Engineering Structures 153 (2017) 525–539

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

KDamper concept in seismic isolation of bridges with flexible piers

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ARTICLE INFO

Keywords:
Seismic isolation
Negative stiffness
Bridge
KDamper

ABSTRACT

Contemporary seismic isolation systems for bridge applications provide (a) horizontal isolation from the effects of earthquake shaking, and (b) an energy dissipation mechanism to reduce displacements. Throughout the years many kinds of seismic isolation mechanisms have been developed, with two concepts being the most promising ones: the introduction of negative stiffness elements and the incorporation of an additional mass. The latter has led to the development of Tuned Mass Dampers (TMDs), engineering devices consisting of a mass, a spring and a viscous damper commonly used to suppress any undesirable vibrations induced by wind and earthquake loads. The negative stiffness behavior 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. Combining the beneficial characteristics of both concepts, a novel passive vibration isolation and damping concept is introduced, the KDamper. The KDamper is based on the optimal combination of appropriate stiffness elements, which include a negative stiffness element. The presence of the additional mass enables structural vibrating energy to be transferred from the structure to the device. The main advantage of the KDamper over other similar concepts including negative stiffness elements is that no reduction in the overall stiffness of the system is required.

In this paper, an initial approach towards the implementation of the KDamper to the absorption of seismic excitation of structures is considered, by applying the KDamping concept to a typical single-pier bridge subjected to three different types of dynamic loading. The contribution of pier is taken into account during the analysis. A comparison with a non-isolated bridge with similar characteristics confirms that KDamper based seismic absorption designs can provide a promising alternative to the conventional seismic isolation bearings, offering numerous advantages, such as increased damping and simple technological implementations.

1. Introduction

In response to the damage generated by earthquakes occurring in densely populated areas, seismic design codes for the design of buildings, bridges and industrial facilities changed with the intention of leading to better seismic performance. In order to mitigate the effects of earthquake shaking on structures, many theories have been developed with seismic isolation being the most popular approach to earthquake-resistant design, as it is based on the concept of reducing the seismic demand rather than increasing the earthquake resistance capacity of the structure. Contemporary seismic isolation systems for bridge applications provide (a) horizontal isolation from the effects of earthquake shaking, by decoupling the bridge deck from bridge substructure during earthquakes, and (b) an energy dissipation mechanism to reduce displacements. In this context, a variety of isolation devices including elastomeric bearings (with and without lead core) [1], frictional/sliding bearings, roller bearings, fluid viscous dampers and viscoelastic dampers have been developed. However, in the past few years, research concerning the next generation of seismic protection devices focuses on two main concepts: (a) the introduction of negative stiffness elements (Negative Stiffness Devices and "Quazi Zero Stiffness" oscillators) and (b) the implementation of an additional mass (Tuned Mass Dampers).

True negative stiffness is defined as a force that assists motion instead of opposing it as in the case of a positive stiffness spring. The concept of introducing negative stiffness elements (or "anti-springs") has a long history, being first introduced in the pioneering publication of Molyneaux [2], as well as in the milestone developments of Platus [3]. 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.

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http://dx.doi.org/10.1016/j.engstruct.2017.10.044
Received 3 September 2016; Received in revised form 14 October 2017; Accepted 17 October 2017
0141-0296/

[4], being thus called “Quazi Zero Stiffness” (QZS) oscillators. In this way, the transmissibility of the system for all operating frequencies above the natural frequency is reduced, resulting in enhanced vibration isolation. Through numerical simulations and experimental testing, a number of researchers have demonstrated the effectiveness of such devices. An initial comprehensive review of such designs can be found in Ibrahim [5]. Nagarajaiah et al. [6] introduced a new structural modification approach for the seismic protection of structures with an adaptive passive negative stiffness device showing that the implementation of the negative stiffness device to structures would result in decreased dynamic forces in the structures, increasing the displacements, which can also be reduced by using a damper in parallel with the negative stiffness device. The negative stiffness behavior 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 [7,8]. Among others QZS oscillators find numerous applications in seismic isolation [9–15] or in torsional vibrations [16]. However, they suffer from their fundamental requirement for a drastic reduction of the stiffness of the structure almost to negligible levels, which limits the static load capacity of such structures.

