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Experimental verification of the effectiveness of elastic cross-ties in suppressing wake-induced vibrations of staggered stay cables

Xuhui He[a,b], Chang Cai[a,b], Zijian Wang[c], Haiquan Jing[a,b,*], Chengwen Qin[d]

[a] School of Civil Engineering, Central South University, Changsha 410075, China
[b] National Engineering Laboratory for High Speed Railway Construction, Changsha 410075, China
[c] Department of Dam Safety Management, Nanjing Hydraulic Research Institute, Nanjing 210029, China
[d] High Speed Railway Section, Guangzhou Railway (Group) Corporation, Guangzhou 510030, China

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ABSTRACT

In the present study, two pairs of cable models were specially designed and tested to reproduce wake induced vibration (WIV) of stay cables in a wind tunnel. The interaction between multi-modes and the flexibility of the stay cables were considered. The downwind cables experienced large vibrations beyond a critical wind speed, similar to classical galloping. The response characteristics in terms of vibration amplitude, frequency, and trajectory were investigated in detail. The observed tendency of the increase in vibration frequency with increasing wind speed is adequately consistent with the previous studies. Finally, elastic cross-ties were vertically installed and connected two neighboring cable models in an attempt to suppress WIV. The wind tunnel tests demonstrated that the elastic cross-tie modified the single-mode dominated WIV into a type of chaotic multi-mode vibration and successfully reduced the vibration amplitude by ~74%. The reason why the elastic cross-tie suppressed RWIV was qualitatively discussed. The scale ratio of the cross-tie stiffness was derived for engineers. Consequently, for the first time, the elastic cross-tie was proposed and verified to be effective to suppress the WIV of stay cables.

1. Introduction

The study of flow-induced vibration (FIV) of cables in a group can be traced back to the first half of the 20th century [12]. Wake-induced vibration (WIV) of two circular cylinders has been a topic of concern for several decades, and plenty of wind tunnel tests and water channel tests have been conducted to investigate their flow patterns, aerodynamic/hydraulic forces, response characteristics, and excitation mechanisms. Zdravkovich [54], Zdravkovich [55], Sumner [47], and Bearman [9] conducted comprehensive reviews about the progress achieved before 2010.

The flow pattern of two circular cylinders plays a crucial role in the understanding of the concept of WIV. Igarashi [32], Igarashi [33] first investigated the flow field of two tandem circular cylinders in a wind tunnel utilizing pressure measurement and flow visualization methods. The center-to-center pitch ratio L/D, where L is the center-to-center pitch and D is the cylinder diameter, was varied from 1.03 to 5.0. They classified the flow field into six patterns [for detailed information, refer to the studies by Ljungkrona [41], Assi et al. [5], and Sumner [47] with respect to the L/D and Reynolds number ($R_e = UD/\nu$, where U is the incoming wind speed and ν is the kinematic viscosity). Then, Zdravkovich [55] subdivided these flow patterns into three basic types: (1) single bluff-body behavior ($1.0 < L/D < 1.2$–1.8), where the downstream cylinder is located in the vortex formation region of the upstream and the two cylinders behave as a single bluff body; (2) shear layer attachment behavior (1.2–$1.8 < L/D < 3.4$–3.8), where the shear layer from the upstream cylinder reattaches on the surface of the downstream cylinder; and (3) vortex shedding from each cylinder (3.4–$3.8 < L/D$), where the vortex shed from the upstream cylinder develops in the gap and the downstream cylinder is periodically impinged by the vortices. Similar classifications were proposed by Xu et al. [51] and Zhou and Yiu [60]. They referred to these three types of flow patterns as "extended-body regime" ($1.0 < L/D < 2.0$), "reattachment regime" ($2.0 < L/D < 5.0$), and "co-shedding regime" ($5.0 < L/D$), respectively, and further subdivided the "reattachment regime" into "after-body attachment regime" and "fore-body attachment regime." In the "after-body attachment regime," the shear layer of the upstream cylinder reattaches on the rear surface of the downstream cylinder, whereas in the "fore-body attachment regime" it reattaches on the leading surface. Carmo et al. [13], Carmo et al. [14] expressed similar concepts through numerical simulation at low R_e. These flow patterns were verified through flow visualizations by Ljungkrona and

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[*] Corresponding author at: School of Civil Engineering, Central South University, Changsha 410075, China.
E-mail address: hq.jing@csu.edu.cn (H. Jing).

