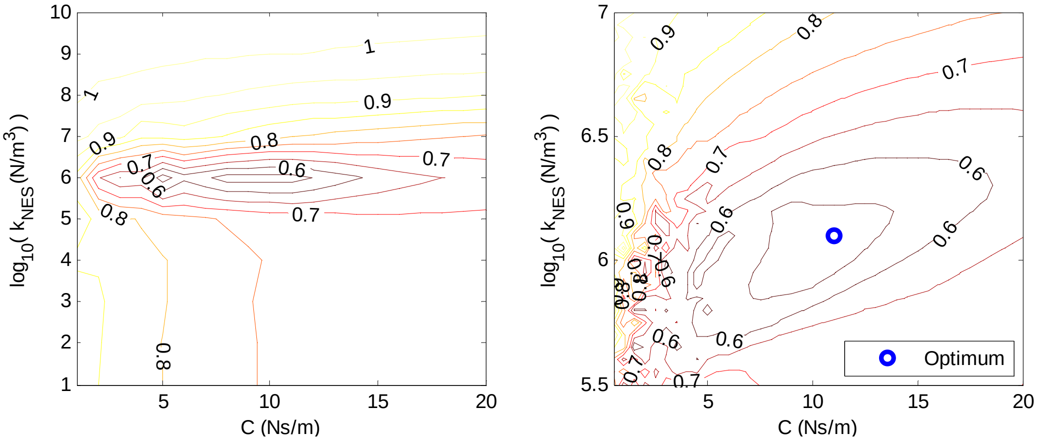
Figure 4: Response of model building with locked TMD/NES to the design input ground motion.

RESPONSE MEASURES

To evaluate the performance of the NES and TMD, a set of measures that assesses the performance of the structure in the time domainwaschosen. Because the NES and TMD are both intended to protect the primary structure by reducing its response, these measures consider only the response of thebuilding structure, not the response of the NES or TMD. The first measure of interest is the maximum displacement of the building structure. This measure was chosen because the amount of damage a structure sustains in a seismic event has been found to correlate well with the maximum displacement of the building[11]. The second response measure used in this analysis is the RMS displacement of the top floor of the building. Like the first measure, this was chosen because of the relationship between damage in the building and the displacement that the building undergoes; however, because this measure accounts for the complete time history response of the building, it is a more general measure of the displacement demand on the structure.

NES OPTIMIZATION

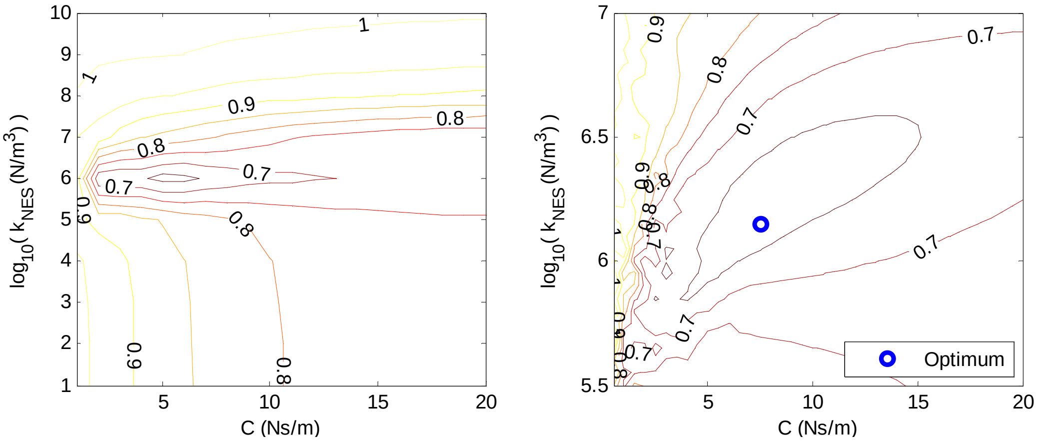
To determine the optimized NES parameters when the model structure with the attached NES is subjected to thedesign ground motion, a parametric study is performed varying the values of k_{NES} and c_{NES}. The numerical simulations for this study are run for 175 seconds to obtain stationary response;however, to avoid the effects of transients in the signal due to the initial conditions, theresponse measures are calculated using only the last 150 seconds of the signal.The range of k_{NES} considered in this study is 10 to 10^{10} N/m^3 and the range of c_{NES} considered is 1 to 20 Ns/m. The response measures are then used in conjunction with those of the structure without the attachment to create a ratio comparing the response measure with and without the NES. The ratio of the maximum displacement with and without the NES is shown in Figure 5. The optimal set of parameters for the NES, in terms of reducing the maximum displacement of the top floor of the structure to this particular loading, are $k_{NES} = 10^{6.1}$ N/m^3 and $c_{NES} = 11$ Ns/m, and the resulting reduction in response is 48.5%. Figure 5 also shows that the effectiveness of the NES in reducing the top displacement of the structure is sensitive to changes in the nonlinear stiffness coefficient but is relatively insensitive to the value of the damping coefficient near the optimal value.



