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Cable vibration control with both lateral and rotational dampers attached at an intermediate location

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A B S T R A C T

Lateral dampers have been extensively studied and implemented for supplementing modal damping in cable vibration mitigation. When considering the cable flexural stiffness that is actually present, albeit small, there is another degree of freedom of the cable at the lateral damper, namely the rotation, that can be constrained by a rotational damper to achieve larger additional damping. This is of particular significance for long cables where the near-anchorage lateral damper alone is usually insufficient. The problem of a cable with bending stiffness, attached with both lateral and rotational dampers at an intermediate point, is therefore considered in this study. The characteristic equation of the resulting system is formulated by assembling the dynamic stiffness from the two segments divided by the damper, which is subsequently solved using argument principle method. Dynamics of the controlled system is thus discussed in general through parametric analysis. For the case where the damper location is close to the anchorage, asymptotic solutions for complex frequency and damping ratio are provided; explicit formulas for determining the optimal damper coefficients are also derived. It is found that when the lateral and rotational damper coefficients are properly balanced, the proposed strategy can achieve up to 30 percent damping enhancement compared to the case with only the lateral damper, in practical cable bending stiffness range.

1. Introduction

1.1. Background

Several types of cable vibrations have been reported world wide in existing cable-stayed bridges [1,2]. One of the most effective and versatile countermeasures to-date is attaching mechanical damper near the cable-deck anchorage to supplement structural damping. The pertinent system has thus been intensively studied for optimal tuning of the damping device in the past three decades; such cable-damper systems are actually of broad interest, e.g. used as control device for wind turbine [3]. In the context of bridge engineering, relevant studies started from dealing with the ideal case where a

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Nomenclature

$\alpha_{()}, \theta_{()}$ dynamic displacement and rotation of cable segment at its ends, with subscript c denoting the damper location and 1 and 2 the cable ends
β =C, P, superscripts indicating clamped or pinned boundary condition
δ offset of the eccentric dampers
Δq increment of q caused by the dampers compared to the case of no damper attached
$\Delta\omega$ increment of ω caused by the dampers compared to the case of no damper attached
Δ_j determinant of dynamic stiffness matrix of tension beam segment j
γ relative cable bending to axial stiffness
$\hat{()}, \tilde{()}$ dimensionless quantities respectively normalized to cable or beam properties
i $\sqrt{-1}$, imaginary unit
ω complex frequency of the system
$\omega_{(o)}^{(j)}$ frequency of segment j when fully clamped at the damper and the second subscript indexes mode
$\omega_{01}^{S}, \omega_{01}^{B}$ fundamental frequency of a taut string or a pinned–pinned beam
Φ quantity in the explicit approximation of the optimal lateral damper coefficient
σ decay rate
ε_j, S_j, C_j shorthands of exponential and trigonometric functions for segment j
ξ_j dimensionless axial abscissa of segment j
ζ damping ratio
$a_{()}^{j}, b_{()}^{j}$ variables in mode shape function of segment j
c_d, c_r lateral, rotational damper coefficients
$F_d(t), M_c(t)$ damping force and torque
i_{01}, i_{12}, i_{02} indexes of three types of nodes of cable mode n
j cable/beam segment index
$k_{()}^{j}$ element of dynamic stiffness matrix of cable segment j, and its subscript denotes the entry
$L_{0n}^{()}$ coefficients defined in linearizing the left sides of the fixed-point iterative formats of characteristic equations and note $L_{0n}^{PP}=1$
l_j, μ_j length of cable segment j and its dimensionless form, with $j=0,1,2$
n vibration mode index and subscript indicating the value of corresponding quantity for mode n
$N_1(\xi_j), N_2(\xi_j), N_3(\xi_j), N_4(\xi_j)$ quantities in shape functions of tensioned beam element j
p, q frequency-related parameters of a tensioned beam
$P_2^{()}, R_2^{()}$ coefficients in expanding $Q_2^{()}$ for varied cases as indicated by their superscripts
$Q_j^{()}, Q_j^{(,)}$ quantities in system characteristic equations with superscripts indicating their physical relation to eigenfrequencies of cable segment j for varied supports and modes
r relative sizing of the rotational to lateral damper
t time
T, EI, m cable tension, bending stiffness and mass per unit length
U, V, D, N, A, B quantities in fixed-point iterative format whose definitions vary for different cases as indicated by the superscripts, and approximately evaluated at q_{0n} when shown with subscript $0n$
$W^{CC,}, H^{CC,}$ quantities in derivation of $V^{CC,}$ and $A^{CC,}$, respectively defined for even- and odd-numbered modes as denoted by the second superscript
$Y(\xi_j)$ non-dimensional mode shape function of the jth segment
$0n$, ∞n subscripts respectively indicating values of the quantity corresponding to zero and infinity large damper coefficients
APM argument principle method
C, P, G superscripts indicating clamped, pinned, or guided supports
opt superscript indicating the optimized value
S, A superscripts indicating odd- or even-numbered mode of cable for clamped supports

viscous damper is attached to a taut string near one support [4–7], and subsequently developed to treat a general problem where the restriction on damper location is relieved in the context of cable networks [8–10]. Also, cable parameters such as flexibility and sag, and damper complexity have been considered in more comprehensive modeling [11–21]. Currently, dynamics of a cable with one linear damper is understood to have the main limitation that the damper has to be installed quite close to the cable anchorage and hence the provided damping is insufficient in particular for long cables. To overcome this limit, active/semi-active cable vibration control has thus been intensively studied in recent years, mostly based on Magnetorheological damper, e.g. [22–29] to name but a few. Other emerging semi-active strategies are also promising to this end [30–32]. Within the realm of passive control, there are also available solutions, e.g., by introducing negative stiffness at the damper [33–37].

Noteworthy is that the presence of cable bending stiffness affects the performance of the cable-damper system in terms of damping enhancement. From the primary perspective, provided that the cable is clamped at both ends, the bending stiffness in practical range of most cable stays has a negative effect on the attainable damping supplemented by a near-anchorage lateral damper [13,38]. This is because the relative deformation at the damper is decreased owing to the higher bending stiffness and hence the dissipation effect is impaired. From an additional important perspective, the cable bending