ABSTRACT: Contemporary seismic isolation systems comprise of special mechanisms, like Tuned Mass Dampers (TMDs) or devices with negative stiffness elements. Exploiting the positive features of these technologies, a novel passive vibration absorption device is proposed, according to the KDamper concept, which
is based on the combination of positive and negative stiffness elements and of an additional mass. The main advantage lies in the fact that no reduction of the total stiffness of the structure is required. In this paper, the implementation of KDamper device to a two-span concrete bridge is investigated, in order to mitigate seismic effects. An optimization algorithm is proposed to facilitate the selection of parameters, during the device’s design. The isolated system’s response is compared to a classical one with elastomeric bearings. The results verify the accuracy and effectiveness of both the proposed device and the optimization algorithm.

INTRODUCTION

During the last decades, seismic isolation has become more and more popular when dealing with the design of earthquake resistant structures. Its basic principle, the reduction of seismic force, imposed to a structure due to earthquake excitation, is in contrast with conventional antiseismic techniques promoting the increase of the structure’s stiffness to sustain dynamic loads. Seismic isolation methods, thus, lead to more economic structures that exhibits improved dynamic performance to seismic excitation. Seismic effects mitigation techniques are commonly used in structures whose functionality needs to be preserved after a seismic event, such as bridge structures. In practice, bridge seismic isolation is achieved through the implementation of special devices and configurations that decouple the response of the deck from the substructure. Elastomeric bearings, lead-rubber bearings, roller bearings and other similar layouts enlist as devices and mechanisms suitable for bridge seismic isolation, with Tuned Mass Dampers (TMDs) and devices with negative stiffness elements, (e.g. “Quasi Zero Stiffness” Oscillators – QZS) being the most recent approaches on this field.

TMDs were first applied by Frahm (1909) and since then, they have been frequently used to absorb vibrations of skyscrapers under earthquake and wind loading (Qin et al., 2009). Their design usually follows the optimal design theory proposed by Den Hartog (1956). A characteristic example of TMD implementation is the Taipei 101 Tower (101 stories, 504 m) in Taiwan (Haskett et al., 2003). Recently, the use of TMDs has been included in studies concerning vibration absorption under seismic or other forms of excitation of bridge structures (Debnath et al., 2015). The salient feature controlling a TMD’s performance is the fact that its natural frequency is tuned in resonance with the fundamental frequency of the primary structure, in order to transfer a large amount of the structural vibrating energy to the TMD. This energy is then dissipated through damping. Besides their effectiveness, TMDs present two main drawbacks: a) they are susceptible even to slight changes of environmental or other external parameters that can disturb the tuning and, by extent, reduce the device’s performance (Weber & Feltrin, 2010) and b) a large oscillating mass is required to achieve the desired vibration reduction, rendering their construction and placement procedure rather difficult.

On the other hand, negative stiffness elements become more and more popular as parts of seismic isolation devices. True negative stiffness is defined as a force that
assists motion instead of opposing it. The use of negative stiffness elements was first introduced in the pioneer publication of Molyneaux (1057), as well as in the milestone developments of Platus (1992). The basic concept of these approaches is to significantly reduce the stiffness of the isolator and hence to reduce the natural frequency of the system even at almost zero levels, as in Carella et al. (2007), namely “Quazi Zero Stiffness” (QZS) oscillators. After the initial comprehensive review by Ibrahim (2008), many researchers have demonstrated the effectiveness of such devices (Nagarajaiah et al., 2010) regarding seismic protection of structures. More precisely, their research showed that the implementation of such devices in the seismic protection of structures alleviates the dynamic forces acting upon them. The negative stiffness behaviour is primarily achieved by special mechanical designs involving conventional positive stiffness pre-stressed elastic mechanical elements (e.g. post-buckled beams, plates, shells and pre-compressed springs), arranged in appropriate geometrical configurations. Some interesting designs are described in Winterflood et al., (2002) and Virgin et al., (2008), whereas numerous applications of QZS in seismic isolation can be found in Iemura & Pradono (2009), and Sarlis et al. (2012). However, the main problem of QZS oscillators is their inherent drawback of the drastic reduction of the total structural stiffness to almost negligible levels, which diminishes the static load capacity of these structures.

