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PARAMETER OPTIMIZATION OF THE KDAMPER CONCEPT IN SEISMIC ISOLATION OF BRIDGES USING HARMONY SEARCH ALGORITHM

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Abstract. *In this paper a novel design methodology for seismic isolation of bridges is presented employing the KDamper passive system and the Harmony Search (HS) optimization algorithm. The implementation of the KDamper concept to the absorption of seismic excitation of bridge structures requires the solution of a linear dynamic problem during which the basic parameters of KDamper design must be predefined. As this selection appears to be a quite complex procedure, the need for an optimization process is of paramount importance. In our work, an emerging metaheuristic algorithm, the Harmony Search algorithm, which has been successfully applied to several engineering problems, is employed to obtain optimum design parameters for a typical bridge structure under seismic excitation. The optimal solution is obtained for a set of 5 earthquake excitation records using as objective function the Root Mean Square of the displacement ratio. Comparative results of the dynamic response between the initial and the isolated structure are presented to verify the effectiveness, validity and reliability of the proposed design method.*

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1 INTRODUCTION

During the last decades, seismic isolation of bridges has gained more and more territory in the domain of antiseismic design of structures. Its basic principle, the reduction of the seismic forces that are imposed to a bridge due to an earthquake, appears to be in contrast with older antiseismic techniques promoting the increase of a structure's bearing capacity to sustain dynamic loads. Consequently, seismic isolation methods lead to more economic structures that simultaneously demonstrate better dynamic response to seismic excitations. In practice, seismic isolation of bridges is achieved through the implementation of special devices and configurations that decouple the deck from the substructure. Thus, the total structure's stiffness is reduced whereas its eigenperiod is increased, resulting in the transition of the descending branch at the design spectrum of accelerations. In this category of devices, elastomeric bearings, lead-rubber bearings, roller bearings and other similar layouts enlist. Latest research on this topic follows two separate directions: a) the introduction of an additional mass into the structure, providing an extra inertia force (Tuned Mass Dampers - TMD), and b) the implementation of negative stiffness elements ("Quazi Zero Stiffness" Oscillators – QZS).

First applied by Frahm [1], TMDs have been frequently used to absorb vibrations of skyscrapers under earthquake and wind loading [2-4], following the optimal design theory proposed by Den Hartog [5]. Taipei 101 Tower (101 stories, 504 m) in Taiwan [6], one of the tallest building worldwide, is a characteristic example of TMD implementation. The use of TMDs has been recently included in studies concerning vibration absorption in seismic or other forms of excitation of bridge structures [7]. In order to transfer a large amount of the structural vibrating energy to the TMD, its natural frequency is tuned in resonance with the fundamental frequency of the primary structure. This energy is then dissipated by damping. Besides their effectiveness, TMDs present two main disadvantages: a) they are susceptible even to slight changes of environmental or other external parameters that can disturb the tuning and thus, they reduce the device's performance [8], and b) they require a large oscillating mass, to achieve the desired vibration reduction, rendering their construction and placement procedure rather difficult.

On the other hand, negative stiffness elements gain their place in modern seismic isolation techniques, proving themselves as a promising alternative to conventional ones. True negative stiffness is defined as a force that assists motion instead of opposing it as in the case of a positive stiffness spring. First introduced in the pioneer publication of Molyneaux [9], as well as in the milestone developments of Platus [10]. The central concept of these approaches is to significantly reduce the stiffness of the isolator and consequently to reduce the natural frequency of the system even at almost zero levels, as in Carella et al. [11], regularly called "Quazi Zero Stiffness" (QZS) oscillators. After the initial comprehensive review by Ibrahim [12], many researchers have demonstrated the effectiveness of such devices, (see e.g. [13]), by introducing a new structural modification approach for the seismic protection of structures with an adaptive passive negative stiffness device, showing that the implementation of such device in structures would result in decreased dynamic forces on them. The negative stiffness behaviour is primarily achieved by special mechanical designs involving conventional positive stiffness pre-stressed elastic mechanical elements, such as post-buckled beams, plates, shells and pre-compressed springs, arranged in appropriate geometrical configurations. Some interesting designs are described in [14-15], whereas in [16-22] numerous applications of QZS in seismic isolation can be found. However, QZS oscillators suffer from their fundamental requirement for a drastic reduction of the total structural stiffness to almost negligible levels, which limits the static load capacity of such structures.

Combining the beneficial characteristics of both aforementioned typed of seismic isolation device, a novel passive vibration isolation and damping configuration is introduced, based on the KDamper concept introduced by Antoniadis et al. [23]. The proposed device incorporates a negative stiffness element, which can exhibit extraordinary damping properties, without the drawbacks of TMDs or QZS oscillators. The KDamper is designed to present the same overall (static) stiffness as a traditional reference original oscillator. However, it differs from both the original SDoF oscillator, as well as from the known negative stiffness oscillators, due to the appropriate redistribution of the individual stiffness elements and the reallocation of the damping. Even though negative stiffness elements usually demonstrate an unstable behavior, the proposed device is designed to be statically and dynamically stable. The presence of an additional mass also serves in mitigating the effects of a vibrating load, operating as an energy dissipation mechanism similarly to the additional mass of the TMDs. However, the KDamper overcomes the sensitivity problems of TMDs as the tuning is mainly controlled by the negative stiffness element's parameters. Once such a system is designed according to the approach proposed in [23], it is shown to exhibit an extraordinary damping behaviour. A first approach to the implementation of the KDamper concept for the seismic isolation of a typical bridge can be found in [24].

