Assessment of cross-tie performance in mitigating wind and rain-wind-induced stay cable vibrations

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ABSTRACT: Cross-ties are often used to mitigate wind- and rain-wind-induced vibrations of stays of cable-stayed bridges. Due to the limitations in the understanding of the vibrations and the dynamics of cable networks, however, they have been designed in the past with few if any guidelines. It is therefore unclear whether the cross-ties so designed are effective or efficient in suppressing the vibrations. To assist future design of cross-ties, this paper reviews the dynamics of cable networks and, in this context, uses long-term full-scale measurement data to evaluate the performance of cross-ties in mitigating wind- and rain-wind-induced vibrations.

KEYWORDS: Stay Cable; Rain-Wind-Induced Vibration; Cross-tie; Cable Network.

1. INTRODUCTION

Wind- and rain-wind-induced vibrations have been a long-standing problem for stays of cable-stayed bridges. Although the mechanisms of the vibrations still remain to be fully understood, a number of mitigation strategies have been developed based on current understanding. These include attachment of dampers in the vicinity of the stay anchorages to supplement the low level of inherent damping (e.g., Pacheco \textit{et al.}\textsuperscript{1}, Main \& Jones\textsuperscript{2}), modification of cable surface to prevent the formation of water rivulets (e.g., Fujino\textsuperscript{3}) and connection of different stays with secondary transverse cables (cross-ties) to redistribute vibration energy within the cable-network formed (e.g., Ehsan \& Scanlan\textsuperscript{4}). In particular, cross-ties have been frequently used since they are considered easy to implement and maintain. To the present date, however, the design of cross-ties and the configuration of cable networks have remained largely based on experience from practice (e.g., Virlogeux\textsuperscript{5}) but not adequate theoretical guidance. To address this issue, analytical formulation was developed to enable quantitative evaluation of the mode shapes and frequencies of cable networks in the in-plane direction (Caracoglia \& Jones\textsuperscript{6} and Caracoglia \& Jones\textsuperscript{7}). In the context of dynamic analysis based on this formulation, this paper interprets the observed performance of cross-ties in mitigating wind- and rain-wind-induced vibrations.

2 THE FRED HARTMAN BRIDGE AND THE INSTRUMENTATION SYSTEM

The study herein is based on data recorded on the Fred Hartman Bridge in Houston, Texas, USA. This bridge is a twin-deck cable stayed bridge with two parallel main spans of 381 m in length. The main spans and the four side spans are supported by 192 stays ranging from 59 m to 198 m in length. To suppress wind- and rain-wind-induced vibrations, both passive viscous dampers of various types and cross-ties have been installed on the stays of the bridge. To study the nature of...
wind- and rain-wind-induced stay cable vibrations and to evaluate the performance of countermeasures in mitigating these vibrations, a full-scale measurement system was installed on the bridge in October, 1997 and since then continuously monitored the bridge until August, 2005. More structural details of the bridge and the configuration of the monitoring system can be found in previous publications of the authors (e.g., D. Zuo & Jones\textsuperscript{8}). In the subsequent sections, cable vibrations recorded with and without cross-ties will be used to assess the performance of this type of mitigation system.

3 SIMULATION AND INTERPRETATION OF THE MODAL BEHAVIOR FOR CABLE NETWORKS

As an example, Figure 1 depicts a typical cable plane, the B-Line stay system (South Tower), on the bridge. Two cable networks are currently present on these stays, labeled as BSU (upper network) consisting of stays BS17 to BS24 connected by three restrainers, and BSL (lower network) between stays BS13 to BS15 with one group of cross-ties.

The simulation of the modal behavior of the cable networks was performed through an analytically-based and numerically-implemented technique for the solution of the free-vibration problem associated with systems of in-plane interconnected cables (Caracoglia & Jones\textsuperscript{6}). This technique simulates the free-vibration dynamics of each cable segment delimited by either two connectors or one connector and anchorage to ground through linear taut-cable theory. Cross-ties are represented through linear springs.

In the analysis, a reference stay is selected with angular frequency $\omega_{01}$. The transverse motion of each $jp$ element (Figure 1) is assumed as periodic in the form of $y_{jp}(x_{jp},t) = Y_{jp}(x_{jp})e^{i\omega_{0j}t}$, in which $\alpha$ is the dimensionless frequency of the network, $x_{jp}$ is the coordinate along the axis of the $jp$ segment, $t$ the time, $Y_{jp}$ the real modal amplitude and $i$ the imaginary unit. Quantities $\omega$ and $Y_{jp}$ are determined from eigenvalue-eigenvector analysis after representing the modal form through trigonometric functions $Y_{jp}(x_{jp}) = A_{jp} \sin(\alpha \pi L_j f_j x_{jp}) + B_{jp} \cos(\alpha \pi L_j f_j x_{jp})$, with $f_j = \omega_{0j} / \omega_{0j}$ and $L_j$ being the length of the $j$-th stay. The method also accounts for three-dimensional orientation of each segment.