Exploiting the positive features of both aforementioned devices, a novel passive vibration isolation and damping configuration is presented, based on the KDamper concept introduced by Antoniadis et al. (2015). The proposed device incorporates a negative stiffness element and 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. Its main difference from other known negative stiffness oscillators is the appropriate redistribution of the individual stiffness elements and the reallocation of damping. Although negative stiffness elements usually demonstrate an unstable behavior, the proposed device is designed to be both statically and dynamically stable. Similarly, to the TMDs, the presence of an additional mass also serves in mitigating the effects of a vibrating load, operating as an energy dissipation mechanism. However, the KDamper overcomes the sensitivity problems of TMDs as the tuning is mainly controlled by the negative stiffness element’s parameters and, hence, is not affected by external factors. An application of KDamper devices to wind turbine towers is proposed in Kapasakalis et al. (2017). A first approach to implement the KDamper concept in the seismic isolation of a typical two-span concrete bridge can be found in Sapountzakis et al. (2016).

In this paper, an effort to find the optimum design parameters of such a device will be presented. For the optimization process, harmony search algorithm (HS), a novel metaheuristic algorithm, first proposed by Geem et al. (2001), is adopted. Recently, HS has been employed for the optimum design of the implementation of TMDs to multistory buildings (Nigdeli & Bekdas, 2017). Finally, an initial effort to optimally design and implement the KDamper concept to a bridge using HS algorithm can be found in Syrimi et al. (2017).
In this study the optimum design and implementation of the KDamper concept to a typical single-pier concrete bridge is investigated. The structure is subjected to three scaled earthquake excitations that took place in Greece. In this respect, the original earthquake records were scaled in order their response spectrum to match, the respective EC8 response spectrum. Moreover, the Root Mean Square (RMS) of the isolated systems kinetic energy is employed 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.

SEISMIC ISOLATION AND KDAMPER ANALYSIS MODEL

Basic Seismic Isolation Principles:

![Figure 1](image.png)

**Figure 1.** Indicative examples of response spectra of (a) accelerations and (b) displacements and their variation over damping.

Seismic isolation of structures and, especially bridges, is based on the following principle: increasing the structure’s eigenperiod leads to the transition to the descending branch of the response spectrum of accelerations (**Figure 1a**). However, it should be mentioned here, that excessively high values of the eigenperiod could result in an undesirable increase of the structure’s displacements. This happens due to the different shape of the response spectrum of displacements, as it can be derived from **Figure 1b**. Even though the implication of dampers seems a rather effective choice to overcome this problem, it is not always a feasible solution, because relatively high values of damping are usually required. An optimum compromise between accelerations and displacements, within an acceptable range of structural
eigenperiods, results in a region of feasible solutions. This region is referred to as
design window and its lower and upper bounds are shown in Figure 2.

![Figure 2. Conceptual illustration of the design window for isolation systems.](image)

More specifically, the left boundary of the design window is imposed by the neces-
sity to reduce accelerations. Its value generally depends on the soil of the structure’s
foundation (soil properties define the margin between the branch of constant accel-
erations and the descending one) and it is roughly estimated to be equal to 2 seconds.
On the contrary, the right boundary cannot be defined as easily as the left one, as it
is relevant to the displacement performance requirements of each structure. Conse-
quently, the upper limit of the design window depends on each structure’s function-
ality, security and implementation demands. In light of the above, the need to
employ an optimization procedure, in order to efficiently design a seismic isolation
system, is inherently apparent.

The KDamper concept

Figure 3a presents the basic layout of the proposed seismic isolation configuration,
based on the KDamper concept, where $k_N$ denotes the algebraic value of negative
stiffness. An initial SDoF system is considered, consisting of a mass $m$, and static
stiffness $k$, which may be undamped or have a low damping ratio. As it can be
observed from Figure 3a, the addition of a mass, $m_D$ inside the device creates a
second hidden degree of freedom. Thus, the resulting isolated system is a 2-DoF
system.

