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Cables interconnected with tuned inerter damper for vibration mitigation

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ABSTRACT

Cables in cable-stayed bridges are susceptible to vibrations induced by wind, wind/rain and indirectly by bridge tower and deck vibrations. It is common practice nowadays to supplement cable damping through external devices. However, for long stay cables, the damping provided by near-anchorage dampers is no longer sufficient. A hybrid cable network consisting of both dissipative devices and cross-ties is found to be a promising solution in this scenario. This study further proposes to embed inerter components into cable networks to improve their dissipation capacity. Specifically, a system of two cables interconnected with a Tuned Inerter Damper (TID) is studied. The system dynamics is formulated via complex modal analysis and system complex frequencies are characterized via parametric analysis. General tuning principle has been found when using the TID to maximize single mode damping and an approximate method is presented for efficient determining the TID parameters for optimal tuning and the corresponding damping ratio. Furthermore, the advantage of proposed system is shown by comparing with other passive strategies for multi-mode cable vibration control.

1. Introduction

Cables are widely used in structural engineering because of their high axial strength-to-weight ratio, e.g. in cable-stayed bridges [1]. However, owing to their high flexibility in the lateral direction and low intrinsic damping, they are susceptible to vibrations excited through varied mechanisms, which commonly include wind, wind/rain induced vibrations, and oscillations indirectly excited by traffic- or human-induced deck vibrations [2,3].

It becomes common practice nowadays to install external damping devices for stay cables [2,4]. Those devices are preferable to be installed close to the cable-deck anchorage, for the convenience of installation and maintenance and also for the aesthetics of the cable-stayed bridge. The performance and optimal design of such near-anchorage dampers have been investigated comprehensively in the last decades [5–16]. The maximal damping effect of this strategy is found to be determined by the ratio between the damper installation distance from the closest cable anchorage and the total cable length, and hence it is unable to provide adequate damping for long cables where the relative damper location is particularly limited.

With increasing span of cable-stayed bridges and hence the cables, cable vibration control by cross-ties, initially proposed in 1990s [17,18], has received considerable attention during the last decade. Increased system damping and the importance of the secondary cable property were evident in earlier experimental and analytical studies on the damping effects of sagged-cables with secondary cables [19,20]. To understand basic dynamics of the cable networks for optimal design, the system was simplified as a set of interconnected truss elements and a general method was presented for formulating the characteristic equations by [21] and applied to investigate an existing cable stayed bridge [22]. Subsequent studies mainly focused on the influence of the mechanical property of the connections or so-called cross-ties and varied configurations on the dynamics of cable networks, based on this analytical approach. For example, a two-cable system connected with a rigid cross-link was studied in detail by [23], and effect of the cross-link stiffness on in-plane responses was considered in [24]. Nonlinearity of the cross-ties was investigated by [25–28]. The number of cross-ties as well as other key system parameters have been studied in the context of a more complex cable network [29–31]. To further increase the dissipation capacity of cable networks, hybrid techniques combining cross-ties and dampers

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have been proposed by [32–34]. A particular hybrid system of a two-cable system with near-anchorage dampers was considered by [35]. Complex hybrid cable networks with various configurations have also been studied in combination with filed measurements, with their effectiveness demonstrated by [36].

The aforementioned studies show that the cable network, especially of hybrid type, is a promising solution for vibration mitigation of long cables, however, due to the complexity of the system, further investigations are still in need for optimizing system performance. Particularly, it is of interest to explore novel hybrid techniques. Recently, Tuned Inerter Damper (TID) has emerged as a relatively new concept in structural vibration control for its superior performance over traditional Tuned Mass Damper (TMD) [37–41]. The use of inerter combined with viscous damper in mitigating cable vibrations was first introduced in [42–44], where the inerter-based device is installed between cable and bridge deck. The analysis thereof shows that the modal damping ratio obtained via TID can be higher than that achieved by a traditional viscous damper or TMD. It is nevertheless still subjected to the location constraint. Noteworthy is that the TID is a two-node device, making it easy to be embedded into cable networks. The introduction of inerter (mass) elements into the previous hybrid cross-ties composing of springs and dashpots can increase the deformation of the cross-ties and hence improve the system dissipation capacity. Therefore, the present study focuses on the dynamics of a two-cable system with a TID. Free vibrations of the system are investigated for understand the damping effect of such connections and optimal tuning.

The rest of this paper is organized as follows. First of all, the concept of TID is introduced, and it is then integrated into a two-cable network whose dynamic characteristic equation is obtained via complex modal analysis. Subsequently, complex frequencies of the system are characterized via parametric analysis, including the tuning principle. Furthermore, an approximate method is provided for determining the optimal damping effect and corresponding TID parameters. The proposed system is further compared with other passive strategies in the context of multi-mode cable vibration control. Lastly, the paper is closed with a conclusion.