Figure 2 depicts the mode-frequency evolution chart of the B-line BSU (triangle symbol) and BSL (cross symbol) networks. In this figure the frequencies of the two networks are also
compared with those of the individual stay, in particular including BS16 which was mitigated with a viscous damper but not in the BSU network. Two examples of modal solutions for a global and a localized mode are indicated in Figure 3a and 3b. Modal amplitudes are scaled in order to highlight the localized behavior (if present).

Cable network frequencies are in general higher than the corresponding quantities associated with the longest individual cables. Another feature of these systems is associated with the distinction between the fundamental global modes (i.e., contribution from all elements), such as BSU_NM01 in Figure 3a with frequency 0.89 Hz, and a large number of localized modes at higher frequencies (modal plateau), for which only portion of the network is actively involved. The latter aspect is evident in Figure 3b, in which BSU_NM04 with frequency 1.93 Hz and dominated by the vibration of BS21, is depicted.

Figure 2 Mode-frequency evolution curves of the central-span B-line (south tower) of the Hartman Bridge. NET_BSU ( ) upper network (BS17 to BS24); NET_BSL ( ) lower network (BS13 to BS15). Individual stays: BS24 ( ), BS23 ( ), BS22 ( ), BS21 ( ), BS20 ( ), BS19 ( ), BS18 ( ), BS17 ( ), BS16 ( ), BS15 ( ), BS14 ( ) , BS13 ( ).

Figure 3 Examples of modal solutions for the upper cable network of the central-span B-line (south tower) of the Hartman Bridge. (a) global mode BSU_NM01, (b) localized mode BSU_NM04.

Increment in the frequencies corresponding to the modal plateau in Figure 2 can be achieved through non-uniform spacing among restrainers, i.e., for diagonally oriented ties, non-orthogonal
to the longitudinal axis of the cables. This design solution reduces the number and combinations of closely-spaced frequencies. In addition, interaction of the global in-plane network modes with deck modes is conceivable; Liu et al.⁹ have shown that this dynamic behavior is possible for the basic case of deck-stay interaction. Finite element analyses suggest, for example, the presence of a lateral deck mode with non-negligible modal contribution of the towers in the close vicinity of the fundamental frequency of BSU (Ozkan¹⁰). Nevertheless, the behavior described above seems excluded in the case of BSU. In fact, mutual interaction is possibly anticipated with an out-of-plane stay vibration, which is marginally influenced by restrainers.

Out-of-plane oscillation of individual cables cannot be excluded due to the limited performance of the restrainers in the lateral direction. Since the modeling and simulation of this behavior was not directly possible through the analytical approach, a comparison with full-scale measurements was proposed and will be summarized in Section 4.

Finally, the overall frequency increment for the lower network, BSL in Fig. 1 (disconnected from BSU) is adequate for mitigation purposes, with the location of the modal plateau consistently above 2.6 Hz. Since most of the frequencies of BSL are above 3.0 Hz and the excitation of the cable network by wind-and wind-rain mechanisms are much less frequent in this frequency interval.

4 ANALYSIS OF FULL-SCALE DATA AND AMBIENT VIBRATION PERFORMANCE ASSESSMENT

The full-scale measurement system on the Fred Hartman Bridge recorded a number of types of stay cable vibration, including the classical low-amplitude Kármán-vortex-induced vibration, the so-called rain-wind-induced vibration and a class of large-amplitude dry cable vibration over a range of high reduced velocity. It was observed that due to the three-dimensional nature of the wind-stay environment, these vibrations can have multiple modal components and that the vibration in the individual modes can have significant components in both the in-plane and out-of-plane directions (Delong Zuo et al.¹¹, Delong Zuo & Jones¹²). In addition to the vibrations induced by the direct excitation of wind or the combination of wind and rain, full-scale data suggest that wind-induced oscillation of the bridge deck can also lead to large-amplitude vibration of the stay cables due to the interaction between the decks and the stays, when the frequency of the deck oscillation and that of a stay mode are close and the phenomenon of frequency curve veering occurs (Liu et al.⁹).

