Mitigation of Stay Cable Vibration – State of the Art

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ABSTRACT: Stay cables exhibit considerable lateral flexibility and possess very low inherent damping. These two factors make the stay cables susceptible to oscillation build-up due to a number of potential mechanisms. Since its discovery in the 1980's, the rain/wind mechanism of stay cables has elevated mitigation of cable vibrations as a major design issue. This paper discusses the background, latest developments, and a recent study aimed at formulating guidelines for the designer.

INTRODUCTION

Cable-stayed bridges have been firmly established as the most efficient and cost effective structural form in the 500-ft to 1500-ft span range in most applications. The cost efficiency and the signature visual quality of the cable-stayed bridges has led to its widespread popularity around the world, with increasingly longer spans being planned and constructed, employing increasingly longer stays.

The stay cables are laterally flexible structural members with very low fundamental frequency and very little inherent damping. Further, the fundamental frequencies of the assortment of cables in a given bridge and their higher modes form a practical continuum of frequencies encompassing the range of external excitations encountered in bridge structures. For this reason, the stay cables have been known to be susceptible to a range of excitations, varying from those encountered during construction, wind, rain/wind, wake effects, and certain parametric excitation conditions.

Recognition of this susceptibility of stay cables led to the incorporation of some mitigation measures on several of the earlier structures. These included cable cross-ties that effectively reduce the free length of cables (increasing their frequency) and external dampers that increase cable damping. Perhaps due to the lack of widespread recognition of the stay cable issues by the engineering community and the supplier organizations, the application of these mitigation measures on early bridges appear to have been fairly sporadic.

During the mid 1980's to mid 1990's, a number of early cable-stayed bridges were observed exhibiting large stay oscillations under certain environmental conditions. From field observations it became evident that these vibrations were occurring under moderate rain combined with moderate wind conditions, and hence were referred to as rain/wind vibrations. However, those bridges incorporating cable cross-ties or external dampers have generally performed well. While these measures were incorporated prior to a full understanding of the issues and development of any criteria or design methods, their implementation as a 'good measure' based on purely the awareness and the appreciation of the potential susceptibilities appear to have been effective.

A considerable effort by many researchers around the world has yielded a good understanding of the rain/wind mechanism. The formation of a water rivulet along the upper side of the cable and its interaction with wind flow has been solidly established as the cause through many recent studies and wind-tunnel tests. Exterior cable surface modifications that interfere with the formation of the water rivulets have been tried and proven to be very effective in the mitigation of the rain/wind vibrations. At the present time, the rain/wind problem had been essentially solved at least for practical provisions for its mitigation.

As a result of the widespread awareness of the problem, today, the potential for stay cable vibrations is generally evaluated and mitigation measures are incorporated into the design. However, with the knowledge base mainly contained in a large number of technical papers, there was a considerable lack of uniformity in application. Further, some of the design criteria were based on very limited tests that had not been duplicated by others. Having recognized this deficiency, Federal Highway Administration (FHWA) commissioned a study to fill in the gaps in existing knowledge and develop some design criteria. The final report from this study is now available through FHWA and is used here as a general reference [1].

STATE-OF-THE-ART MITIGATION METHODS

While there are a number of mechanisms that can possibly lead to vibrations of stay cables, the key mechanisms that should be considered typically in design (at a minimum) include:

- Rain/wind induced vibrations of cables
- Galloping of single cables inclined to the wind
- Parametric excitations

The first two are more traditional considerations and are included in the current PTI recommendations on stay cable design, testing and installation [2]. Parametric excitations are due to general bridge modes. For example, a small amplitude vortex excitation of the bridge deck or tower due to wind may lead to a large amplitude build up of a cable with a sympathetic mode of vibration. Recent field data reported in [1] suggests that the parametric type excitations could also produce pronounced excitations of stay cables. Similarly, fluctuation of cable tension due to live load or the general bridge response due to live load could also (theoretically) lead to parametric excitations. However, parametric excitations under live loads are not expected to be a real issue under normal circumstances. On the other hand, vortex excitations of bridge elements are not rare, and the frequencies of the typical modes of response fall right within the range of frequencies of the cables. Even though parametric excitations have not been reported on existing bridges as a recurring serviceability problem, some level of attention to this aspect during design is justifiable.