In this paper, an effort to find the optimum design parameters of such a device, taking into account general aspects of contemporary seismic isolation techniques, will be presented. For the optimization process, harmony search algorithm (HS), a novel metaheuristic algorithm, is adopted. First proposed by Geem et al. [25] in 2001, HS can handle problems with both discrete and continuous variables [26,27] and is characterized by the distinguishing features of algorithm simplicity and search efficiency. Not being a hill-climbing algorithm, the probability of becoming entrapped to a local optimum is significantly reduced. Moreover, it uses a stochastic random search instead of a gradient search, as other metaheuristic algorithms do, gaining in simplicity. Stochastic derivatives are useful for a number of scientific and engineering problems where mathematical derivatives cannot be calculated or easily treated [28] and also serve to the reduction of the required number of iterations. The aforementioned advantages render HS suitable for various optimization problems including the traveling salesman problem [25], optimization of data classification systems [29], pipe network design [30] and generalized orienteering problem [31]. As far as structural problems are concerned, HS has been successfully applied to the optimum design of truss structures [32], steel sway frames [33] and grillage systems [34]. Recently, HS has been employed for the optimum design of the implementation of TMDs to multistory buildings [35, 36].

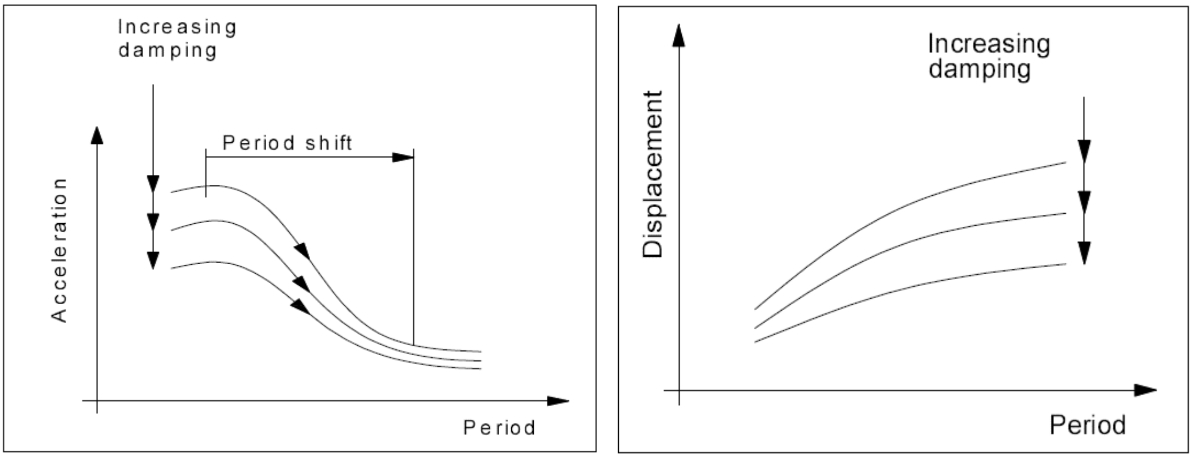
In the test case considered, the optimum design and implementation of the KDamper concept in a typical single-pier concrete bridge is examined. The device's parameters are optimized under five, commonly used in relevant literature, seismic excitation records with different frequential content, using the Root Mean Square (RMS) of deck's displacement weighted ratio (displacement of the deck of the isolated over displacement of the deck of the initial structure) as an objective function. Finally, comparative results of the dynamic response between the initial and the isolated structure are presented to verify the validity and reliability of the proposed design method.

2 SEISMIC ISOLATION AND KDAMPER ANALYSIS MODEL

In this section, the motive to design the optimal parameters of a KDamper device with respect to general aspects and regulations of current seismic isolation methods and techniques, is described.

2.1 Basic Seismic Isolation Principles

The basic principle in seismic isolation of bridges is the increase of the structure's eigenperiod, in view of the transition to the descending branch of the response spectrum of accelerations (Fig. 1a). However, excessively high values of the eigenperiod could result in an undesirable increase of the structure's displacements due to the different shape of the response spectrum in terms of displacements, as it can be derived from Fig. 1b. Even though the implication of dampers seems a rather effective choice, it is not always a feasible one, as relatively high values of damping are usually required. An optimum compromise of the acceleration and the displacement, within an acceptable range of the period creates an area that provides possible solutions avoiding the negative effects described previously. This area is called design window and its lower and upper bounds are shown in Fig. 2.



(a) (b)

Figure 1: Response spectra of (a) accelerations and (b) displacements.

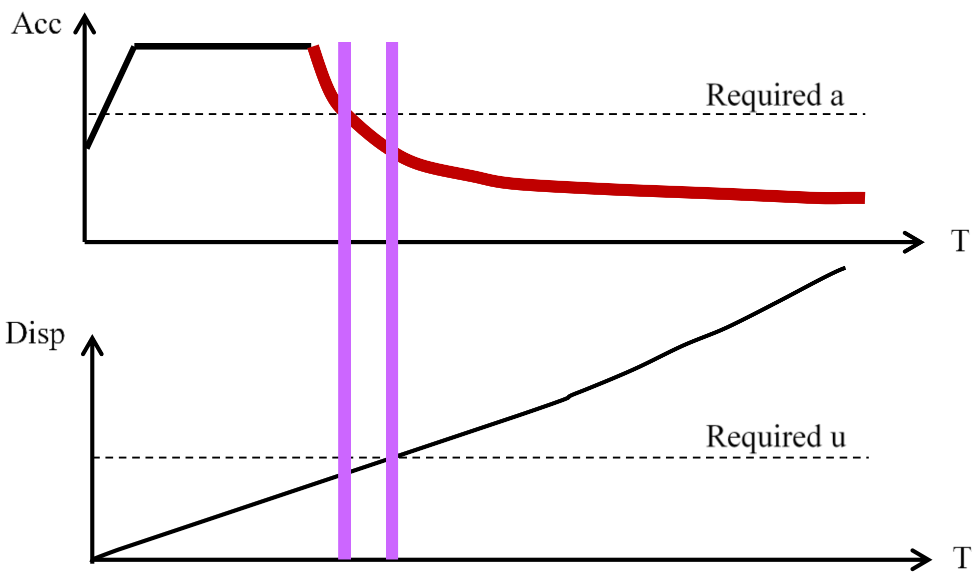


Figure 2: Conceptual illustration of the design window for isolation systems.

More specifically, the left boundary of the design window is imposed by the necessity to reduce accelerations and depends generally on the site (margin between the branch of constant accelerations and the descending one). It is roughly estimated to be equal to 2 seconds. Concerning the right-side boundary of the design window, this cannot be defined as easily as the left one, as it is relevant to the displacement performance requirements of each structure. The upper limit of the design window is thus depending on each structure's functionality, security and implementation demands. In light of the above, the need to introduce an optimization procedure for an efficient design of a seismic isolation system is inherently apparent.