2. Tuned inerter damper

The concept of inerter was first introduced into vibration absorption problem by [45]. One mechanical realization of the inerter is shown in Fig. 1, where the rack is sliding in the outer cylinder and driving the flywheel through pinions and gears. The force between the two terminals is generated by their relative acceleration as [45]

$$F = b(\ddot{z}_2 - \ddot{z}_1) \quad (1)$$

where b represents the inertance of the device and it is measured in kilogram, and $\ddot{z}_2$ and $\ddot{z}_1$ denote the accelerations at its two terminals. The overall inertance of the device depends on the rotational inertance of the flywheel as well as the gear ratio. Therefore, one apparent advantage of an inerter is that it is not subject to the limitation of traditional equivalence between mass elements and its energy absorbing capacity. The inerter is usually combined with spring and dashpot elements for energy absorption, resulting in a so-called TID [42,43], as shown inside the dashed box in Fig. 2 where k and c are the spring coefficient and damper coefficient respectively.

3. Problem formulation of a two-cable system with a TID

A two-cable system is formulated by connecting two adjacent cables with a TID, as depicted in Fig. 2. Following [21], the cables are modeled as taut flat strings without intrinsic damping [21], which is a reasonable simplification for highly tensioned cable stays and widely used for studying damped cable systems [7,9,22]. For each cable, m_j = cable mass per unit length and H_j = cable tension; L_j = cable total length; and the subscript j is cable index. Without loss of generality, it is assumed that $L_1 > L_2$. Each cable is divided by the TID into two segments indexed by p and with length l_j and $L_j - l_j$ respectively.

The governing differential equation for each cable segment is given as [9,21]

$$H_j \frac{\partial^2 y_{jp}}{\partial x_{jp}^2} = m_j \frac{\partial^2 y_{jp}}{\partial t^2}, \quad \text{for } p = 1,\ 2 \quad \text{and } j = 1,\ 2 \quad (2)$$

where $y_{jp}(x_{jp}, t)$ = lateral deflection and x_{jp} = coordinate along cable chord from each cable end, and t = time. Solution to the preceding equation can be generally expressed as $y_{jp} = Y_{jp}(x)\exp(\mathrm{i}\omega t)$ where $Y_{jp}(x)$ is the complex mode shape and $\exp(\mathrm{i}\omega t)$ denotes the time variation with system eigenfrequency ω and $\mathrm{i} = \sqrt{-1}$. Each segment has one fixed end, i.e. $y_{jp}(x_{jp} = 0, t) = 0$, so that the complex mode shape is simply expressed as [7,21]

$$Y_{jp} = a_{jp} \sin\left(\omega\sqrt{\frac{m_j}{H_j}} x_{jp}\right) \quad \text{for} \quad p = 1,\ 2 \text{ and } j = 1,\ 2 \quad (3)$$

where a_{jp} is coefficient. The displacement continuity of each cable at the connection and the force equilibrium between the two cables at the connection regardless of the cross-tie property give the following three equations [21]

$$y_{j1}(x_{j1} = l_j,\ t) = y_{j2}(x_{j2} = L_j - l_j,\ t) \quad \text{for } j = 1,\ 2 \quad (4)$$

$$H_1\left(\left.\frac{\partial y_{11}}{\partial x_{11}}\right|_{x_{11}=l_1} + \left.\frac{\partial y_{12}}{\partial x_{12}}\right|_{x_{12}=L_1-l_1}\right) + H_2\left(\left.\frac{\partial y_{21}}{\partial x_{21}}\right|_{x_{21}=l_2} + \left.\frac{\partial y_{22}}{\partial x_{22}}\right|_{x_{22}=L_2-l_2}\right) = 0 \quad (5)$$

The relative displacement of the two cables at the TID is denoted as

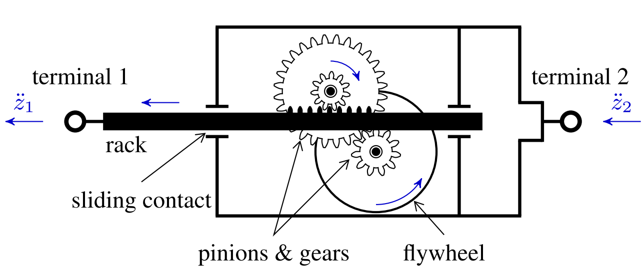

Fig. 1. Mechanical model of an inerter (modified from [45]).

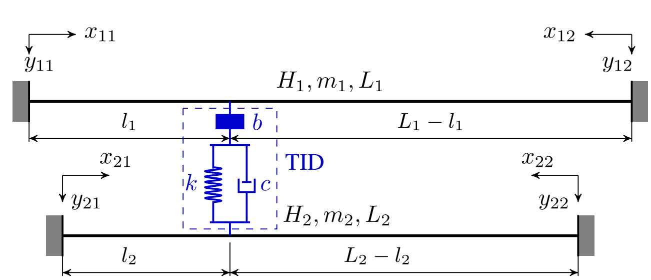

Fig. 2. Two cables interconnected with a TID.