

Friction Damper Performance on Stay Cable Bridges in Vietnam, Solution Prediction, and In-Situ Testing



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1 Introduction

Stay cable structures, with the architectural and structural advantages, have become a widespread solution for medium to long-span bridges over the past several decades. In parallel, with the structural slenderness and excitation sensibility, the serviceability problems with large amplitude vibrations of cables stay due to environmental conditions have been observed. The term “rain/wind vibration” [1] for example was familiar to specify the large amplitude vibration occurred under a certain condition of rain and wind combination. On another hand, large amplitude vibrations at high wind speeds have also been reported as possible in the literature [2] without specific rain conditions and known as “galloping of dry inclined cables”. An amount of theoretical and experimental research on this subject had been conducted by worldwide researchers and stay cable specialist contractors. With this understanding, mitigation measures such as various cable surface modifications as well as external/internal dampers and/or cable cross-ties have been proposed and tested with the development of stay cable technology. Those technics are aimed to disrupt the water rivulet interaction with the wind flow considering as the root cause of the rain/wind vibration or to dissipate the cable vibrations energy by adding damping to the cables’ stay.

Since the inauguration in 2000 of My Thuan bridge, the first stay cable bridge built in the territory of Vietnam, large amplitude vibration mitigation measures were adopted in several types such as hydraulic external dampers in My Thuan bridge,

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hollow cable surface modification in Can Tho bridge and Nhat Tan bridge, double-helix cable surface modification and friction dampers in Tran Thi Ly and Vam Cong bridges ...

The lack of standardized criteria and local design guidelines have made the consistent practical design and application of the mitigation measures difficult. Furthermore, the cable damping characteristics depend on many parameters of cable system nature but also environmental conditions and the accurate value is difficult to predict. Testing field is generally considered as the most effective solution to evaluate and/or verifying the damping characteristics. However, not much local research, field-testing report, or publication on those issues have been recorded.

This paper presents an assessment of the large amplitude vibration possibility on two stay cable bridges recently completed in Vietnam in considering the vibration mitigation measures using friction dampers system. The results were then confronting with the field damper test to confirm the theoretical prediction and evaluate the performance of the friction damper system.

2 Stay Cables Vibration

2.1 Direct Excitations

Based on the existing world-wise research data, wake galloping, galloping of dry inclined cable, and rain/wind combination excitations mechanisms appear to be the biggest concerns for vibration mitigation.

Wake galloping is caused by variations in drag and cross-wind forces leading to elliptical movement of the cables in the wake of other elements (towers or other cables). The phenomenon characterizes by large amplitude oscillations at high wind speeds. That could theoretically be the cause of possible fatigue on the stay cable bridges. Even if wake galloping is generally not a major design concern for normal cable arrangement conditions, it's recommended to pay some attention in the unusual cases. The cable shall be stable up to a higher wind velocity by increasing the Scruton number or natural frequency (Eq. 1).

Galloping of Dry Inclined Cables defines the phenomenon of possible large amplitude vibrations of single cable-stayed occur at high wind speeds which is not normal to the cable axis. For inclined cable, wind acts on the cable cross-section of elliptical form defined by the cable inclination. When the cable structural damping is very low, galloping instability is then possible.

Rain/Wind induced vibrations have been observed worldwide on many stay cable bridges and researched in detail. The phenomenon specifying as cable vibrations with high amplitude at low frequencies causes by a combination of rain and moderate wind speeds. Experimental researches [1, 3] have shown that raining water rivulets running in the upper and lower surface of the cable cross-section under perturbed

wind condition is the essential component of the phenomenon. Under that condition, the effective shape of the cable is changed when the cable oscillates causing cyclic changes in the aerodynamic forces leading to the oscillation.

2.2 Design Criteria

Regarding the wake galloping effect, an approximate equation for the minimum wind velocity U_{crit} based on an important parameter, the Scruton number (S_c), has been proposed by Irwin [4] and Cooper [5] and adopted by PTI [6] as a critical wind speed above which, instability due to wake galloping can be expected.

$$U_{\text{crit}} = c f D \sqrt{S_c} \quad (1)$$

In the equation, c is a constant depending on the clear spacing between cable ($c = 25$ for closely spaced and $c = 80$ for normally spaced). D and f are the cable diameter and natural frequency, respectively.