2.2 The KDamper concept

As it was also mentioned in the introduction, the KDamper is a novel passive vibration absorption and damping concept, exploiting the advantageous characteristics of both TMDs and negative stiffness elements. Fig. 3 presents the basic layout of the proposed seismic isolation configuration, where k_N denotes the algebraic value of negative stiffness. The device is designed to minimize the response $x(t)$ of a SDoF system of mass m_s and static stiffness k_o to a base excitation $x_G(t)$. The SDoF system may be undamped or have a low initial damping ratio. As it can be observed from Fig. 3, an additional mass, m_D is added inside the device, creating a second hidden degree of freedom.

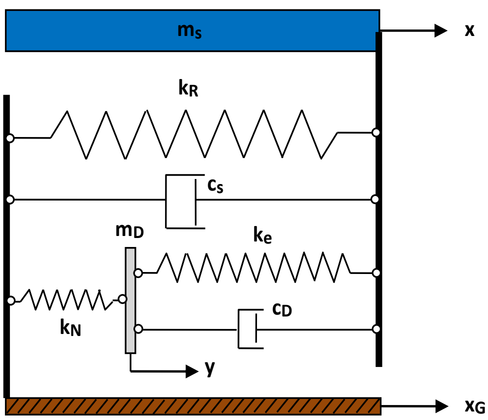


Figure 3: Schematic representation of the considered vibration absorption concept.

Further information on the equations of motion, the detailed design, the realization of the negative stiffness element and a possible implementation of a such a device into a bridge structure can be found in Sapountzakis et al. [24]. However, some useful remarks are also noted hereafter.

The device's performance depends on the parameters, μ, κ, and ζ_D designated by the following equations [24]

$$\mu = \frac{m_D}{m_s} \tag{1}$$

$$\kappa = -\frac{k_N}{k_e + k_N} \tag{2}$$

$$\zeta_D = \frac{c_D}{2\sqrt{(k_e + k_N)\, m_D}} \tag{3}$$

where ζ_D represents the equivalent damping ratio of the additional artificial damper with constant c_D.

Based on these parameters, all the other constants of the KDamper elements are defined. Limitations are imposed in order the device to be economical and easy to place, regarding each structure's specific requirements and demands. Caution concerning the maximum allowable displacement of both DoFs (internal and external) has to be also taken into account. Analytical description of the relevant restrictions will be given later in this paper.

Due to the nature of these parameters and their effect on the device performance along with the imposed limitations, proposing an accurate optimization procedure is of paramount importance to facilitate the implementation of the KDamper concept.

2.3 Test case considered

(a)

(b)

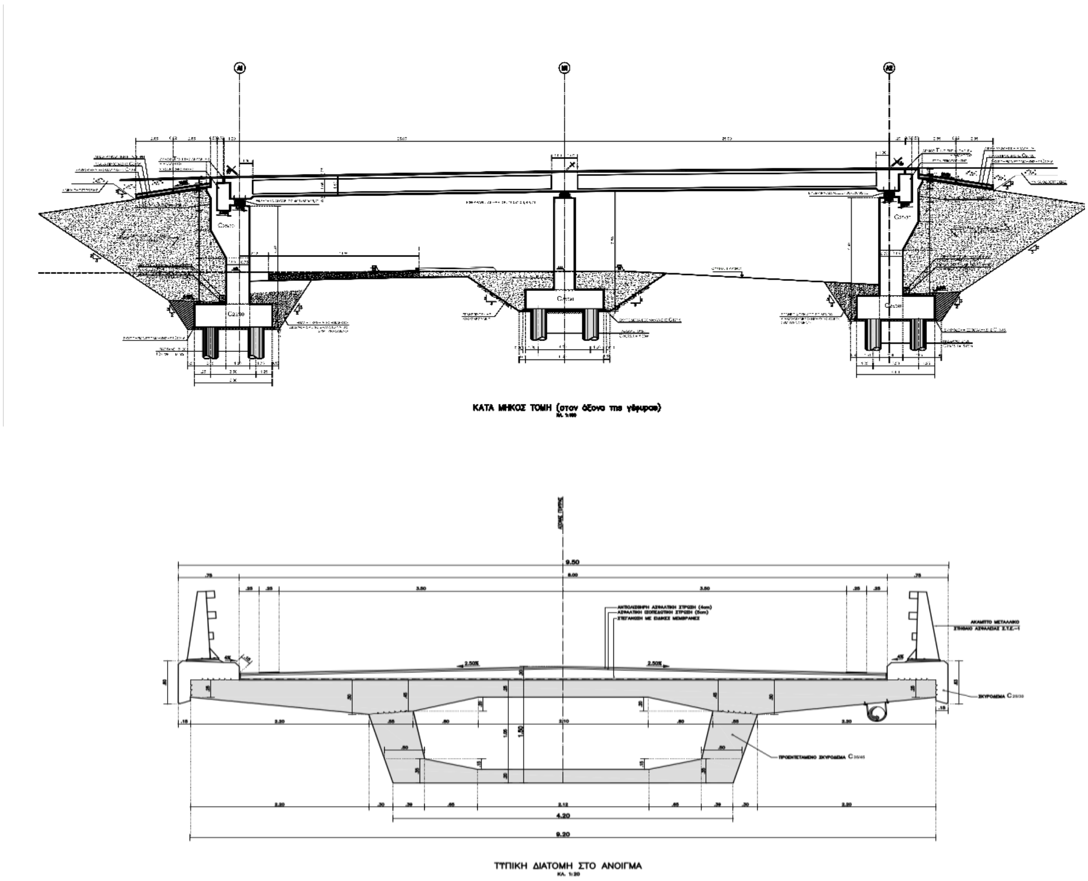


Figure 4: Schematic representation of the bridge considered. (a) Longitudinal section, (b) Transverse section.

