Insights into the Understanding of Stay Cable Vibration

Nicholas P. Jones
Dean, Whiting School of Engineering
Johns Hopkins University, Baltimore, USA
npjones@jhu.edu

Introduction

Cable-stayed bridges have frequently exhibited large-amplitude vibrations of the main stays, frequently associated with the simultaneous occurrence of wind and rain. These vibrations have been of concern because they potentially induce fatigue in the cables and cable anchorages. Early research on excitation mechanisms had generally been conducted using wind tunnels, and several distinct aerodynamic mechanisms were proposed. While considerable progress has been made in understanding and mitigating these vibrations, the state of the art has still not enabled the prediction of field behavior based on a set of supplied parameters, nor does a plausible, fully accepted model exist for the phenomenon.

This presentation will summarize recent research efforts that have attempted to advance the state of understanding of this complex fluid-structure interaction problem. Both early efforts and recent investigations – primarily based on the collection and interpretation of comprehensive full-scale data – will be considered. In presenting these perspectives, focus will be placed on the use of a combined approach comprising observation, full-scale and laboratory (wind tunnel) investigations, analysis, and computational tools to develop understanding of aspects of this phenomenon and its mitigation, with it often being necessary to question past assumptions or assertions on the part of researchers and designers. The overall goal of these efforts has been to better understand the mechanics of stay-cable vibration at a more fundamental level and enabling the recommendation of more effective and economical mitigation strategies.

Stay-Cable Vibration

Development of a comprehensive understanding of stay cable vibration has been a particularly challenging and elusive goal. Over the past two decades, considerable efforts by many researchers in many countries have contributed greatly to the advancement of the understanding of this phenomenon. Along the way, much has been learned, but there have also been examples of misinterpretation of observations or applications of controlling limiting assumptions that have at times misdirected these efforts.

Part of the challenge is that early reports were frequently qualitative, or based on limited quantitative data, and it was not until the results from comprehensive experimental efforts at full scale or in the laboratory were available that important insights could be developed. Subsequent analysis and modeling, including computational modeling has progressively revealed a number of important understandings, including the following.

- Initial observations suggested that the motion was simple in-plane one-dimensional oscillation. Analysis revealed that the motions were two-dimensional loci in the plan perpendicular to the stay, and – as they contained multiple frequency components – were often complex patterns.

Frequency decomposition resulted in better understanding of these underlying vibrational characteristics.

- Stay cables usually cover a large spatial extent in the vertical direction. This three-dimensional environment means that stays can be excited by different mechanisms in different modes at different locations, adding complexity to the observed data.
- That there are many types and sources of large- and moderate-amplitude stay cable vibration. Careful analysis reveals that many of these types can be grouped by common characteristics e.g., frequency and amplitude patterns. Proper interpretation and understanding required that these different types be grouped to facilitate understanding.
- Deck-induced vibration has been implicated as a cause of large-amplitude oscillation. This has been demonstrated to be a plausible mechanism, but simplistic approaches that treat the stays as cables or strings with end support excitation do not capture the true nature of the interaction between the superstructure and cable system.
- Much wind tunnel modeling of yawed and inclined stays has been conducted, with few exceptions as section models. Two concerns about this modeling approach emerge:
    - Three-dimensional effects associated with the end condition can have a major influence on the flows around the section model; and
    - The modeling of simulated water rivulets using fixed protuberances does not necessarily faithfully capture prototype conditions.
- Most modeling of the large-amplitude stay-cable vibration phenomenon is based on two-dimensional flow structures and models extrapolated into three dimensions. This approach does not capture the fully three-dimensional flow structures that have been observed in the wind tunnel and verified with computational modeling.
- Interpretation of data and modeling focused on the assumption that the large-amplitude oscillations occurred only with a combination of wind and rain. Careful mining of full-scale data demonstrated that while these events often occurred with rain, that rain was not always necessary for their occurrence. Thus it appears that rain is a facilitator, but not necessary for these occurrences.

Dampers

Dampers have been popular mitigation devices for many years, and there are examples of successful installations of damper-based systems around the world. There are also examples of installations that have failed for reasons that are not always clear, leading one to conclude that the systems were design and/or installed without a full understanding of the performance expectations.

Examples of areas where misunderstanding or misinterpretations have been evident include the following:

- Misunderstanding of the damper universal curve. The addition of a linear damper to a linear string or cable system results in a linear system, albeit one that is complex to analyze. As the damper constant is increased from zero to a large value, there is an optimal point at which the damper provides maximum damping capability. Beyond this point, the damper decreases in effectiveness. While well understood by researchers, this is sometimes not fully understood by others (e.g., designers). Doubling a damper constant may or may not result in improved effectiveness, depending on where on the optimal curve the damper lies.

- Manufactured dampers are not always linear in their characteristics, even if assumed to be that way in design. Specifications must articulate the degree of nonlinearity that is acceptable for the performance of the damper to be consistent with what was predicted in the analysis. These nonlinear effects include static friction as well as deviations from a linear force-velocity curve. If the characteristics of the damper are known and understood, they can be taken advantage of in the design, in some cases leading to better performance characteristics than a linear damper.

Cross-Ties

Cross-ties or aiguilles have also been popular systems for the control of stay-cable vibration. As with dampers, there are many instances of successful implementation of cross-tie-based mitigation systems, but also other examples of failures. Addition of cross ties to a cable arrangement results in a new, complex dynamical system that must be carefully and fully understood for successful deployment of this type of mitigation approach. A number of common misunderstandings have been demonstrated in the past, including the following:

- There is limited or no benefit to mitigation of vibrations in the lateral direction. This is expected, and has been confirmed with measurements.
- A cross-tie system, unless specifically designed to be so with the addition of dampers, are not an energy-dissipating system.
- Cross ties can be very effective in mitigating large amplitude oscillations in lower (global) modes of the coupled system. This is in part due to shifting of frequencies, but in large part due to the large increment in modal mass that results when the stays are linked together.
- In addition to the modified fundamental modes, the coupled system exhibits a large number of localized vibration modes that are more difficult to control as they can occur on individual stays between the cross ties anchor points. This is often overlooked by designers.
- A related issue is that symmetric configuration of the ties may not a good practice. It is noted that if cross-ties are designed to reduce sag effects in the stays, they are usually symmetrically placed. However, for the dynamic circumstances, the in-plane antisymmetric mode of an individual cable is not suppressed.
- Hybrid cross-tie-damper systems are even more complex, and must be analyzed as coupled systems with supplemental dampers. Adding cross ties to a stay configuration changes the dynamic characteristics completely and can render the dampers ineffective or in some instances vulnerable to damage if they become inadvertently expected to damp global cable network modes.

Closing Remarks

Great progress has been made in furthering the understanding of large-amplitude stay-cable vibration over the past two decades. Much of this progress has been made through careful measurement and analysis of full-scale field data, which has revealed many inconsistencies in the way in which past qualitative and quantitative data had been interpreted. In both understanding of the basic phenomenon, as well as in understanding the performance of mitigation systems, it became evident that preconceived notions about performance and assumptions in some instances clouded rather than aided the advancement of understanding.

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