A Tuned Mass Damper (TMD), sometimes referred to as a dynamic vibration absorber, is a classical engineering device consisting of a mass, a spring and a viscous damper. It is usually attached to a vibrating primary system in order to suppress any undesirable vibrations induced by wind and earthquake loads. The TMD concept was first applied by Frahm [17]. Since Den Hartog [18] first proposed an optimal design theory for the TMD for an undamped SDoF structure, the TMD has been employed on a vast array of systems with skyscrapers being among the most interesting ones [19–21]. A characteristic example of its implementation to skyscrapers can be found in one of the tallest buildings in the world, Taipei 101 Tower (101 stories, 504 m) in Taiwan [22]. Recent studies also include the use of TMDs for vibration absorption of seismic or other forms of excitation in bridge structures [23]. The natural frequency of the TMD is tuned in resonance with the fundamental mode of the primary structure. Thus, a large amount of the structural vibrating energy is transferred to the TMD and then dissipated by damping. Even though TMDs are known for their effectiveness and their reliability, the main disadvantage of such devices is the sensitivity of their properties. Environmental influences and other external parameters may alter the TMD properties, disturbing its tuning. Consequently, the device’s performance can be significantly reduced [24]. Another essential limitation of the TMD is that a large oscillating mass is required in order to achieve significant vibration reduction, rendering its construction and placement procedure rather difficult.

Exploiting the advantages of both previously mentioned concepts, a novel passive vibration isolation and damping concept, the KDamper concept, has been proposed in Antoniadis et al. [25,26], incorporating a negative stiffness element, which can exhibit extraordinary damping properties without presenting the drawbacks of the traditional linear oscillator, or of the “zero-stiffness” designs. This oscillator is designed to present the same overall (static) stiffness as a traditional reference original oscillator. However, it differs both from the original SDoF oscillator, as well as from the known negative stiffness oscillators, by appropriately redistributing the individual stiffness elements and by reallocating the damping. Although the proposed oscillator incorporates a negative stiffness element, it is designed to be both 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 (energy is transferred from the structure to the additional mass). The device 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 [26], it is shown to exhibit an extraordinary damping behavior. An initial effort to implement the KDamper concept to wind turbine towers can be found in [27]. Moreover, a drastic increase of several orders of magnitude has been observed for the damping ratio of the flexural waves propagating within layered periodic structures incorporating such negative stiffness oscillators [28]. Similar approaches, incorporating metamaterials with negative stiffness inclusions, have been adopted in the field of acoustic waves insulation, too [29,30].

In this paper, an initial approach towards the implementation of the KDamper to the absorption of seismic excitation of structures is considered, by applying the KDamping concept to a typical single-pier bridge with conventional bearings. The negative stiffness element is realized by a non-linear bistable element, which operates around an unstable equilibrium point. This bistable element takes the form of two symmetric linear horizontal springs, connected with the rest of the elements through an appropriate articulated mechanism. The dynamic response of the bridge under three different types of loading is examined before and after the implementation of nine KDamper devices that replace the conventional bearings. Two kinds of KDampers are optimally selected, regarding their position in the structure. The contribution of the pier is taken into account during the analysis. New system’s damping ratio is calculated and comparative results between the test case considered herein and the corresponding one described in Sapountzakis et al. [31] are presented.

2. Methodology

2.1. Overview of the KDamper concept

Fig. 1a presents the basic layout of the vibration isolation and damping concept to be considered. 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 of $x_G(t)$. The SDoF system may be undamped or have a low initial damping ratio.

The first basic requirement of the KDamper is that the overall static stiffness of the system is maintained, as it is stated in Eq. (1), where k_R and k_e represent the stiffness of the conventional springs, k_N is the algebraic value of the stiffness of the negative stiffness element and k_o stands for the stiffness of an equivalent undamped SDoF system.

$$k_R + \frac{k_e k_N}{k_e + k_N} = k_o \tag{1}$$

In this way, the KDamper can overcome the fundamental disadvantage of the QZS oscillator, which is the reduction of the overall stiffness of the system that simultaneously limits the static loading capacity of the structure.

The equations of motion after the implementation of the KDamper are presented below.

$$m_s \ddot{u}_s + (c_s + c_D)\dot{u}_s - c_D \dot{u}_D + (k_R + k_e)u_s - k_e u_D = -m_s \ddot{x}_G \tag{2a}$$

$$m_D \ddot{u}_D - c_D \dot{u}_s + c_D \dot{u}_D - k_e u_s + (k_e + k_N)u_D = -m_D \ddot{x}_G \tag{2b}$$

where

$$u_s = x - x_G \tag{3a}$$

$$u_D = y - x_G \tag{3b}$$

c_s is the initial system’s damping coefficient and c_D is the damping coefficient of the additional damper.

At this point, it should be mentioned that the KDamper essentially consists an indirect approach to increase the inertia effect of the additional mass m_D without, however, increasing directly the mass m_D itself.