On another hand, inclined dry cable galloping is generally not a common phenomenon in completed bridges during service. Saito [2] suggested however an instability criterion based on a series of wind tunnel experimental. The equation was given in a different form from the Eq. (1) with $c = 40$.

$$(U/fD)_{\text{crit}} = 40\sqrt{S_c} \quad (2)$$

Rain-wind oscillation excitation is suggested by PTI to be reduced to a harmless level using a criteria for Scruton number based on the Saito's rig test data [2] and the wind tunnel test performed by other researchers [1, 5].

$$S_c = \frac{m\xi}{\rho D^2} \geq 10 \quad (3)$$

Based on limited tests on cable with double-helix surface modification, Larose et al. [7] have suggested that $S_c > 5$ may be acceptable. PTI also suggested that a value of 5 could be proposed in lieu of the higher limit of 10 for special helix or dimpled stay pipes with special testing to verify this value [6]. This criterion can be used to specify the amount of damping that must be added to the cable to mitigate rain/wind vibrations.

FIB (International Federation for Structural Concrete) on another hand suggested that an effective damping of $\delta = 3\text{--}4\%$ has often been found to be sufficient to control wind-/rain-induced stay cable vibrations in practice [8]. Those values are quite in line with the recommendation by CIP (French International Commission on Prestressing) for a logarithmic decrement (damping) of the cable greater than 3% for cable of more than 80 m in length to avoid rain and wind instability [9].

Fig. 1 Friction damper assembling on Vam Cong bridge (photo provided by VSL Vietnam)



3 Friction Damper

3.1 Energy Dissipation and the Threshold Amplitude

The principle of the friction damper system is to dissipate the maximum of mechanical energy through the interface contact between the friction elements. The key point of system design is to keep the threshold vibration amplitude below a specific value considering as structural and user comfort acceptable. Figure 1 shows the on-site assembling of friction damper in Vam Cong bridge (Dong Thap, Vietnam).

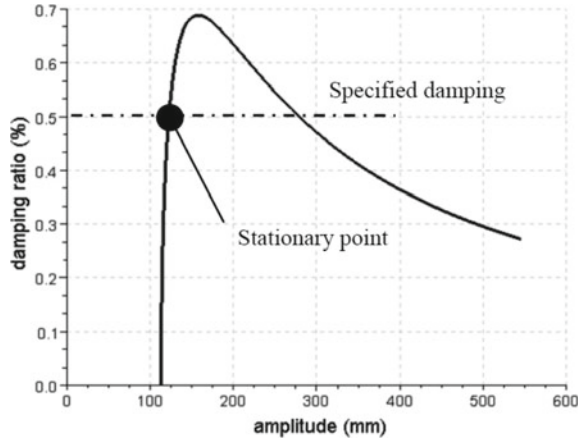
The mechanical energy dissipation is mobilized in the relative movement at the prestressed contact between two specific friction patterns. It consists of a first pattern connected to the moving cable and another one connected to the support assuming to be fixed. As consequence, the movements are damped to a certain threshold amplitude of vibration.

3.2 Damping Behavior

Figure 2 presents a typical relationship of vibration amplitude dependent on damping ratio (ξ) provided by friction damper. It shows that at a level of less than a hundred millimeters, the cable vibration amplitude cannot induce a deviation force sufficiently important to overcome the friction force and make the cable move at the external damper installed location. Once the threshold vibration amplitude is exceeded, the friction force is activated and provides sufficient damping to the cable to dissipate external excitation energy. The cable movements are quickly stabilized to a level of amplitude defined by the specific demanded damping ratio of 0.5% (see Fig. 2).

The damper remains activated after the excitation stops until the vibration amplitude decreases to a certain level lower than the initial threshold [10].

Fig. 2 Modal characteristics and typical friction damper behavior in the Incheon bridge [10]



4 Field-Testing Performance

4.1 Field-Testing

We present in the following the damping test results performed on two stay cable bridges recently built in Vietnam. They are Tran Thi Ly bridge (2015) and Vam Cong bridge (2020). The testing campaigns were performed in post-evaluation of the wind-induced vibration assessment to confirm the theoretical damping values and the performance of the mitigation friction dampers solution.

The damping of the cable and the friction damper performance were measured during the assumed free response of the stay cable to an impulse excitation. The testing procedure had been repeated to acquire the vibration data for three first mode of cable vibrations.

4.2 Friction Damper Solution

For the studied stay cable bridges, the excessed wind vibration assessment is evaluated based on the criteria specified by PTI [6] and FIB [8] with regard to the Scruton Number (Eq. 3), the critical wind velocity (Eq. 2), and the intrinsic damping.

Figure 4 presents the relationship between the critical wind velocities and the cable length for the interested bridges. If considering a very common design wind speed of 20 m/s, we can observe that additional damping is required for nearly all the cables to eliminate completely the risk of vortex vibration on all the three stay cable bridges. It should be noted however that the approach is considering as very conservative in practice without considering the aerodynamic damping which increases with wind speed [9].