SURFACE MODIFICATIONS - The use of surface modifications to disrupt the formation of water rivulets has been proven to be fairly effective as a direct method of mitigating rain/wind vibrations. There are several modifications that have been proposed and tested. The double helix fillet protrusion type modification appears to be the most popular both in the U.S. and abroad (Figure 1). This is commonly manufactured integral (co-extruded) with the HDPE cable sheathing used currently in lieu of the PE pipes used on the older structures. The graph of the observed vibration amplitude with and without fillet is from one cable manufacturer’s (Freyssinet) literature on a commonly used HDPE sheathing with a co-extruded double-helix fillet. This is probably the most cost-effective rain/wind mitigation measure available and should be used wherever possible. The Charles River Bridge in Boston, MA, marks the first use of this technology in the U.S.

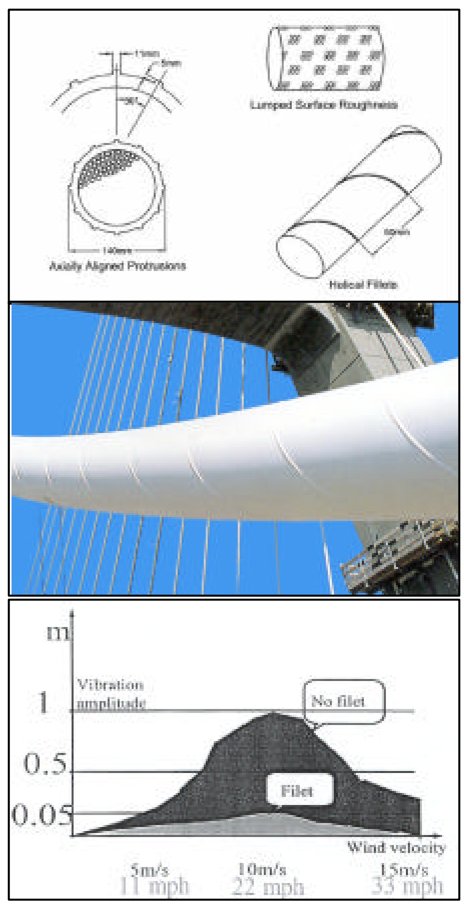


Figure 1: Surface Modifications

No rational methods exist for designing or sizing the surface modifications. As a manufacturer proprietary item, test data demonstrating their effectiveness is generally available from the cable suppliers.

EXTERNAL DAMPERS - The first use of external dampers in the U.S. was on the Sunshine Skyway Bridge, completed in 1987 (Figure 2).

Figure 2: Sunshine Skyway Bridge Dampers

It is not clear how they were sized at the time. However, the Universal Damper Curve for a linear viscous damper on a idealized cable published by Pacheco et al., in 1993 [3] is quite helpful in understanding the key issues and used at the present time in sizing dampers for stay cables. The Universal Damper Curve is a plot of the normalized effective damping $\zeta / (l / L)$ versus the normalized damper size κ.

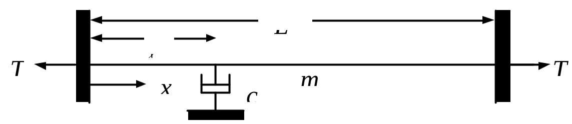
$$\frac{?_{i}}{(\ell / L)} \cong \frac{p^{2}?}{(p^{2}?)^{2}+1} \qquad (1)$$

$$\kappa \equiv \frac{c}{mLw_{o1}} i \frac{\ell}{L} \qquad (2)$$

Where i is the mode of vibration, c is the damping coefficient, ζ is the damping ratio, *m* is the cable mass per unit length, w_{o1} is the fundamental frequency of the cable and *l / L* is the normalized damper location.

