Engineering Structures 122 (2016) 62–71

Contents lists available at ScienceDirect

Engineering Structures

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

Vibration suppression of cables using tuned inerter dampers

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A R T I C L E I N F O

Article history:
Received 21 June 2015
Revised 6 April 2016
Accepted 7 April 2016

Keywords:
Cable dynamics
Tuned inerter damper (TID)
Vibration suppression

A B S T R A C T

This paper considers the use of a tuned inerter damper (TID) system for suppressing unwanted cable vibrations. The TID consists of an inerter, a device that exerts a force proportional to relative acceleration, coupled with a parallel spring and damper. It may be thought of as similar to a tuned-mass-damper, but requiring two terminals. As a two terminal device, the performance of the TID is compared to the classical use of viscous dampers (VD) located close to one of the cable supports. We show that the limitation that exists with VDs, where the modal damping of the cable cannot exceed a maximum level for a given damper location, can be overcome through the use of the TID at the same location. A practical design methodology, based on the minimisation of the displacement amplitude at the mid-span of the cable subjected to support excitation, is proposed. An example where a cable is subjected to the El-Centro earthquake demonstrates that the system's response is improved when a TID is used instead of a VD.

1. Introduction

Cables are widely used structural elements capable of bearing tensile forces. Cables experience vibration problems due to their very low damping. The problems associated with cable vibration are especially important for bridge design and retrofitting. Bridge cables are subject to vibrations induced by wind, wind-rain, traffic and earthquakes. These unwanted vibrations need to be reduced to acceptable levels. Irvine gives an overview of cable dynamics in [1]. More recently, Rega published a review on the nonlinear vibrations of suspended cables in [2,3].

In order to limit unwanted vibration in cable-stayed bridges, viscous dampers can be attached between the cables and the deck, near the anchorage point of each cable. Several studies have been made in order to understand the subsequent dynamic behaviour. Kovacs [4] was the first to define the concept of maximum attainable modal damping. Later, Yoneda & Maeda [5] proposed the use of a set of empirical equations for defining the optimum damper size and Uno et al. [6] introduced the use of non-dimensional damping coefficients. Later, Pacheco et al. [7] determined the universal curve for estimating the modal damping of stay cables and Krenk [8] gave an analytical formula for the universal curve, based on complex modes analysis. Then, Cremona [9] extended the universal curve formulation to inclined cables. Main and Jones [10] extended these studies to the case where the damper is installed further away from the support. There have been several case studies looking into the performance of bridges with attached viscous dampers [11], where their effectiveness has been demonstrated. Magneto-rheological (MR) dampers have also been considered as an alternative to viscous dampers [12–14].

However, it has been shown that there are limitations to the effectiveness of dampers mounted on cables because their installation is restricted to be near the end of the cable, generally at distances lower than 5% of the cable length, see for example [15]. Over this range, regardless of the damping coefficient, there is a maximum modal damping that can be achieved using a viscous damper [8]. This disadvantage may be overcome by the use of tuned mass dampers (TMD) that can be installed anywhere along the cable length, as they require no attachment to the ground or bridge deck [16]. Such systems have already been designed and tested.

A parametric study was conducted by Wu & Cai in [17] to quantify the influence of parameters such as TMD mass and damping ratio, cable inclination and TMD location on the system's performance. Casciati & Ubertini [18] extended the use of TMDs to the mitigation of spatial vibrations of shallow cables by adopting a variable inclination device attached to the cable.

Anderson et al. [19] made a comparison between cables with attached VDs and TMDs and assessed the performance of the two types of systems. It was shown that a TMD located at 40% distance from the support is more efficient than a damper located very close to the support. The clear disadvantage of the TMD option is the access issues at these locations.

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http://dx.doi.org/10.1016/j.engstruct.2016.04.017
0141-0296/© 2016 The Author(s). Published by Elsevier Ltd.

The aim of this paper is to investigate whether an inerter-based system can be used to overcome the performance limitations of a VD while retaining its advantage that it is mounted close to the anchorage point and so it is easily accessible.

The inerter was originally designed by Smith [20] to complete the force-current analogy between mechanical and electrical networks. This is the equivalent of a capacitor and the force produced is proportional to the relative acceleration between the device terminals. The proportionality constant is called inertance and is measured in kilograms. Initially designed for Formula 1 racing car suspension systems, under the name of J-damper [21], the inerter is used today in vehicle [22–24], train [25] and building [26,27] suspension systems. The use of inerters for civil engineering applications has been extended to suppression systems in the form of tuned viscous mass dampers [28,29], tuned mass-damper-inerter systems [30] and tuned inerter dampers (TID) [31]. Unlike the mass in a TMD, the inerter can be geared such that the apparent mass is far higher than the actual mass of the device; gearing ratios of 200:1 have been achieved [28]. This offers the potential for much higher mass ratios than those feasible for TMDs [31].