Further information including a detailed description of the proposed device’s per-
formance, the equations of motion of the isolated system, the realization and treat-
ment of the negative stiffness element and a possible implementation of such a
device to a bridge structure can be found in Sapountzakis et al. (2016). A first step
towards the optimal design of the proposed device and the resulting isolated system
has been presented in Syrimi et al. (2017).
The device’s performance is controlled by three parameters, $\mu$, $\kappa$, and $\zeta_D$ designated by the following equations

$$\mu = \frac{m_D}{m_s}, \quad \kappa = -\frac{k_N}{k_e + k_N}, \quad \zeta_D = \frac{c_D}{2\sqrt{(k_e + k_N)m_D}}$$

where $\zeta_D$ represents the equivalent damping ratio of the additional artificial damper with constant $c_D$.

Based on these three parameters, all the other constants (regarding either stiffness or damping) of the KDamper elements are defined. Certain limitations are imposed to the values of the three parameters in order for the device to be economical and easy to place, regarding each structure’s safety and functionality requirements and demands. Restrictions concerning the maximum allowable displacement (stroke) of both DoFs (internal and external) have to be also taken into consideration. More specifically, the maximum allowable value of the internal DoF depends on the mechanical equipment used to realize the negative stiffness element at each specific case/structure. For all these reasons, proposing an accurate optimization procedure is of paramount importance to facilitate the selection of the device’s basic parameters and, by extent, the implementation of the KDamper concept.

**Test case considered**

A typical concrete bridge of two equal spans, is considered, as shown in Figure 4, represents the initial system. The bridge is based on five conventional ALGABLOC...
NB 400x500/99/71 bearings, with a horizontal stiffness of $k_b = 2730$ kN/m each. In this effort, the pier is considered stiff enough to be neglected, hence the total horizontal stiffness of the system is equal to the stiffness of the bearings. A similar approach to implement the KDamper device to a concrete bridge with flexible pier can be found in Sapountzakis et al. (2017). Further information concerning the geometric characteristic and the dynamic properties of the bridge – bearings system is given in “Table 1”.

![Figure 4](image_url)

**Figure 4.** Schematic representation of the bridge considered (longitudinal section).

<table>
<thead>
<tr>
<th>Span length, $L$ (m)</th>
<th>Mass, $m_s$ (tn)</th>
<th>Total stiffness, $k_o$ (kN/m)</th>
<th>Damping ratio, $\zeta$ (%)</th>
<th>Damping factor, $c_s$ (kN/s/m)</th>
<th>Period, $T$ (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>729.3</td>
<td>13650</td>
<td>5</td>
<td>315.5146</td>
<td>1.45</td>
</tr>
</tbody>
</table>

**Earthquake records considered**

The aforementioned two span concrete bridge is subjected to three different earthquake excitations that took place in three different locations of Greece, namely, in Athens, in Aigio and in Kalamata. However, in order for the design to be as close as possible to Eurocode seismic requirements, the original earthquake records – from now on referred to as origin records – were scaled so that each record’s response spectrum approximately matches the EC8 design spectrum (Spectrum type 1, Soil type B, Zone 3). The earthquake records were scaled using SeismoMatch software (Seismosoft, 2016). The resulting earthquake records will be referred to as matched records. In **Figure 5a**, **Figure 6a** and **Figure 7a**, the frequency content of both origin and matched records are presented for Athens, Aigio and Kalamata earthquakes, respectively. The response spectrum of the origin record as well as the
corresponding one of the matched record, compared to the EC8 spectrum, are depicted in Figure 5b for Athens earthquake, in Figure 6b for Aigio earthquake and in Figure 7b for Kalamata earthquake.

Figure 5. (a) Frequency content of Athens origin and matched earthquake records. (b) Response spectra of Athens origin and matched earthquake records compared to the EC8 response spectrum.