In Figure 3, the original curve published by Pacheco [3] is shown (solid) with later developments by Caracoglia and Jones [4] to include the effect of static friction in the damper. The following become evident from the damper curve:

1. There is a maximum value to the amount of damping that can be affected to a given cable. Increasing the damper size beyond that corresponding to the maximum damping (critical damper size) quickly reduces the effective damping in the cable.
2. As the damper can only be mounted fairly close to the ends of the cable (l/L ˜ 0.02), the maximum damping that can be effected on a cable is around 1.0%
3. The friction in a viscous damper (leading to a stick-move-stick type motion) reduces the effective damping in the cable. The graph suggests that the friction should be minimized and / or accounted for in the design.



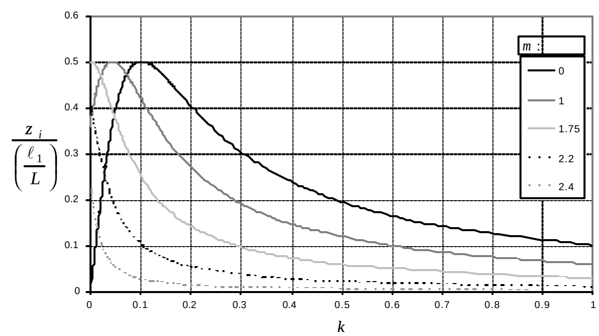


Figure 3: Universal Damper Curve (Modified)

Most types of wind-induced vibrations tend to be mitigated by increasing the Scruton number (S_c), given by

$$S_c = m\,\zeta / \rho D^2 \qquad (3)$$

where *m* is the mass of cable per unit length, ζ is damping as ratio (of critical damping), ρ ?is density of air, and D is cable diameter. It can be seen that increasing the damping ratio ζ by providing external dampers linearly increases the Scruton number, S_c. For mitigation of rain/wind vibrations, the following minimum Scruton Numbers (S_c) have been recommended [1]:

$S_c = m\ \zeta / \rho D^2 > 10$ For regular cable arrangements

$S_c = m\ \zeta / \rho D^2 > 5$ For regular cable arrangements provided with effective surface treatment for suppressing rain/wind vibrations ($S_c > 10$ is preferable as the proposed reduction is based on limited test data)

The level of damping inherent in a cable is very low, assumed in the 0.1% range for longer cables. To raise $S_c > 10$, the level of damping must be typically raise to about 0.5%, a goal well within the maximum of 1.0% discussed previously.

CABLE CROSS-TIES - Cable cross-ties are secondary small diameter transverse secondary cables (wire-rope type) that provide in-plane connectivity between the stay cables. The connections transform individual cables into a more complex cable network (Figure 4). The first bridge in the U.S. to include cable cross-ties was the Dames Point Bridge in Jacksonville, FL, designed in the mid 1970's and completed in 1988 (Figure 5).

Figure 4: Cable Cross-ties

Figure 5: Dames Point Bridge

The most direct result of cross-ties is the reduction in the free length of cables in the plane direction. This increases the frequencies of the in-plane vibrations of the cables. The number of cross-ties can be selected to increase the in-plane cable frequencies to be above a pre-determined level. The behavior of the resulting 'cable-net' is fairly complex. The out-of plane direction is theoretically unaffected by the cable cross-ties. This makes any analysis on how the cable cross-ties would prevent a complex mechanism such as rain/wind vibrations difficult. Perhaps this elimination of the lower in-plane frequencies may sufficiently alter the loci of the cable movement, which may be of critical importance to cable-water rivulet-wind interaction.