In this paper, the authors propose the use of a TID system, where the traditional TMD mass is replaced by an inerter. A schematic diagram of the resulting system is shown in Fig. 1. The potential advantage of using a TID comes from the use of gearing in the inerter, allowing a much higher apparent mass then the mass of the device. For example, a commercially available inerter, the Penske 8760H, has an apparent mass (inertance) to device mass ratio of 38, with higher mass ratios available on demand. Therefore, it is feasible for the inerter's physical mass to remain low regardless of its inertance. This is in contrast to the mass in a TMD, which is generally limited to 10% of the host structure mass. As in the case of cables with attached dampers, the TID needs to be located next to the support (in the range of 0–5%), connected between the deck and the cable. This can be advantageous in terms of maintenance or for retrofitting.

The paper discusses the performance of VDs and, building on this, proposes an optimisation and tuning strategy for TIDs installed on cables. For a convenient design process, contour plots are proposed for both VD and TID systems. For VDs, the only tuning parameter is the device's damping coefficient and, based on the contours plots provided, the user can select the optimal damping ratio using the device location. For TIDs, there are three design parameters, namely the apparent mass ratio, the damping ratio and the frequency ratio (between the TID and the host structure). Therefore, after selecting the desired apparent mass ratio and the connection point location, the user is provided with two extra contour plots where the matching damping and frequency ratios can be identified. Hence, a practical design method that can be employed by the engineer for both VD and TID systems is provided, see Section 4.

To support the theoretical findings, a numerical application where a cable is subjected to sinusoidal and earthquake support excitation is presented in Section 5. It is shown that the performance of an optimal damper can be achieved by attaching a TID with a mass ratio of only 10% of the total cable mass. Moreover, while there is only one optimal damper that can be used in a certain connection point, the performance of a TID can be improved further by increasing its apparent mass ratio. This can be easily achieved in practice, given the inerter's capacity of generating high apparent masses [28,33].

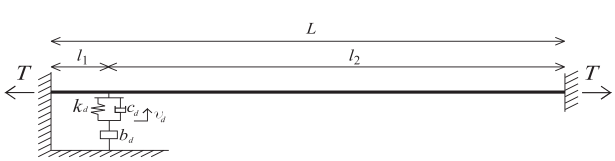

Fig. 1. Cable with attached TID.

2. Study of cables with attached dampers

Several numerical solutions have been proposed for the case when dampers are attached to cables, starting from the partial differential equation describing the cable vibration and by proposing different functions for the cable's mode shapes. Such algorithms are described in greater detail in [8] and [10]. However, the analysis of the TID is more complex due to the additional degree of freedom within the device. In order to reduce the computational effort necessary for numerically solving a system of partial differential equations, a finite element model of the cable was created using axial elements.

2.1. Finite element model

A 20 axial elements model of the cable was used. The accuracy of the model was validated against the analytical expressions for the combined cable-TID system using the approach reported for cable-damper systems in [8]. To accommodate the TID and VD when selecting the elements' lengths, the device-cable connection point was included as a node. For example, if the connection point is located at 1% distance from the support, the first element will have a length of $0.01L$, the second element will have a length of $0.09L$ and the other elements will have the length $0.05L$. As expected, this change will influence the natural frequency of the finite element modelled cable. However, the changes are very small and the impact on the overall response is arguably negligible (less than 0.1%).

Having chosen the number of elements, the mass and stiffness matrices are assembled for the simple cable. Since the VD does not alter the mass and stiffness of the cable, these matrices remain unchanged. The damping matrix changes, allowing for the added damping to be taken into account. When adding a TID, an additional degree of freedom is added to these matrices. All matrices are described in the Appendix at the end of the paper, along with the conversion of the resulting equation of motion into state space.

2.2. Performance analysis

The problem of cable vibration suppression by means of magneto-rheological (MR) or viscous dampers (VD) has been studied in-depth in the existing literature. The results presented in [8] prove the existence of an optimum set of parameters that need to be used in order to obtain the best performance of the cable plus damper system. By employing the optimal damping ratio corresponding to a given location of the damper, it can be ensured that the maximum amount of damping is transferred to the cable. This also translates into optimum performance in terms of maximum displacement amplitude. In the current study, the damping ratio is defined as

$$\xi_{VD} = \frac{c}{2\sqrt{Tm}} \tag{1}$$

where c represents the VD damping coefficient, T is the tension in the cable, and m is the cable mass per unit length.

Fig. 2(a) shows the modal damping ratios obtained in the first, second and third mode of the cable, when a damper is attached at $0.05L$ distance from the left support. It can be seen that, for all three modes, the maximum modal damping ratio is approximately $\zeta_1 = 2.7\%$, achieved for different device damping ratios, $\xi_{VD} = 3.2$ for mode 1, $\xi_{VD} = 1.6$ for mode 2 and $\xi_{VD} = 1.1$ for mode 3. This indicates that a device tuned to suppress vibration of the first