Full-scale data suggest that the cross-ties installed on the stays were generally effective in preventing the onset various types of wind- and rain-wind-induced vibrations. As an example, Figure 4a shows the root-mean-square (RMS) vibration amplitudes of stay AS1 recorded from October 1997 to September 1998, before the crossties were added, and Figure 4b shows the vibration amplitudes of the same stay from May 1999 to December 2003, when AS1 was interconnected to a number of other stays with crossties. A reduction of vibration amplitude by the cross-ties is apparent.
A problem with the current application of cross-ties, however, is that the localized modes of the cable networks, such as those shown in Figure 3b, are often overlooked in design. Figure 5 shows modal vibrations (modes of the cable without cross-ties attached) of significant amplitude for stay AN24 after it was connected to adjacent stays. This figure suggests that while the cross-ties successfully suppressed vibrations in many of the lower modes of the stay, they appeared ineffective in mitigating vibrations in the 4th and the 8th modes. This ineffectiveness of the cross-ties is due to the fact they are evenly spaced and tied to stay AN24 at locations very close to the nodal points of the 4th mode so that modes 4, 8, 12 etc. of this stay remain as localized modes of the cable network and that therefore motions in these modes are essentially not restrained by the presence of cross-ties.

Another often overlooked limitation of cross-ties is, as described above, that they are essentially a mechanism in the in-plane direction and that their effectiveness is marginal in the lateral direction. Figure 6 shows the time histories and power spectra of the responses of stay AS18 in the in-plane (z) and lateral (x) directions for an example record, when the stay was mitigated with cross-ties. When not restrained, the fundamental frequencies of this stay in the in-plane and lateral directions are both about 1.0 Hz. For this record, while the response in the in-plane direction has significant frequency components in two local stay modes (when the stay is unrestrained, 2.08 Hz and 3.07 Hz) and a localized mode (2.29 Hz) of the network (modal plateau in Figure 2) due to the presence of the cross-ties, the response in the lateral direction only
has a component in a local stay mode. This suggests that the effect of the cross-ties is only present in the in-pane direction, but not the lateral direction. Such ineffectiveness of the cross-ties in the lateral direction can also be seen in the statistics of recorded vibrations. For example, Figure 7a shows the RMS vibration amplitudes of stay AS20 while it was inter-connected to a number of adjacent stays with cross-ties. Cluster A in the graph represents quasi-static vibrations of the stay due to deck oscillation (Liu et al.), and cluster B represents rain-wind-induced vibrations associated with wind approaching in a direction very close to the projection of the cable axis in the horizontal plane. While the quasi-static vibration is not a matter of primary concern, the rain-wind-induced vibration in the lateral direction is problematic since the restraint by the cross-ties is limited in this direction. Also, Figure 7a indicates that large-amplitude lateral vibrations did not occur often for stay AS20. This is, however, due to that fact that at the Fred Hartman Bridge, simultaneous occurrence of rain and significant wind approaching in directions close to the bridge axis were not observed often. For stays located in an environment where wind directions are close to the axial directions of the stays, this ineffectiveness of cross-ties can be more problematic.

The limitation of the cross-ties in the lateral direction has also manifested itself in the inability of the cross-ties in suppressing deck-induced stay cable vibration in the lateral direction. Figure 7b shows the vibration locus of stay BS24 during an event when the deck was oscillating in its
third vertical mode at about 0.57 Hz, which is close to the fundamental frequency of this stay (Liu et al\(^9\)). Although the deck oscillation was in the vertical direction, it can be seen that the vibration of stay BS24 is more significant in the lateral direction than in the in-plane direction. This lateral vibration of stay BS24 is believed to be induced by deck-induced quasi-static oscillation of the adjacent stays (BS 17 to BS23) in the cable network shown in Figure 1, whose vertical planes are not coincident with that of BS24 because of the three-dimensional layout of the cables on this bridge. It can be inferred that when the oscillation of the deck does have a lateral component, such as in the case of oscillation in the torsional modes, the ineffectiveness of the cross-ties can be more pronounced.

![Figure 7](image.png)

Figure 7 Examples of cross-tie inadequacy in suppressing lateral vibration: (a) Displacement amplitude of stay AS20 after installation of cross-ties; (b) vibration locus of stays BS24 under the excitation of deck oscillation.

5 CONCLUSIONS

In the context of a dynamic model of cable networks, this paper uses long-term full-scale measurement data to evaluate the performance of cross-ties in mitigating wind- and rain-wind-induced stay cable vibrations. Dynamic analysis suggests that cable networks have global modes that involve simultaneous participation of the stays in the network, which is difficult to excite, as well as localized modes that involves individual cables only. According to full-scale data, when properly designed, cross-ties are effective in mitigating vibrations of various types, except when the vibrations are primarily in the lateral direction, in which the effectiveness of the cross-ties are inherently limited. Field observations also suggests that if some localized modes of cable networks coincide with unrestrained modes of the corresponding stays, cross-ties will be ineffective in suppressing vibrations in these modes. It is recommended therefore that cross-ties should not be designed to be evenly spaced.

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