Conceivably, the connection of secondary cables to the primary cables introduces small amounts of damping at these locations. However, this small amount of damping is placed at a highly effective location. Using the Universal Damper Curve previously discussed, 0.33% (or one 300^{th}) of the damping placed near the cable end (say at $l/L \sim 0.02$) is needed at the 3^{rd} point along the cable to produce an overall damping ratio of 0.5% in the cable in its first mode. Conversely, a damper placed at the 3^{rd} point along the cable is 300 times more effective in the first mode as a damper placed near the cable end.

In addition to the damping, the cross-ties also provide a path for re-distributing energy within the cable net. For example, if one cable were to be excited by plucking it, the cross-ties quickly transfer energy from the plucked cable to the others. This transfer of energy results in a very rapid decay of the vibration amplitude of the plucked cable, resulting in a very high apparent damping. This is however mostly due to the transfer of energy within the system rather than dissipation of energy, and cannot be considered 'damping'. The transfer of energy is evident from the small amplitude build up in the adjacent cables. This effect was clearly observed during the field damping measurements on the Charles River Bridge cables by FHWA [1].

The in-plane dynamic characteristics of the cable-net resulting from the use of cable cross-ties for the Fred Hartman Bridge reported by Main and Jones [5] clearly show the presence of a frequency plateau that correspond to the modes of the internal portions (free-lengths) of the stays between the cross-ties.

Thus the overall benefits of cable cross-ties are likely to be the net result of many beneficial effects including:

1. Reduction in free length, increase in modal frequencies and the formation of a cable net in the in-plane direction
2. Frequency separation of modes involving in-plane and out-of-plane displacements affecting 2-dimensional dynamics of the cable cross section
3. Addition of small amounts of damping at highly effective locations along the cable length
4. The mechanism of energy transfer from one cable (being excited) to other cables in the net

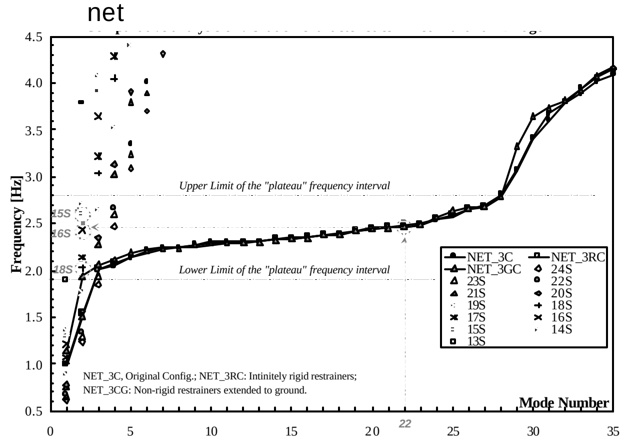


Figure 6: Network Vibration Characteristics and Individual Cable Behavior; Fred Hartman Bridge.

All except item 1 above involves parameters which are hard to quantify. For this reason, developing a rational design approach to cross-ties accounting for all of the possible effects becomes difficult, if not impossible. Thus the designs of cross-tie systems are based on raising the in plane-frequencies above a certain threshold by limiting the free-length of cables. The other design considerations include providing sufficient pre-tension in the cross-ties to prevent development of slackness during service conditions and use of details and proper tie materials (such as wire rope) with good fatigue resistance (to prevent premature failure of the ties under normal service conditions).

DESIGN IMPLEMENTATION OF VIBRATION MITIGATION

Considering a 11-inch diameter, 350-ft long cable with a mass of 127 lb/ft under a permanent tension of 1485-kips, the frequencies of the first three modes of vibration are computed to be f_1 = 0.875, f_2 = 1.750 and f_3 = 2.625 Hz. For $S_c = m\zeta/\rho D^2 \geq 10$ (as required by the current PTI recommendations [2]), using ρ = 0.0765 lb/ft^3, the minimum damping required for $S_c \geq 10$ is $\zeta \geq 0.005$ (0.5%). Assuming an external damper is to be mounted at a location 11'-8" from the end anchorage of the cable, the damper coefficient 'c' required to provide 0.5% damping in the first cable mode can be obtained from the Universal Damper Curve.