A typical single-pier concrete bridge of mass $m_s = 729.3$ tn with two spans of 25m each and conventional bearings is considered. The deck is 9.50m wide. A schematic representation of the bridge is given in Fig. 4. The damping factor of the system is equal to $c_s = 314.3443$ kNs/m, corresponding to reinforced concrete's damping ratio, $\zeta_s = 5\%$. Five conventional ALGABLOC NB 400x500/99/71 bearings are used, two above of each abutment and one above the pier, with a horizontal stiffness of $k_b = 2730$ kN/m for each one of them. The total structural stiffness is $k_o = 5x2730 = 13650$ kN/m, and the natural period of the structure is calculated as follows

$$T_s = 2\pi \sqrt{m_s / k_o} = 1.45 \sec \tag{4}$$

As an initial approach, the pier is considered to be stiff enough to be neglected and the total structural stiffness is equal to the horizontal stiffness of the bearings.

The bridge is subjected to five different seismic excitation records, commonly used in anti-seismic design literature (El Centro, Tabas, Leukada, Northridge, Kobe).

3 HARMONY SEARCH ALGORITHM AND OPTIMIZATION PROCESS

In this section, the HS metaheuristic algorithm is briefly described, and a detailed example of the proposed optimization procedure is also presented.

3.1 HS algorithm

Although, a detailed description of the HS algorithm can be found in [30] and [35-37], the four basic steps of the algorithm are the following:

Step 1: Initialization of the HS Memory matrix (HM). HM matrix contains vectors representing possible solutions to the examined optimization problem. The initial HM matrix is created using randomly generated solutions. For an n-dimension problem, HM has the form

$$HM = \begin{bmatrix} x_1^1, x_2^1, \ldots, x_n^1 \\ x_1^2, x_2^2, \ldots, x_n^2 \\ . \\ . \\ . \\ x_1^{HMS}, x_2^{HMS}, \ldots, x_n^{HMS} \end{bmatrix} \tag{5}$$

where $\left[x_1^1, x_2^1, \ldots, x_n^1\right] \left(i = 1, 2, \ldots, HMS\right)$ is a solution candidate. HMS is typically set to values between 50 and 100. The value of the objective function is calculated for every solution vector of the HM matrix.

Step 2: Improvisation of a $\left[x_1', x_2', \ldots, x_n'\right]$ new solution from the HM. Each one of the components of this new solution, x_j', is obtained based on the Harmony Memory Considering Rate (HMCR), which is defined as the probability of selecting a component from the HM members. 1 – HMCR is, therefore, the probability of generating a new component randomly. If x_j' is chosen from the HM matrix, it is further mutated according to the Pitching Adjusting Rate (PAR), that determines the probability of a candidate from the HM to be mutated.

Step 3: Update of the HM matrix. The value of the objective function of the new solution, obtained in Step 2, is calculated and compared to the ones that correspond to the original HM matrix vectors. If it results in a better fitness than that of the worst member in the HM, it will replace that one. In the typical case of a minimization optimization process, the new solution replaces a member of the HM matrix, only if that member has a bigger value of objective function than the new one. If there are more than one members in the HM with larger values of the objective function that the new solution, the one with the higher value is replaced. Otherwise, the new solution is eliminated and HM matrix remains intact.

Step 4: Repetition of Steps 2 and 3 until a preset termination criterion is met. A commonly used termination criterion is the maximum number of total iterations.

The flowchart of the proposed HS algorithm is presented in Fig. 5.

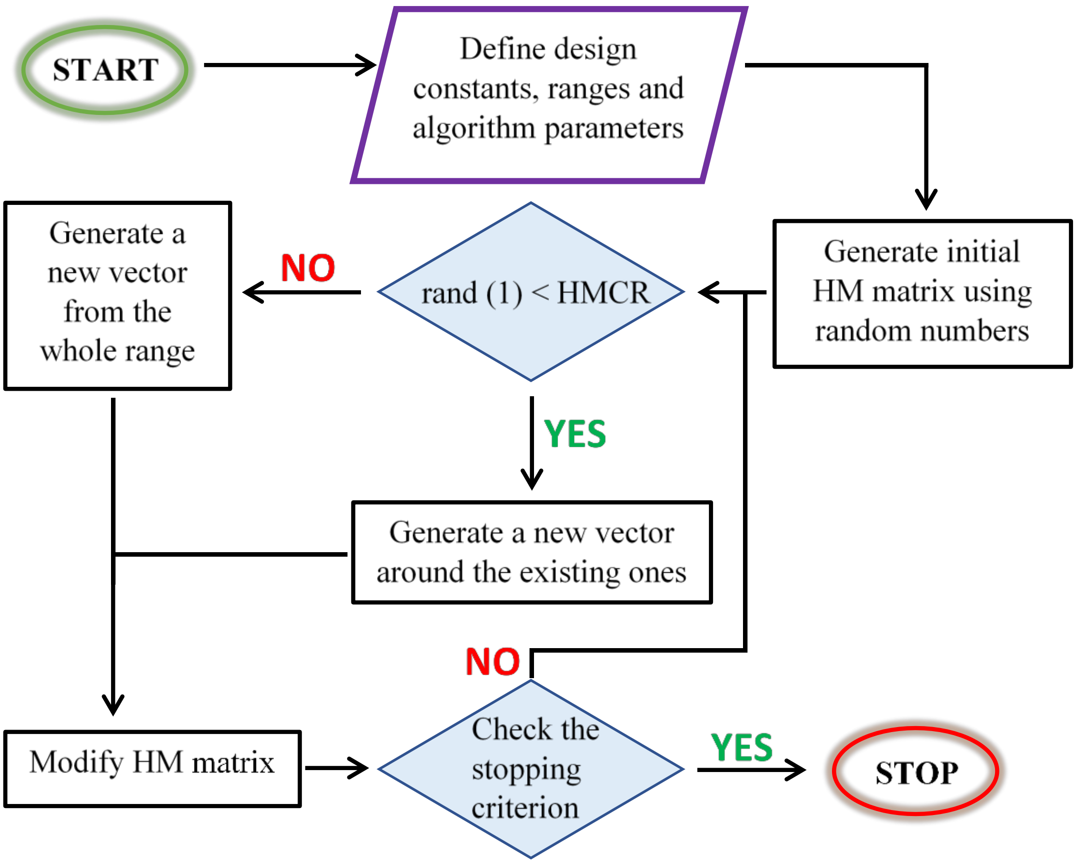


Figure 5: Flowchart of the proposed HS algorithm.