(a) (b)

Figure 5: Contour plot showing the ratio with and without the NES for reducing the maximum top displacement of the structure versus k_{NES} and c_{NES} (a) full view (b) refined view of area near optimum.

Figure 6 shows a similar plot with respect to the RMS displacement of the top floor of the structure. From this plot we see that the optimal values of the NES parameters are $k_{NES} = 10^{6.15}\ N/m^3$ and $c_{NES} = 7.5\ Ns/m$, resulting in a response reduction of 38.3%.Although not identical, this point is quite near the optimumwith respect to the maximum displacement of the top floor of the structure. This figure also demonstrates that the sensitivity with respect to changes in the NES parameters is similar to that foundin the previous case.



(a) (b)

Figure 6: Contour plot showing the ratio with and without the NES for reducing the top RMS displacement of the structure versus k_{NES} and c_{NES} (a) full view (b) refined view of area near optimum

Due to the strong nonlinearity of the NES, the optimum NES parameters are dependent on the amplitude of the loading as well as natural frequency changes in the building. In Figure 7 contour plots show the response ratio for the top floor displacement of the structure with NES when the load is reduced by 50%, when the 1st natural frequency of the structure is decreased by 15%, and when both the load is reduced by 50% and the 1st natural frequency is reduced by 15%. The contour plots have a similar shape in all cases presented. Here, decreasing the amplitude of the load results in an increase in the optimal nonlinear stiffness. The primary reason for this increase is due to the fact that with lower displacements, a higher stiffness is needed to engage the moving mass. Additionally, as shown in the figure,for the cases presented decreasing the natural frequency of the building had the effect of decreasing the performanceand generally shifting the most effective region further to the right, into areas of higher damping.

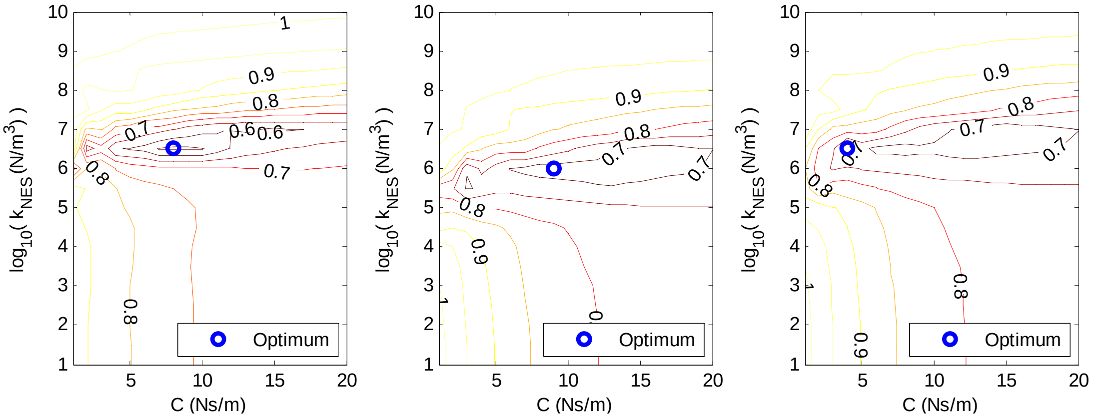


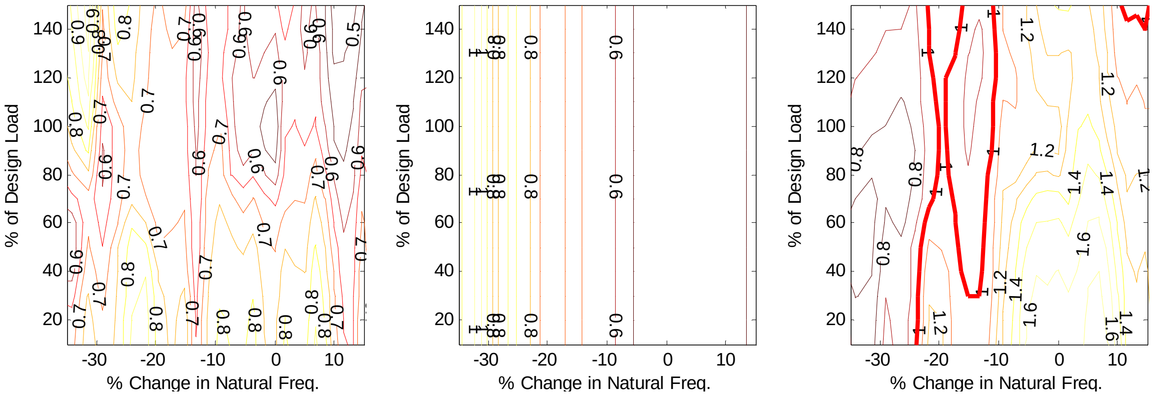
Figure 7: Contour plot showing the ratiowith and without the NES for reducing the maximum top floordisplacement of the structure versus k_{NES} and c_{NES} (a) load reduced by 50% (b) 1st natural frequency of buildingreduced by 15% (c) load reduced by 50% and 1st natural frequency of building Rreduced by 15%