Figure 6. (a) Frequency content of Aigio origin and matched earthquake records. (b) Response spectra of Aigio origin and matched earthquake records compared to the EC8 response spectrum.
Figure 7. (a) Frequency content of Kalamata origin and matched earthquake records. (b) Response spectra of Kalamata origin and matched earthquake records compared to the EC8 response spectrum.

HARMONY SEARCH ALGORITHM AND OPTIMIZATION PROCESS

A detailed description of the HS algorithm is beyond the scope of this study. However, the interested reader is referred to Refs. (Geem et al., 2001), (Gao et al., 2015), (Nigdeli & Bekdas, 2017).

KDamer concept optimization process

According to the procedure presented in Syrimi et al. (2017), the features of the examined optimization problems can be derived. The only steps that are different are presented in the following.

Starting from the design variables, the three parameters that control the device’s performance $\mu$, $\kappa$, and $\zeta_D$ are selected. Furthermore, the allowable range of values for these parameters is defined by determining their limits, given in “Table 2”. At this point, it is reminded that the choice of the parameter limits lies on safety, stability and manufacturing aspects that need to be taken into account. Concerning the parameters inherently involved in the HS algorithm, values commonly found in relative literature are adopted (“Table 3”). Similarly, in this effort, the maximum number of total iterations is selected as the termination criterion.

In view of finding the optimum solution, the Root Mean Square (RMS) of the deck’s absolute kinetic energy for all three excitations is selected as the objective function. Finally, the following constraint is imposed: the value of deck’s relative displacement is set lower than 0.15 m.
Table 2: Variable design limits.

<table>
<thead>
<tr>
<th></th>
<th>μ</th>
<th>κ</th>
<th>ζ_D</th>
</tr>
</thead>
<tbody>
<tr>
<td>min</td>
<td>0.01</td>
<td>2.234</td>
<td>0.01</td>
</tr>
<tr>
<td>max</td>
<td>0.10</td>
<td>2.831</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Table 3: Values of the HS algorithm parameters.

<table>
<thead>
<tr>
<th>HMS</th>
<th>HMCR</th>
<th>PAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>75</td>
<td>0.5</td>
<td>0.1</td>
</tr>
</tbody>
</table>

NUMERICAL RESULTS

The optimum values of the design variables, obtained using the HS optimization procedure are presented in “Table 4”. The dynamic eigenfeatures of both the initial and the isolated systems are given in “Table 5”, whereas comparative results between the two aforementioned systems for each one of the three earthquake excitations can be found in “Table 6”, in terms of the deck’s absolute acceleration and relative displacement.

Table 4: Optimum values of the design variables.

<table>
<thead>
<tr>
<th>μ</th>
<th>κ</th>
<th>ζ_D</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0657</td>
<td>2.2617</td>
<td>0.1165</td>
</tr>
</tbody>
</table>

Table 5: Dynamic eigenfeatures of both the initial and the isolated system.

<table>
<thead>
<tr>
<th></th>
<th>T (sec)</th>
<th>ζ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial system</td>
<td>1.45</td>
<td>5</td>
</tr>
<tr>
<td>Isolated system</td>
<td>2.28</td>
<td>24.6</td>
</tr>
</tbody>
</table>

Table 6: Deck’s absolute accelerations and relative displacements of both systems.

<table>
<thead>
<tr>
<th></th>
<th>Initial system</th>
<th>Isolated system</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>a_s (m/s^2)</td>
<td>u_s (m)</td>
</tr>
<tr>
<td>Athens</td>
<td>3.33</td>
<td>0.177</td>
</tr>
<tr>
<td>Aigio</td>
<td>3.67</td>
<td>0.195</td>
</tr>
<tr>
<td>Kalamata</td>
<td>3.69</td>
<td>0.196</td>
</tr>
</tbody>
</table>
CONCLUSIONS

- The isolated system demonstrates an improved dynamic behavior for all considered excitations, as lower values are obtained for both relative displacements and absolute accelerations.
- The implementation of the KDamper device results in high values of damping.
- The employment of the HS algorithm facilitates the implementation of KDamper, rendering the device an easy and applicable tool for future seismic isolation systems.

REFERENCES