$$\frac{?_i}{l/L} = \frac{0.005}{11.67\text{ft}/\ \ 350\text{ft}} = 0.15$$

Assuming negligible friction (μ = 0) and using Eq. (1) and (2):

$$k = \frac{c}{m L w_{ol}} i \frac{l}{L} = 0.0125$$

$c = \frac{2850}{i}\frac{slugs}{\sec} = \frac{2850}{i}\frac{lbf\ \sec}{ft} = 2850\,\frac{lbf\ \sec}{ft}$; gives the damper coefficient for 0.5% damping in mode 1 Using this damper (c = 2850 lbf-sec/ft) will result in ζ_2 = 0.0077 (0.77%) and ζ_3 = 0.0120 (1.2%) damping in the higher modes, satisfying the $S_c \geq 10$. Also of interest is the maximum level of damping that can be provided corresponding to the peak of the Universal Damper curve, ζ_{1max} = 0.5*(11.67/350) = 0.0166 (1.66%).

The current PTI [2] also recommends providing against dry inclined cable galloping by meeting:

$$U_{CRIT} = c\ f\ D\sqrt{S_c} \qquad (4)$$

where the constant c is taken as 40.

With f_1 = 0.875 Hz, U_{crit} > 150 mph requires the Scruton number $S_c \geq 47$ and ζ_1 > 0.0235 (2.35%) which is beyond the maximum damping that can be practically provided to the cable with a damper placed at 11'-8" from the cable end regardless of damper size. The only effective solution here is to provide cross-ties to limit the free length of the cables. By providing two tie-cables at the third points, the first in-plane natural frequency is raised to $f_{1,\ new}$ = 2.63 Hz, providing a computed critical velocity of 200 mph, high enough for the application. In this application, it is probably reasonable to assume that the tie cables would also raise damping in the stay cable to about 0.5%, and to consider omitting the external dampers.

PTI Guide Specifications [2] also discuss the need for pre-tensioning the cable ties. The method outlined however lead to very demanding levels of pre-tension. The recommended pre-tension is twice the dynamic wind load on the main cable over the contributory length. Assuming a drag coefficient of 0.8 and gust factor of 2, this force in the present application is nearly 20-kips. The application of such high pre-tension loads on the cables, especially on the uppermost cable where the pre-tension is applied only on one side, becomes problematic. A reasonable alternative may be to use a rational engineering analysis of the cable net (say non-linear dynamic procedures) to obtain the level of pretension.

LATEST DEVELOPMENTS

The dry cable galloping criterion discussed above, while a theoretical possibility that cannot be ignored, is based on fairly limited test data, and little evidence exists of its actual occurrence. As the mitigation of this in almost all instances lead to the need for cross-ties, it has also been somewhat controversial issue with little consensus. This was one of the key issues examined in the FHWA sponsored study [1].

The tests conducted by the team member RWDI at the Propulsion Wind Tunnel at the University of Ottawa indicated that the dry cable galloping can only occur if the damping levels are very low (<0.1%). These tests have shown that the dry cable galloping can be ignored if the damping levels are kept above 0.3%, which is less than that required for mitigation of rain/wind vibrations. The conclusion being that keeping the damping provided for mitigation of rain/wind vibrations is sufficient to prevent dry cable galloping without taking any further steps. A new stability line developed for dry cable galloping based on new tests [1] is shown in Figure 7. This establishes the mitigation criteria for galloping as $S_c \geq 3$.