DETUNED RESPONSE

The sensitivity of the response of the structure with the TMD and with the NES to changes in the load amplitude and the natural frequency of the building structure was also investigated. Numerical simulations of the model structure subjected to the design ground motion were performed for three configurations: (i) with the NES, (ii) with the TMD, and (iii) with no attachment. The amplitude of the load and the story stiffness were varied in the building structure. The range of amplitudes that were investigated was 10% to 120% of the design ground motion and the range of change to the 1st natural frequency was -35% to +15%. For this analysis, the NES parameters optimized to reduce the maximum top floor displacement of the structure and the optimized TMD parameters proposed by Warburton [9] were utilized.

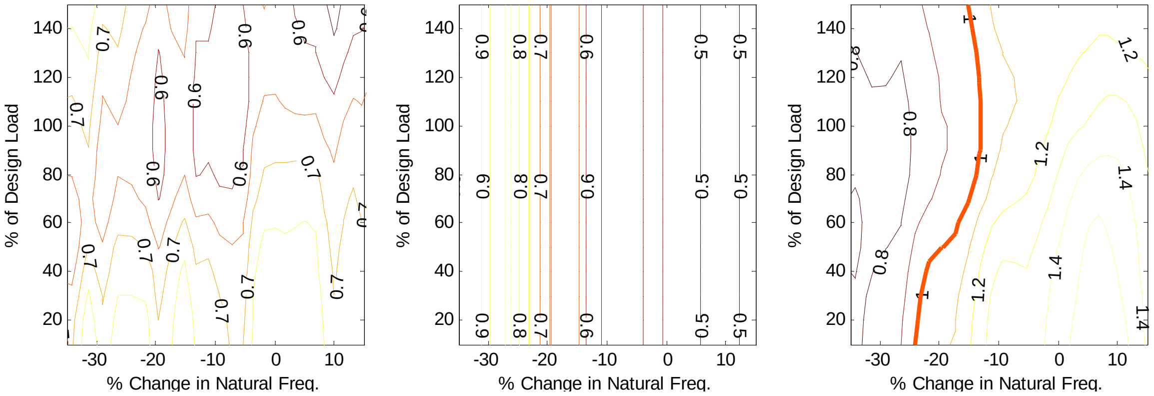
Contour plotsshowing the ratio of the maximum top floor displacement of the system with NES and the system with TMD to the system with no attachmentacross the range of values simulated is shown in Figure 8. Here, the effectiveness of the NES varies with changes in the amplitude of loading, and with changes due to the natural frequency of the building structure, while the effectiveness of the TMD only changes with changes due to the natural frequency of the building structure. This figurealso shows that when the change in natural frequency is low, the TMD generally outperforms the NES; however, as the change in natural frequency increases, the NES outperforms the TMD.Additionally, Figure 8 shows that unlike the TMD, which is completely ineffective at reducing the top floor maximum displacement at high changes to the natural frequency, the NES reduces the response of the building across the entire range of frequencies examined. This behavior is also seen in (a) (b) (c)

Figure 9, which shows a similar plot, except that the change in top floor RMS displacement is evaluated.



(a) (b) (c)

Figure 8: Contour plot ofthe maximum top floor displacement across range of amplitudes and natural frequenciesof (a) the system with NES compared to the system with no attachment, (b) the system with TMD compared to the system with no attachment, and (c) the system with NES compared to the system with TMD



(a) (b) (c)

Figure 9: Contour plot of the top floor displacement across range of amplitudes and natural frequencies of (a) the system with NES compared to the system with no attachment, (b) the system with TMD compared to the system with no attachment, and (c) the system with NES compared to the system

CONCLUSION

In this paper, the use of a passive nonlinear energy sink (NES) for the response reduction of a model building structure under seismic loading was explored,and a comparison was made to a traditional linear tuned mass damper (TMD). A parametric study was conducted to find optimal NES parameters to reduce specificdisplacement measures. Once the optimal parameters were established, the sensitivity of both the NES and TMD to changes in amplitude of the loading and natural frequency of the building was investigated. The traditional TMD was shown to have superior performance when the natural frequency of the building structure matched the TMD; however, when the natural frequency shifted, the TMD was detuned, and the NES was superior at controlling the response of the structure.

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