3.2 KDamper concept optimization process

As it is also stated previously in this paper, in order to optimally design and implement the KDamper concept into a bridge structure, Harmony Search algorithm is employed. Following the procedure and flowchart presented above, the features of the examined optimization problems can be derived.

Starting from the design variables, whose value shall be optimized, the three parameters that control the device's performance μ , κ , and ζ_D are selected.

Secondly, the limits of the design variables are determined. Their choice lies on safety, stability and manufacturing parameters that need to be taken into account. These parameters may differ from structure to structure, however, as far as bridges are concerned, the limits presented below provide satisfying results at most cases.

	μ	κ	ζ_D
min	0.01	2.234	0.01
max	0.05	2.831	0.70

Table 1: Variable design limits.

In Table 1 the lower and upper limits of the three design variables are indicated. Regarding the ratios μ and ζ_D, their values are upper limited due to manufacturing reasons, so as for the system to be economic and the device to be easy to construct and place. The limits of the third design variable, κ , are dictated by the basic stability requirement of the KDamper. The latter is introduced in the KDamper design methodology in order to avoid excessive values of the negative stiffness element that could disturb the static stability of the whole system. The desired stability is ensured by the implication of the static stability margin, ε . More information on ε and its relation with the other design parameters and especially with κ can be found in Sapountzakis et al. [24]. Primary numerical examples indicate that values of ε between 20% and 30% are acceptable. Consequently, $\kappa_{\max}$ and $\kappa_{\min}$ are calculated through a Goal Seek command with the condition that ε is equal to 20% and 30% respectively.

Concerning the parameters inherently involved in the HS algorithm, values commonly found in relative literature are adopted (Table 2). The same holds for the termination criterion, as the maximum number of iterations is pre-selected.

HMS	HMCR	PAR
75	0.5	0.1

Table 2: Values of the HS algorithm parameters.

Aimed to find the optimum solution for all 5 excitations to which the considered bridge is subjected, the Root Mean Square (RMS) of the displacement ratio (deck displacement of the isolated structure over the deck displacement of the initial structure) is selected as the objective function, that needs to be minimized.

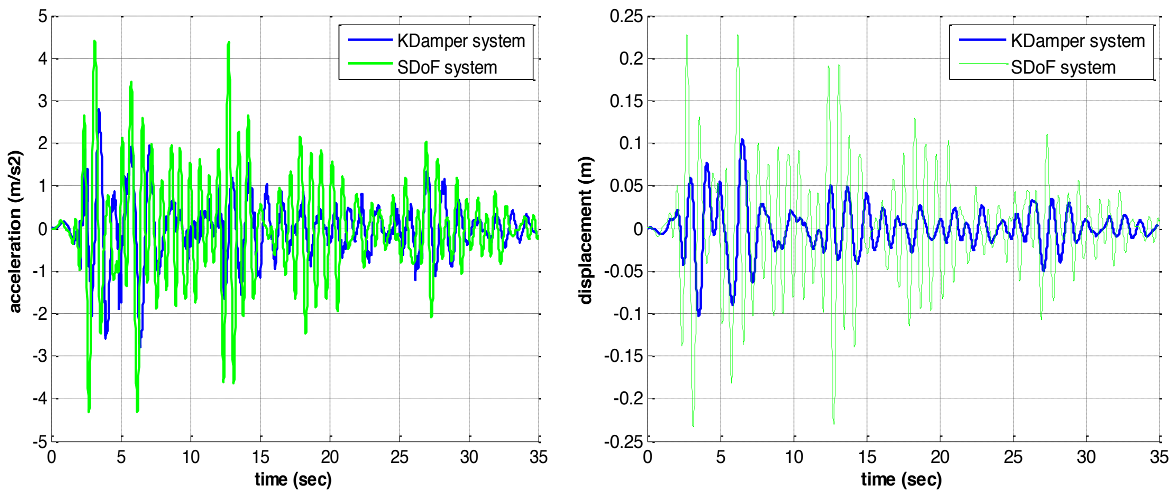
Finally, the constraints of the examined optimization problem are defined. In order for the design to be compatible with the mechanical configuration proposed in [24], the constant of the negative stiffness element should not exceed the value of 1872.1 kN and the displacement of the internal DOF should be lower than 70 cm. The last constraint prevents the maximum deck relative acceleration of the new structure to exceed the maximum deck relative acceleration of the initial one.

4 NUMERICAL RESULTS

In Table 3, the optimum values of the design variables, obtained through the HD optimization procedures are presented. Comparative results between the initial and the isolated structure for each earthquake excitation are presented in Figures 6-10, in terms of deck absolute accelerations and relative displacements. Their maximum values are also depicted in Table 4.