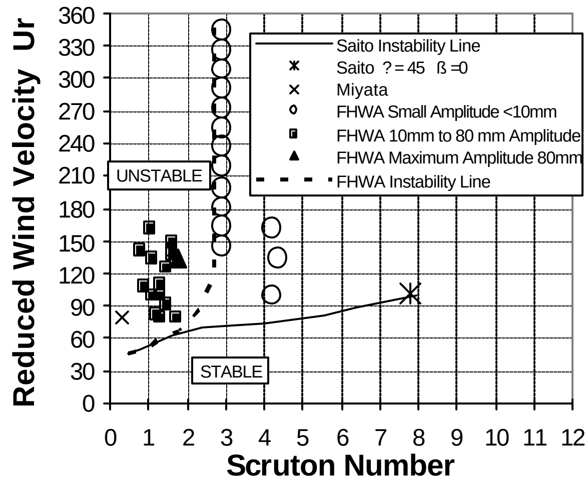


Figure 7: Stability Line for Dry Cable Galloping

This allows the omission of the cable ties in the mitigation design discussed previously. However, cable cross-ties remain the only means of mitigating the parametric type excitations (by raising the in-plane cable frequencies sufficiently high) and must be considered if conditions warrant such provisions.

The aesthetic impact of cross-ties has been one of the negative factors often cited. Historically, it appears that the level of attention paid in refining the cross-tie details are somewhat limited, leading to purely utilitarian and poor quality appearance. However, this can be overcome with some attention to making the quality and appearance of the details more compatible with the cables, as this would facilitate their wider acceptance (Figure 8).

There have also been several important field measurements of vibration and damping levels of stay cables, notably by Jones on Fred Hartman Bridge, TX and Sunshine Skyway Bridge, FL and by Bosch on Charles River Bridge, MA [1]. The significance of measurements on Fred Hartman is two folds. First, it verified damper performance; it also showed a classic case of parametric excitation involving bridge deck-stay cable interaction due to vortex shedding from the bridge deck. The significance of the cable damping measurements on Sunshine Skyway Bridge, FL, stems from the absence of any known cable vibrations on this bridge (incorporating external dampers).

Figure 8: Improving Visual Quality

Following are the damping estimates in the first three modes of the bridge cables from the field measurements:

- Mode 1: 0.66% average (0.30%-1.53% range)
- Mode 2: 0.36% average (0.10%-0.70% range)
- Mode 3: 0.26% average (0.11%-0.56% range)

The above results from the Sunshine Skyway Bridge clearly show that moderate levels of damping are sufficient in preventing objectionable vibrations that have plagued several of the other bridges without any countermeasures.

The cable system on the Charles River Bridge in Boston, MA incorporated double-helix surface modifications, external dampers and cable cross-ties (to meet the inclined dry cable galloping criteria existing at the time of its design). During its construction, cable damping measurements were made by FHWA [1] prior to the installation of dampers, after installation of dampers and then after adding the dampers and the cross-ties. The field measurements of the oscillation decay after excitation by pulling with a rope were made for the above three stages. The damping estimates obtained by H. Bosch of FHWA are given below:

- Prior to installation of dampers: 0.20% average
- After installation of dampers: 0.37% average

A typical collection of records corresponding to the three different stages for the same cable is shown in Figure 9. The key observation here is the profound effect of cross-ties that prevented the cable from developing a prolonged response despite multiple excitations.