Even the determination of the exact intrinsic damping for cable-stayed is very difficult, in practice, it is common to consider that the value is in proportional with the cable-free length (L):

$$\delta_{\text{int}} = 2\pi(0.24 - 6 \times 10^{-4}L) \quad (4)$$

The estimation of intrinsic damping however needs to be confirmed by an adequate testing campaign as per presented in the following. Figure 5 shows the relationship between the evaluated value of Scruton Number (S_c) and the first mode of cable natural frequency on the bridges. We can notice that most of the estimated values of (S_c) are even lower than 3 and all of them are lower than the critical value specified by PTI [6].

In the three studied bridges, in combining with double helical surface treatment for cable pipe the external friction dampers have been proposed to mitigate the wind vibration excitation on the in-risk cables stayed.

4.3 Field-Testing and Results

Due to the important amount of time-consuming, the field test was performed only on selected cables representatives for each bridge. Table 1 presents the characteristic of testing cables performed on Tran Thi Ly (TTL) bridge and Vam Cong (VC) bridge, respectively.

The objectives of the tests were to confirm the intrinsic damper evaluated values and the need for additional external damping but also to prove the performance of the proposed friction damper solution.

It's to be highlighted that the measurement data was acceptable if the environment conditions, the wind and dynamic loads excitation on the deck level were controllable and then their effects could be removed from the measured data. The portable accelerometers were used for the data collection which were installed on the cable

Table 1 Testing cables characteristics

Cable No./Bridge name	Cable length (m)	Num. of strands	Cable incl. (deg.)	Cable outer dia (mm)	Cable mass (kg/m)	1st mode theo. freq. (Hz)	Tension force (kN)
301/TTL	275.09	95	26.80	250	123.5	0.50	9014
308/TTL	230.06	78	28.89	225	101.4	0.62	7901
316/TTL	179.45	66	32.72	210	85.8	0.81	6857
106/TTL	218.46	54	32.38	180	70.2	0.65	5340
C1S8/VC	119.21	41	36.82	200	53.3	1.15	4059
C1C11/VC	150.85	46	29.95	200	59.8	0.88	4245
C1C18/VC	234.06	61	24.14	2.25	79.3	0.58	5519

at specified height from deck (see Fig. 3) individually for each cable in considering each of the first three modes of vibration (*i*th). A correction factor (α) was added to correct the error on the measurement location (L_s) and the maximum displacement location on the cable-free length (L_c).

$$\alpha = \left(\sin \frac{L_s i \pi}{L_c} \right)^{-1} \tag{5}$$

At first, the friction damper has been disconnected for cable intrinsic damping measurement. The operations have been executed by distressing the friction pads in assuring the free movement of the cables. The additional damping was then measured



Fig. 3 Installation of the accelerometers for damping test on the Tran Thi Ly stay cable bridge (photo provided by VSL Vietnam)

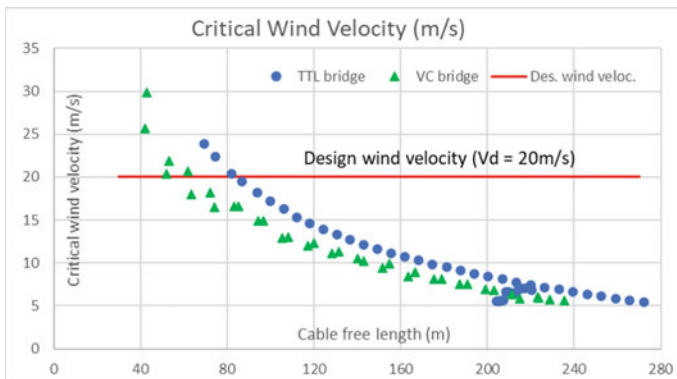


Fig. 4 Critical wind velocity evaluated in regard to the cable length

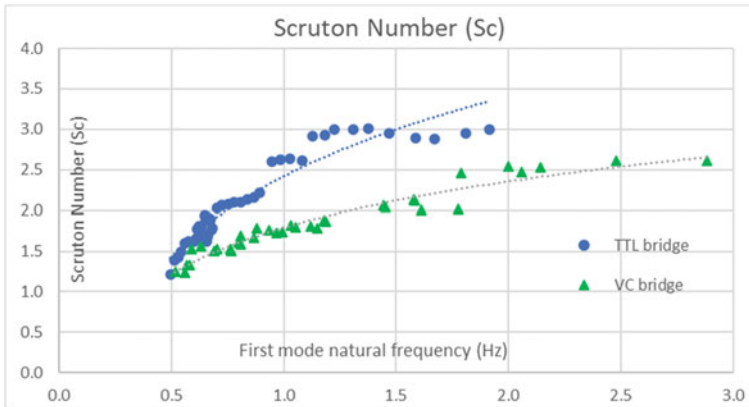


Fig. 5 Scruton Number and the cables' first mode natural frequency

by engaging the friction pads by stressing patterns. A post-measurement data treatment was performed to eliminate the measured values which had been affected by environment excitation conduiting to exaggerated damping value.