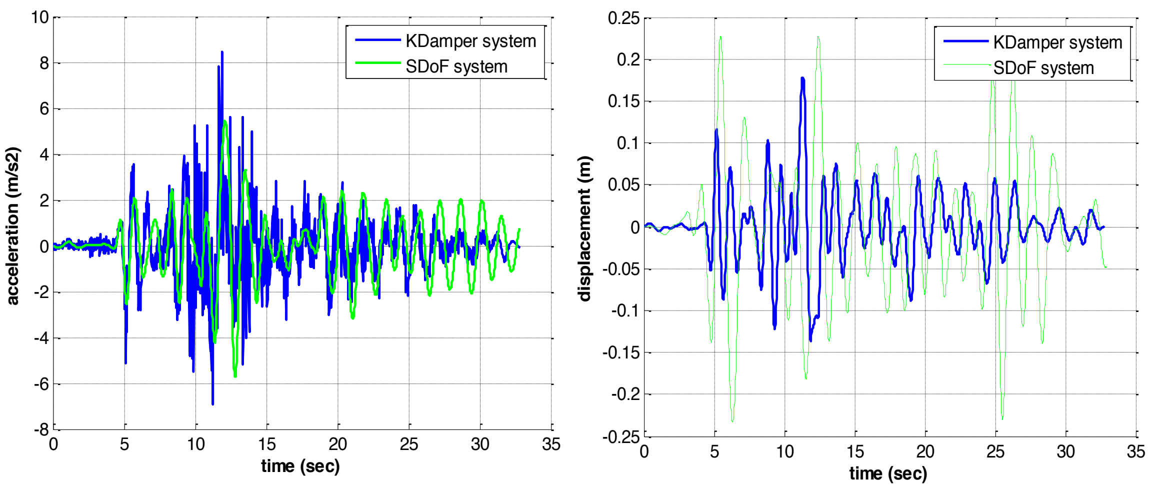
μ	κ	ζ_D
0.0488	2.7274	0.6041

Table 3: Optimum values of the design variables.



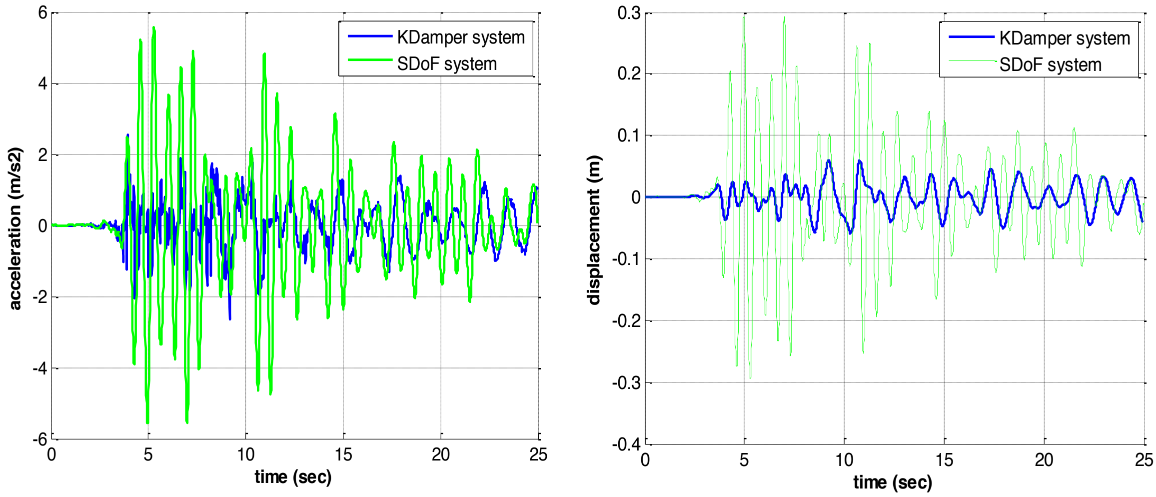
(a) (b)

Figure 6: Comparative results between the initial and the isolated system under El Centro earthquake (a) absolute accelerations in *m/s*^{2} ($\max|a_{KD}| = 2.79$, $\max|a_{SDoF}| = 4.41$) and (b) relative displacements in *m* ($\max|u_{KD}| = 0.10$, $\max|u_{SDoF}| = 0.23$).



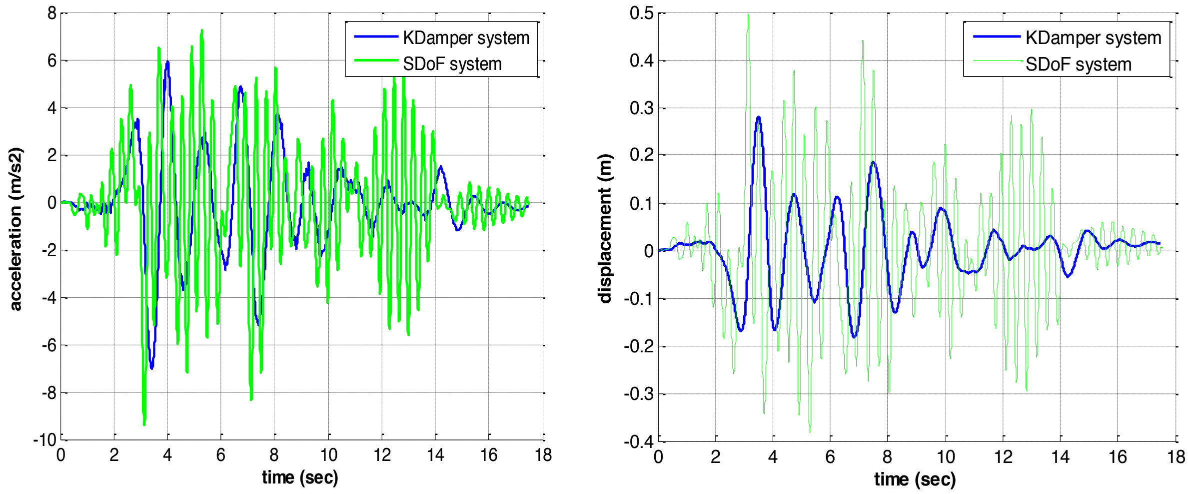
(a) (b)

Figure 7: Comparative results between the initial and the isolated system under Tabas earthquake (a) absolute accelerations in m/s^2 ($\max|a_{KD}| = 8.47$, $\max|a_{SDoF}| = 5.72$) and (b) relative displacements in m ($\max|u_{KD}| = 0.18$, $\max|u_{SDoF}| = 0.30$).