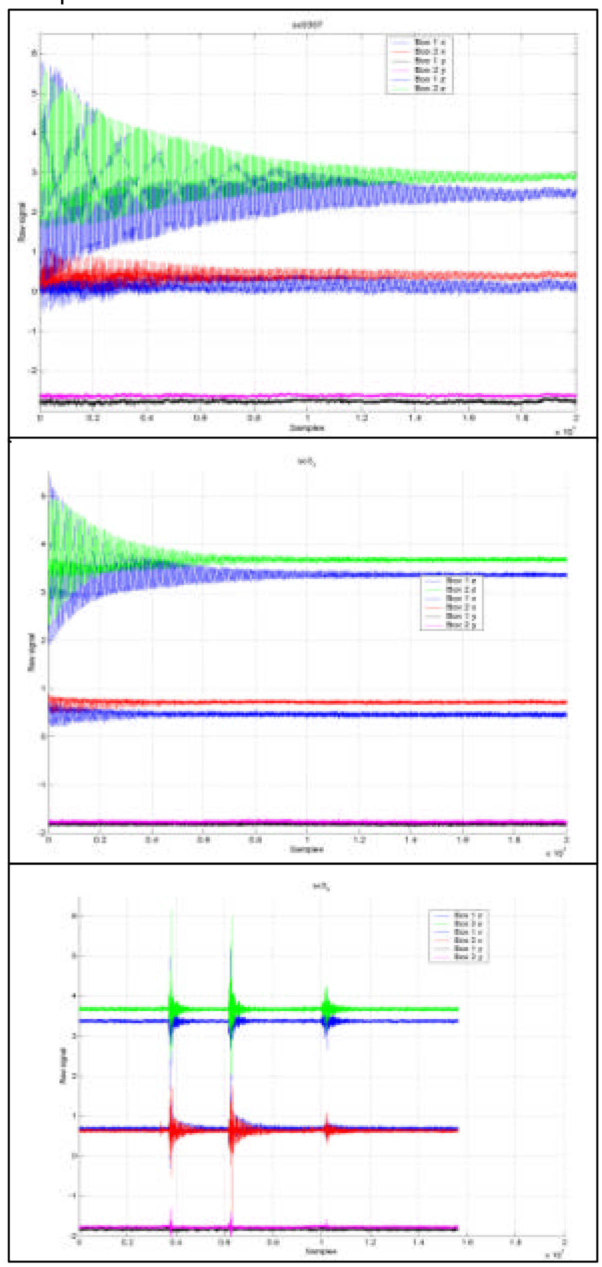


Figure 9: Results of Vibration Testing of the Charles River Bridge

LOOKING TO THE FUTURE

Even though the resolution of the dry cable galloping issue appears to eliminate the need for cross-ties in stay cable vibration mitigation, the cross-ties are expected to have some application, at least under special circumstances such as very long cables, hybrid cable supported bridges incorporating cable net systems, and cases where the potential for developing parametric excitations is significant.

Further development of cable cross-ties is certainly possible, to improve their visual quality as discussed above and also improve their functionality. Most significantly, cable cross-ties can be combined with suitable damping and elastic stiffness (spring). The advantages of such an application are two folds. First, due to its location along the length of the cable the damper size would be reduced significantly. This may be especially important for longer cables where the conventional damper mounting methods and locations are insufficient. Maintenance free small dampers, made from either elastomeric or other newer applications such as memory alloys, are ideal for such applications. Further, incorporating the elastic stiffness into the cross-ties would enable elimination of slackness at a considerably lower level of pre-tension in the cross-ties.

As the cables are laterally flexible elements, moderate levels of lateral movements typically do not produce stress conditions that are very significant from a strength or fatigue perspective. Cables are exposed to the action of wind and other dynamic loading conditions. Thus, even a properly designed cable system will exhibit some level of dynamic response under certain conditions. The establishment of limits of user perception and design methods that ensure performance within these tolerance limits remain the most logical approach to cable vibration mitigation. From a preliminary study of user perception conducted as a part of the FHWA project [1], within 0.5 to 2.0 Hz range, the following vibration amplitude limits were established with respect to user perception (where D is the cable diameter):

- 0.5 D (Preferred)
- 1.0 D (Recommended)
- 2.0 D (Not to Exceed)

However the current established analysis and design methods are not sufficient to allow the reliable computation of cable displacements under service conditions.

The susceptibility of cables to vibration such as rain/wind and parametric excitations under vastly different vibration frequencies in two orthogonal directions, as obtained with in-plane cable cross-ties, is an issue not understood fully. It could be that the restraint in one direction is sufficient to prevent the development of key vibration mechanisms, or that a system that provides two dimensional restraints is the only solution for some cases. This complex issue requires further research.

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