Rigorously, the cable movements were extracted from the measured acceleration signal by a double integration process. However, to eliminate the noise and measurement error that could lead to the unsuitable signal, the integration process was performed over the frequency domain. The logarithmic decrement (damping) was obtained from the envelope of displacement signal with the below formula in which (f) is the frequency of the harmonic signal [10].

$$\delta(t) = -\frac{1}{f} \frac{A'(t)}{A(t)} \quad (6)$$

Figure 6 presents a comparison between the measurement intrinsic damping and the theoretical evaluation in regard to the 1st mode natural frequency of the cables. We observe that the measured intrinsic damping values are comparable to those given in most of the International Standard [6, 8, 9] and quite in line with the theoretically evaluated ones.

Figure 7 shows the respective logarithmic decrement with the friction damper engaging in comparing to the measured intrinsic cable damping in Tran Thi Ly (TTL) and Vam Cong (VC) bridges. We observe a net increase of cable damping values proving the performance of the installed friction damper solution.

The average addition damping due to the friction damper system could reach a minimum of 4%.

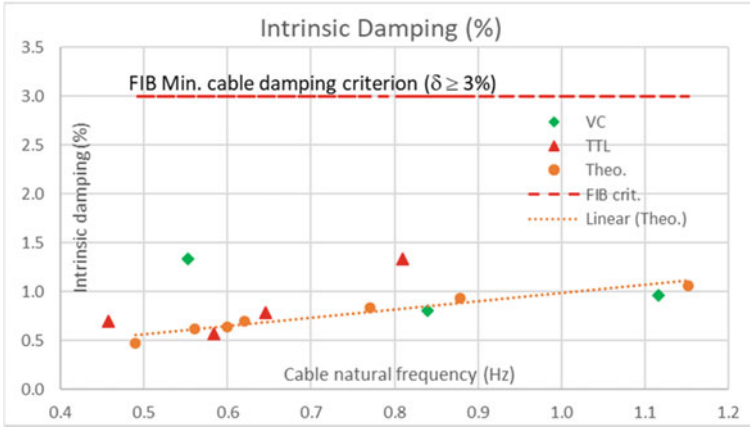


Fig. 6 Theoretical and measured Intrinsic Damping cable confrontation

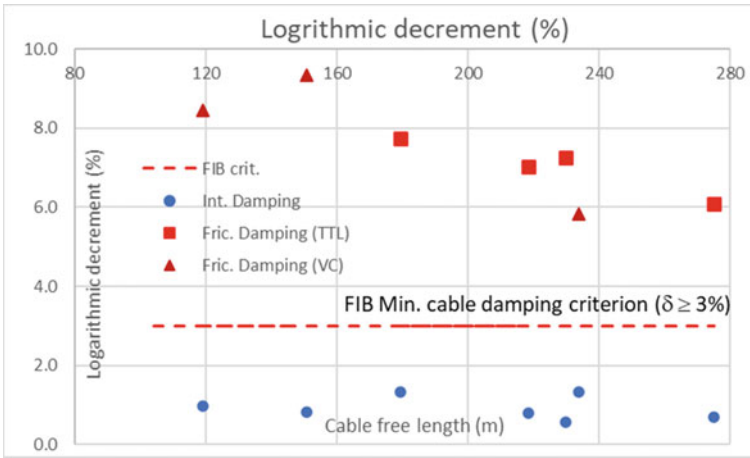


Fig. 7 Measured additional damping with friction damper engaged (Friction damping)

5 Conclusions and Discussion

The evaluation process of the possibility of excessive wind-induced vibration seems to be too conservative based on the approach by PTI recommendation. Furthermore, the evaluation of intrinsic damping is difficult to be accurate. The stay cable damping estimation needs to be confirmed by a suitable testing campaign for determining the cable logarithmic decrement.

The damping test process, correlation, and data treatment processes were presented for reference and future works.

The testing results show that the measured intrinsic damping of cables were in line with the evaluated ones and the values specified in the current International Standards and Specifications.

The performance of the friction damper system installed on the bridges had been also proved through the experimental data by increasing the cable logarithmic decrement by more than 4%.

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