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Sundén [42], Lin et al. [43], and Zhou and Yiu [60]. Gu and Sun [26] classified the flow field around staggered cables into three patterns, namely wake, shear, and neighborhood interference, based on the pressure measurement and flow visualization. Sumner et al. [49], Sumner et al. [48] also investigated the flow features of staggered cylinders utilizing particle image velocimetry (PIV) and videos of flow visualization techniques and classified the flow field around the staggered cylinders into nine patterns.

The aerodynamic/hydraulic force coefficients of two circular cylinders are significantly more complicated than those of a single cylinder. Zhang and Melbourne [58], Alam et al. [1], and Sumner and Schenstead [50] summarized the variation characteristics of the aerodynamic/hydraulic force coefficients of cylinders in tandem arrangement. There is a sharp increase in the aerodynamic/hydraulic force coefficients of cylinders at separations of 3.5D to 3.8D, depending on R_e. These separations were referred to as the drag-inversion separation. Zdravkovich [55], Gu and Sun [26], and Carmo et al. [13] explained that the discontinuity of the aerodynamic/hydraulic force coefficients of the cylinders was caused by the shift in flow pattern. Recently, Assi et al. [5] reported several detailed maps of the means and fluctuations of the drag and lift force coefficients of a downstream cylinder.

Both flexible and rigid models have been employed to investigate the response characteristics of WIVs. The experiments with flexible models mainly focused on the characteristics of vibration amplitude, velocity range, and dominant frequency [40], whereas the rigid model experiments were more motivated by the original reasons of WIV. King and Johns [39] conducted water channel tests with two flexible circular cylinders in tandem arrangements and measured the responses of both the cylinders. Both cylinders were free to vibrate parallel and transverse to the wind direction. They observed that the upstream cylinder response was similar to the VIV of a single cylinder for large L/D, whereas the downstream one displayed large vibration after the lock-in range. They defined the downstream cylinder response as a type of buffeting. Huera-Huarte and Bearman [28] and Huera-Huarte and Gharib [30] also investigated the WIV of two long flexible cylinders. Both cylinders are free to respond parallel and transverse to the wind direction. They observed that for the near-wake interference ($2.0 < L/D < 4.0$), the cylinders experienced three types of oscillation: VIV, WIV, and combinations of both; meanwhile, for the far-wake interference ($4.0 < L/D < 8.0$), the downstream cylinder mainly experienced WIV and exhibited large amplitudes at higher reduced velocities. Brika and Laneville [11] investigated the response of a flexible cylinder immerged in the wake of a rigid cylinder in a wind tunnel. The L/D ratio was changed from 7D to 25D, and R_e ranged from 0.5×10^4 to 2.7×10^4. They reported that the downwind cylinder response was not hysteretic, and the synchronization occurred at higher reduced velocity and covered a wider range. Recently, Huera-Huarte et al. [29] measured the vibration responses of a flexible downstream cylinder behind a stationary one. They observed higher multi-mode vibrations and synchronization regions according to different structural modes. They concluded that L/D does not exert strong influence on the vibration frequency and amplitude, whereas the incoming wake enhanced the vibration amplitude to a considerable extent.