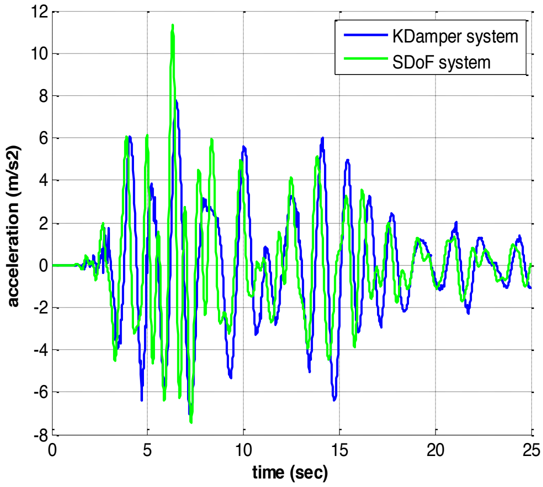
(a) (b)

Figure 8: Comparative results between the initial and the isolated system under Leukada earthquake (a) absolute accelerations in m/s^2 ($\max|a_{KD}| = 2.66$, $\max|a_{SDoF}| = 5.58$) and (b) relative displacements in m ($\max|u_{KD}| = 0.06$, $\max|u_{SDoF}| = 0.29$).



(a) (b)

Figure 9: Comparative results between the initial and the isolated system under Northridge earthquake (a) absolute accelerations in m/s^2 ($\max|a_{KD}| = 7.02$, $\max|a_{SDoF}| = 9.39$) and (b) relative displacements in m ($\max|u_{KD}| = 0.28$, $\max|u_{SDoF}| = 0.50$).



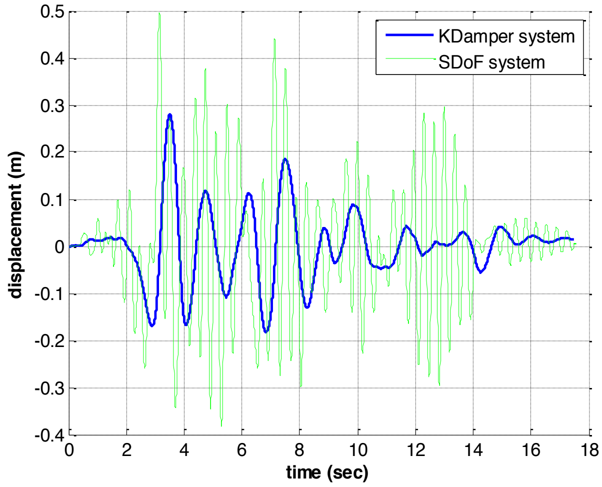


Figure 10: Comparative results between the initial and the isolated system under Kobe earthquake (a) absolute accelerations in m/s^2 ($\max|a_{KD}| = 7.73$, $\max|a_{SDoF}| = 11.30$) and (b) relative displacements in m ($\max|u_{KD}| = 0.29$, $\max|u_{SDoF}| = 0.60$).

	SDoF system		Isolated system	
	a (m/s^2)	u_s (m)	a (m/s^2)	u_s (m)
El Centro	5.17 (4.41)	0.23	3.08 (2.79)	0.10
Tabas	10.20 (5.72)	0.30	9.46 (8.47)	0.18
Leukada	7.54 (5.58)	0.29	3.96 (2.66)	0.06
Northridge	8.59 (9.39)	0.50	7.28 (7.02)	0.28
Kobe	8.36 (11.30)	0.60	8.27 (7.73)	0.29

Table 4: Deck accelerations and relative displacements of both the isolated and the initial SDoF structure. (The numbers in the parenthesis represent the maximum value of absolute accelerations).

Finally, the damping ratio of the isolated structure is estimated after subjecting the isolated structure to free vibration with initial conditions, following the equation

$$\ln\left[\frac{u_s(t)}{u_s(t+T)}\right] = \frac{2\pi\zeta}{\sqrt{1-\zeta^2}} \tag{6}$$

where T is the time between two consecutive peaks of the dynamic response of the system and u_s is the deck relative displacement. The new value of the damping ratio is given in Table 5 together with the eigenperiod of the isolated structure.

	T (sec)	ζ (%)
Initial system	1.45	5
Isolated system	2.20	21

Table 5: Dynamic eigenfeatures of both initial and isolated structures.

5 CONCLUSIONS

- The isolated system demonstrates an improved dynamic behavior for all considered excitations. More precisely, the reduction of the deck's relative displacement almost reaches 50 %.
- The implementation of the KDamper concept, results in extraordinary high values of damping, which consequently yields reduced displacements, and lower values of relative acceleration.
- The optimization process is robust, providing accurate and realistic results.
- The employment of the HS algorithm facilitates the implementation of the KDamper concept, rendering the system an easy, accessible, accurate and reliable tool for future engineers.

REFERENCES

[1] H. Frahm, *Device for Damping Vibrations of Bodies*. US patent #989958, 1909.

[2] L. Qin, W. Yan, Y. Li, Design of frictional pendulum TMD and its wind control effectiveness. *Journal of Earthquake Engineering and Engineering Vibration,* **29**, 153-157, 2009.

[3] R.J. McNamara, Tuned mass dampers for buildings. *Journal of the Structural Division ASCE,* **105**, 2766-2772, 1979.

[4] R.W. Luft, Optimal tuned mass dampers for buildings. *Journal of the Structural Division ASCE,* **103**, 1985-1998, 1977.

[5] J.P. Den Hartog, *Mechanical Vibrations, 4th Edition*. McGraw Hill, 1956.

[6] T. Haskett, B. Breukelman, J. Robinson, J. Kottelenberg, *Tuned mass dampers under excessive structural excitation*. Report of the Motioneering Inc. Guelph, Ontario, Canada NIK 1B8.

[7] N. Debnath, S.K. Deb, A. Dutta, Multi-modal vibration control of truss bridges with tuned mass dampers under general loading. *Journal of Vibration and Control,* **22**, 4121-4140, 2015.

[8] B. Weber, G. Feltrin, Assessment of long-term behaviour of tuned mass dampers by system identification. *Engineering Structures,* **32**, 3670-3682, 2010.

[9] W. Molyneaux, *Supports for vibration isolation.* ARC/CR-322, Aer Res Council, G. Britain, 1957.

[10] D.L. Platus, Negative-stiffness-mechanism vibration isolation systems. *Proc. SPIE 1619, Vibration Control in Microelectronics, Optics, and Metrology*, 44 (February 1, 1992); doi:10.1117/12.56823.

