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Dynamic characteristics of stay cables with inerter dampers

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ABSTRACT

This study systematically investigates the dynamic characteristics of a stay cable with an inerter damper installed close to one end of a cable. The interest in applying inerter dampers to stay cables is partially inspired by the superior damping performance of negative stiffness dampers in the same application. A comprehensive parametric study on two major parameters, namely, inertance and damping coefficients, are conducted using analytical and numerical approaches. An inerter damper can be optimized for one vibration mode of a stay cable by generating identical wave numbers in two adjacent modes. An optimal design approach is proposed for inerter dampers installed on stay cables. The corresponding optimal inertance and damping coefficients are summarized for different damper locations and interested modes. Inerter dampers can offer better damping performance than conventional viscous dampers for the target mode of a stay cable that requires optimization. However, additional damping ratios in other vibration modes through inerter damper are relatively limited.

1. Introduction

The increasing span of cable-stayed bridges increases the vulnerability of excessive oscillations under wind and traffic loads because of high flexibility and low damping level [1]. The suppression of cable vibrations using dampers (including passive, semi-active, and active dampers) was extensively investigated to prevent premature fatigue failure in stay cables and connections and ensure the serviceability and integrity of bridges. Dampers are usually installed close to the end of stay cables in the transverse direction.

As simple, practical, and reliable solutions, passive viscous fluid dampers are widely applied in vibration mitigation of stay cables. Systematic studies on the use of passive dampers to suppress cable vibration [2–9] showed that the optimal damping ratio offered by a passive linear viscous damper to a stay cable is capped by approximately one-half of the ratio of the distance from the cable anchorage to the damper over the entire length of the cable. Semi-active control techniques were proposed as more efficient solutions that can provide higher damping to stay cables than passive dampers do. Their control effectiveness has been proven through numerical [10–13] and experimental [14,15] investigations. Full-scale tests of semi-active dampers on stay cables were also conducted [16,17]. The performance of semi-active dampers was further evaluated through the comparison with the reference case of ideal active control [18–20]. However, despite their superior control performance,

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semi-active and active controls for stay cables require external power supply, sensor network, and controllers. System complexity hinders their widespread applications in civil structures.

An active actuator may produce a force–deformation relationship with a beneficial negative-stiffness feature [21] in some active control studies including the vibration mitigation of stay cables [19]. This fact has inspired the investigations of semi-active and passive negative stiffness dampers (NSDs) for stay cable vibration mitigation, which are sometimes called pseudo- and truly-NSDs, respectively. Webber and Boston [20] designed semi-active magnetorheological dampers to demonstrate negative stiffness behavior; their evaluation of vibration control performance in stay cables indicated that semi-active NSDs produced twice as much damping as conventional viscous dampers. Shi et al. [22] were the first to conduct analytical examination of the dynamic behavior of a taut cable with a passive NSD and found that a considerable damping ratio of stay cable can be achieved. Shi et al. [23] conducted a laboratory experiment of a scaled stay cable with a recently invented magnetic NSD [24,25]; in the experiment, a passive NSD can offer optimal damping ratio four times as large as that achieved by a conventional viscous damper. Other types of NSD, such as negative stiffness-generating pre-stressed springs plus oil dampers, were also tested and demonstrated to be able to achieve good control performances on stay cable [26]. The recent comparative study [27] indicated passive NSD can provide control performances comparable to active controllers.

Inerter dampers, as another emerging type of passive dampers, introduced a new concept of inertance into structural dynamics. Interest in the application of inerter dampers to stay cables was partially inspired by the similarity of force–deformation relationships between inerter dampers and NSDs (Fig. 1). Most of the past studies were focused on stay cable vibration mitigation using tuned inerter dampers (TIDs) [28,29] or more complex inerter-based vibration absorbers [30], where TIDs are typically a combination of inertance, spring and damping components with the system resonant frequencies tuned to a target value. Although inerter dampers consisting of parallel inertance and damping components show more similar behavior to NSDs, their applications to stay cables has rarely been discussed. The only reference was from Lu et al. [31] who adopted finite element method to investigate the optimal performance of inerter damper on stay cables and noticed the existence of optimal inertance and its corresponding optimal damping coefficient.

Despite the similar hysteretic loops produced by an NSD and an inerter damper, the following notable differences should be examined: (1) The introduction of negative stiffness into a host structure decreases the natural frequencies and amplifies static responses. Extremely strong negative stiffness may endanger structural stability. The addition of inertance to a system also decreases the natural frequencies, but it does not impair structural stability. (2) An inerter exhibits a negative slope in the force–deformation relationship, but this negative slope is dependent on excitation frequencies. Given these differences, the vibration mitigation mechanism of inerter dampers on stay cables remains unclear and warrants detailed analysis. This study presents a systematic analytical investigation on the dynamics of stay cables with inerter dampers installed close to the ends of a cable. To the best of the authors' knowledge, such an analytical study has not been reported in the literature. Compared with the past finite element study, the parametric study based on the analytical model in this paper provides more insight into the principle of inerter dampers for stay cable vibration mitigation. An optimal design method for inerter dampers is then proposed. The control performance of inerter dampers is verified through numerical simulations of dynamic cable responses.

2. Inerter damper

The concept of inerter was initially proposed by Smith [32] to complete the force-current analogy between mechanical and electrical networks. The force produced by an inerter is proportional to the relative acceleration between two terminals of the inerter; the proportionality constant is called inertance [33–35]. As an efficient tool in vibration suppression, inerter has been studied in various applications, such as vehicle suspensions [36], train suspensions [37], and building isolation systems [38,39]. By emulating the concept of tuned mass dampers (TMDs), researchers also developed a number of tuned networks with inerter, namely, tuned viscous mass dampers [40,41], tuned mass-damper-inerter systems (TMDI) [42], and tuned

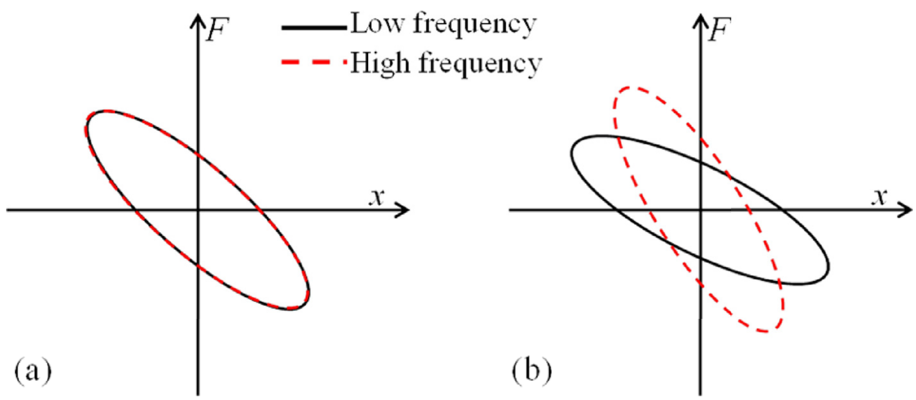

Fig. 1. Force-displacement of NSD and inerter damper. (a) NSD, (b) Inerter damper.