For the rigid models, Bokaian and Geoola [10] conducted experiments in a water channel and investigated the WIV of two circular cylinders in tandem arrangement. The upstream cylinder was static, whereas the downstream one was elastically mounted and was free to respond in the transverse direction. They observed that the vibration of the downstream cylinder could be “a vortex-resonance, galloping, combined vortex-resonance and galloping, or separated vortex-resonance and galloping” depending on the separation width and structural damping. Zdravkovich [56] also utilized rigid models to investigate the responses of two rigid circular cylinders ($L/D = 4.0$) in a wind tunnel. Both cylinders were free to respond parallel and transverse to the wind direction. Because $m^*\xi$ (m^* is the mass ratio, ξ is the damping ratio) was relatively large, he observed large vibration only when the reduced wind speed ($U_r = U/Df_0$, where U is the incoming wind speed and f_0 is the vibration frequency) was above 50, and the maximum displacement of the downstream cylinder asymptotically reached 1.7D at a reduced wind speed of 80. Zdravkovich and Medeiros [57] then conducted similar wind tunnel tests and investigated the effects of $m^*\xi$. They concluded that it was challenging to suppress the WIV with increasing $m^*\xi$. Subsequently, Hover et al. [31] utilized a closed-loop control system to measure the forces and displacements of two rigid cylinders in a water channel. They observed that large vibration occurred for all flow velocities higher than a critical threshold and for a separation of $L/\mathrm{D} = 4.75$; the vibration amplitude reached 1.9D under the reduced wind speed of 17. Recently, Assi et al. [8], Assi et al. [5] measured the responses of a pair of rigid cylinders in a water channel. The upstream cylinder was fixed, whereas the downstream cylinder was free to respond in the transverse direction. Their results approximate that measured by Hover et al. [31]. They observed that the WIV of the downstream cylinder did not occur in the absence of the unsteady vortices. Moreover, Chaplin and Batten [18] developed a special experiment setup, which permits the rigid downstream cylinder free to simultaneously undergo wake- and vortex-induced vibrations in multiple modes. They concluded that the feature of the flow–structure interaction is likely to be significantly influenced by the participation of higher modes or multiple direction vibrations.

Compared with the classic Karman vortex-shedding-induced vibration [19] and rain-wind induced cable vibration [35,37,36], the excitation mechanisms of circular cylinders in a group are significantly more complicated. The investigations on the subject mainly focused on explaining the original causes of the excitations of the downstream cylinder. Zdravkovich [54] proposed a wake-displacement mechanism, wherein “*the displacement of the wake of the upstream cylinder by the downstream one, toward the wake centerline would induce a lift force toward the centerline*”. However, he did not explain the phase lag between the lift force and vibration displacement, which was necessary to maintain the cable vibrations as emphasized by Mysa et al. [44]. Recently, according to numerical simulations at low Reynolds numbers, Carmo et al. [14] indicated that the physical mechanism of the difference between WIV and VIV was related to the oscillatory flow in the gap, “which caused the front stagnation point of the downstream cylinder to shift alternatively along the upstream portion of the cylinder wall.” Assi et al. [5], Assi et al. [7] further investigated the mechanism of WIV in a water channel and determined that the WIV could not be excited in the absence of the unsteady vortices shed from the upstream cylinder. They concluded that the WIV should be excited by the unsteady vortex-structure interaction between the upwind wake and the downwind cylinder, and the quasi-steady assumptions, used in classical galloping theory [20,59], is not likely to be suitable for the WIV. Bearman [9] expressed a similar concept. Assi et al. [6] then observed large amplitude WIVs notwithstanding the absence of structural stiffness and proposed a new concept “wake stiffness” to explain the characteristics of the displacement and frequency of the WIV. They concluded that “the restoration force provided by wake stiffness is adequately strong to balance the flow excitation and produce oscillation motion for a system without structural stiffness.” However, they also indicated that although the wake stiffness could reasonably predict the characteristics of the WIV both in terms of displacement and frequency, it could not adequately explain the excitation mechanism of WIV.

These summaries of previous studies reveal that substantial efforts had been undertaken on the flow patterns, aerodynamic/hydrodynamic forces, response characteristics, and the original causes of the WIV of tandem/staggered stay cables. A majority of these studies simplified the stay cables as two rigid cylinders, and the movements of the downstream stay cables were restricted to a single-degree-of-freedom vibration or double-degree-of-freedom vibration. These are likely to be different from the actual situations of the stay cables. Moreover, to the present authors’ knowledge, study on the suppression of wake-induced