[11] A. Carella, M. Brennan, T. Waters, Static analysis of passive vibration isolator with quasi-zero-stiffness characteristic. *Journal of Sound and Vibration,* **301**, 678-689, 2007.

[12] R. Ibrahim, Recent advances in nonlinear passive vibration isolators. *Journal of Sound and Vibration,* **314**, 371-452, 2008.

[13] S. Nagarajaiah, A.M. Reinhorn, M.C. Constantinou, D. Taylor, D.T.R. Pasala, A.A. Sarlis, Adaptive negative Stiffness: A New Structural Modification Approach for Seismic Protection. *5th World Conference on Structural Control and Monitoring (WCSCM 2010),* p. no. 103, 2010.

[14] J. Winterflood, D. Blair, B. Slagmolen, High performance vibration isolation using springs in Euler column buckling mode. *Physics Letters A,* **300**, 122-130, 2002.

[15] L. Virgin, S. Santillan, R. Plaut, Vibration isolation using extreme geometric nonlinearity. *Journal of Sound and Vibration,* **315**, 721-731, 2008.

[16] R. DeSalvo, Passive, nonlinear, mechanical structures for seismic attenuation. *Journal of Computational and Nonlinear Dynamics,* **2**, 290-298, 2007.

[17] H. Iemura, M.H. Pradono, Advances in the development of pseudo-negative stiffness dampers for seismic response control. *Structural Control and Health Monitoring,* **16**, 784-799, 2009.

[18] N. Attary, M. Symans, S. Nagarajaiah, A.M. Reinhorn, M.C. Constantinou, D. Taylor, A.A. Sarlis, D.T.R. Pasala, Application of Negative Stiffness Devices for Seismic Protection of Bridge Structures. *Proc. of ASCE Structures Congress,* Chicago, March 2012.

[19] N. Attary, M. Symans, S. Nagarajaiah, A.M. Reinhorn, M.C. Constantinou, D. Taylor, D.T.R. Pasala, A.A. Sarlis, Performance Evaluation of a Seismically-isolated Bridge Structure with Adaptive Passive Negative Stiffness. *15th World Conference on Earthquake Engineering,* Lisbon, Portugal, September, 2012.

[20] D.T.R. Pasala, A.A. Sarlis, S. Nagarajaiah, A.M. Reinhorn, M.C. Constantinou, D. Taylor, Negative Stiffness Device for Seismic protection of Multistory Structures. *Proc. of ASCE Structures Congress,* Chicago, March 2012.

[21] A.A. Sarlis, D.T.R. Pasala, M.C. Constantinou, A.M. Reinhorn, S. Nagarajaiah, D. Taylor, Negative Stiffness Device for Seismic Protection of Structures – An Analytical and Experimental Study. *3th International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering (COMPDYN 2011),* Corfu, Greece, May 26-28, 2011.

[22] A.A. Sarlis, D.T.R. Pasala, A.M. Reinhorn, M.C. Constantinou, S. Nagarajaiah, D. Taylor, Negative stiffness device for seismic protection of structures. *Journal of Structural Engineering,* **139**, 1124-1133, 2012.

[23] I. Antoniadis, D. Chronopoulos, V. Spitas, D. Koulocheris, Hyper-damping properties of a stable linear oscillator with a negative stiffness element. *Journal of Sound and Vibration,* **346**, 37-52, 2015.

[24] E.J. Sapountzakis, P.G. Syrimi, I.A. Pantazis, I.A. Antoniadis, KDamper Concept in Seismic Isolation of Bridges. *1th International Conference on Natural Hazards and Infrastructure (ICONHIC 2016),* Chania, Crete, Greece, June 28-30, 2016.

[25] Z.W. Geem, J.H. Kim, G.V. Loganathan, A new heuristic optimization algorithm: harmony search. *Simulation*, **76**, 60-68, 2001.

[26] K.S. Lee, Z.W. Geem, S.H. Lee, K.W Bae, The harmony search heuristic algorithm for discrete structural optimization. *Engineering Optimization*, **37**, 663-684, 2005.

[27] K.S. Lee, Z.W. Geem, A new meta-heuristic algorithm for continuous engineering optimization: Harmony search theory and practice. *Computer Methods in Applied Mechanics and Engineering*, **194**, 3902-3933, 2005.

[28] Z.W. Geem, Novel derivative of harmony search algorithm for discrete design variables. *Applied Mathematics and Computation*, **199**, 223-230, 2008.

[29] X. Wang, X.Z. Gao, S.J. Ovaska, Fusion of clonal selection algorithm and harmony search method in optimization of fuzzy classification systems. *International Journal of Bio-Inspired Computation*, **1**, 80-88, 2009.

[30] Z.W. Geem, J.H. Kim, G.V. Loganathan, Harmony search optimization: Application to pipe network design. *International Journal of Modelling and Simulation*, **22**, 125-133, 2002.

[31] Z.W. Geem, C. Tseng, Y. Park, Harmony search for generalized orienteering problem: Best touring in China. *Springer Lecture Notes in Computer Science*, **3412**, 741-750, 2005.

[32] K.S. Lee, Z.W. Geem, A new structural optimization method based on the harmony search algorithm. *Computers and Structures*, **82**, 781-798, 2004.

[33] M.P. Saka, Optimum design of steel sway frames to BS5950 using harmony search algorithm. *Journal of Constructional Steel Research*, **65**, 36-43, 2009.

[34] F. Erdal, M.P. Saka, Harmony search based algorithm for the optimum design of grillage systems to LFRD-AISC. *Structural and Multidisciplinary Optimization*, **38**, 25-41, 2009.

[35] S.M. Nigdeli, G. Bekdas, C. Alhan, Optimization of seismic isolation systems via harmony search. *Engineering Optimization*, **46**, 1553-1569, 2014.

[36] S.M. Nigdeli, G. Bekdas, Optimum tuned mass damper design in frequency domain for structures. *KSCE Journal of Civil Engineering*, **21**, 912-922, 2017.

[37] X.Z. Gao, V. Govindasamy, H. Xu, X. Wang, K. Zenger, Harmony search method: Theory and applications. *Computational Intelligence and Neuroscience*, **2015**, 1-10, 2015.