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# Wind induced vibration of stay cable bridge evaluation based on the operational accelerometers monitoring data and field testing

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Wind induced vibrations are considering as one of the major concerns of the owner, the engineers and contractors of stay cable bridges. This paper presents in premier lieu the assessment of the vibration monitoring data from the pre-installed accelerometers on the longest cables of the Bach Dang bridge, Quang Ninh province. The identified cables natural frequencies based on the ambient vibration monitoring data were then compared to the taut string vibrating model calculation based on lift-off tension forces showing a good concordant. The enhanced damping of the cables stayed were then estimated and compared to the damping test results of another stay cables bridge recently performed in Vietnam with similar range of cables length. The damping prediction are quite in line with the damping test results and comparable also to those given in most of International Standard for stay cable. Finally, the identified natural frequencies and predicted intrinsic damping were used for an assessment of the wind induced vibration instability including the wind/rain induced vibration, wake galloping and vortex excitation.

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## 1 Introduction

Over the past decade, stay cable bridge with the architectural advantage and structural effectiveness has become the structural form of choice for medium to long span bridge in Vietnam. However, laterally the stay cables are structural members with very low fundamental frequency. Thus, it is more probable that one or more cables with either a fundamental or higher mode frequency could be sympathetic to any excitation mechanism with arbitrary frequency. Cables also have very little intrinsic damping and are not able to dissipate much of the excitation energy. For this reason, the stay cables have been known to be susceptible to excitations, especially under special wind, and rain/wind conditions but also during construction. Unlike the cable natural frequency or shape mode, an accurate identification of the cables damping ratio is still challenging. Kareem et al. (1996), Moon et al. (2006) and Jeary (1992) [1-3] were respectively observed many complex interaction factors

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affected to the reliability of the damping ratio identification such as: friction between connection, soil-structure interaction, aerodynamic/hydraulic damping, environment factors, nonlinear and nonstationary wind loading… That the reason why Operational Modal Analysis (OMA) technique for accurately identified the cable natural frequency from the monitoring data [4] together with reference field damping test are required for reliable results [5].

Even though very few reports of the serviceability problems with large amplitude vibration of cables-stayed due to environmental conditions have recorded locally, the phenomenon is still the high important concerns. In that regards, health monitoring system is systematically and mandatorily equipped for new stay cable bridge development. We can see appearance in a number of bridges recently built such as Bach Dang bridge (Quang Ninh), Nhat Le 2 bridge (Quang Binh), Nhat Tan bridge (Hanoi), etc… Those systems are for the end objective to provide necessary data for bridge health monitoring, detecting in the early stage any signs of abnormal behaviour and/or evaluating any extreme phenomenon such as wind induced vibration, rain/wind vibration… On another hand, in order to evaluate the performance of their vibration mitigated measure, field damping test programs have been performed and reported by the stay cables specialist contractors and made available [6].

In this paper, we present a study on the vibration characteristics of the Bach Dang stay cable bridge, in three steps: the cable-stayed natural frequencies were identified based on the environment vibration monitoring data in comparing to the theoretical calculation values based on the cables tensions lift-off records; Enhanced damping of the cables were then estimated in confronting to the field tests data recently performed on the Nhat Le 2 stay cable bridge [6] which have very similar range of cables-stayed length; Finally, using the identified natural frequencies and estimated intrinsic damping of the cables, an evaluation of potential excessive vibration based on criterions specified by the 2001 PTI Recommendations for Stay Cable Design, Testing and Installation [7] were presented.

## 2 Ambient vibration monitoring data

### *2.1 Bach Dang stay cable bridge*

Bach Dang bridge is crossing the Da Bach river separated Hai Phong and Quang Ninh provinces. It is the very first concrete multi-span cable-stayed bridge in Vietnam with the total length of 700m including two continuous cable-stayed spans of 240m length and three height restrictive pylons.

### *2.2 Stay cable natural frequencies identification and assessment*

During the construction of the bridge, health monitoring system including the 3D movements of pylons and decks, strain gauges and temperatures, stay cable tensions as well as vibration of 6 longest cables-stayed… was installed. The acceleration data of a period of 15 days (from 1st to 15th April 2019) were used for assessment in this study.

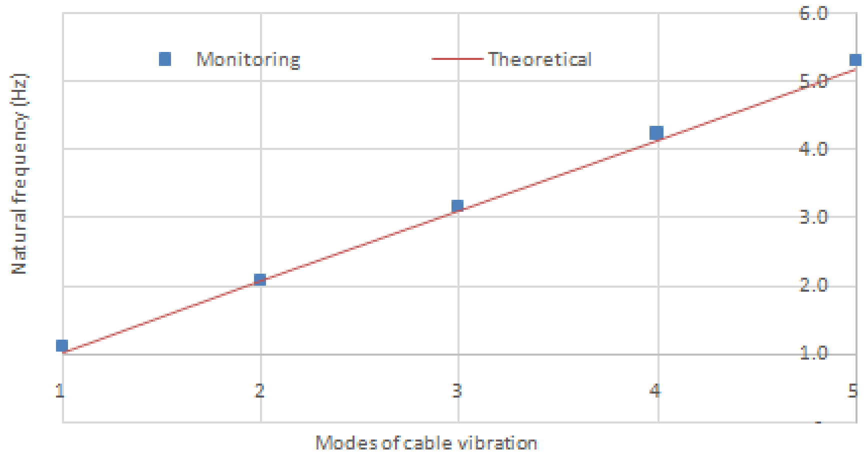


***Fig. 1 –Identified cable modal natural frequencies of the cable T29-CVG12 from the ambient acceleration monitoring***

The figure 1 shows the identified modal natural frequencies using OMA technique for the first 5 modes of the cable-stayed CVG12 of the pylon T29 (central pylon). The modal natural frequencies are quite linear and in good agreement with the theoretical calculation based on the lift-off cable tensions at the completion of the tuning process. The results confirm that for that study, the modal natural frequencies could be confidentially determined from the lift-off tensions in the cables. The Table 1 presents the geometrical parameters of the longest cables where the monitored accelerations data were available and the respective lift-off tensions.

**Table 1 –Cable ambient monitoring data for the longest cables on the bridge**

| Cable ID | No. of strands | Cable length (m) | Inclination (°) | Cable mass (kg/m) | Free length (m) | Identified natural frequencies (first 5 modes) * (Hz) | Tension force** (kN) |
|---|---|---|---|---|---|---|---|
| **T28-CVB12** | 80 | 117.21 | 22.93 | 104.0 | 116.04 | 2.11; 3.20; 4.24; 5.32 | 6648 |
| **T29-CVG12** | 80 | 123.94 | 20.56 | 104.0 | 120.89 | 1.11; 2.09; 3.16; 4.25; 5.31 | 6528 |
| **T30-CVB24** | 78 | 123.11 | 19.50 | 101.4 | 121.11 | 1.09; 2.10; 3.21; 4.27; 5.28 | 6552 |
| **T28-CVB24** | 78 | 123.11 | 19.50 | 101.4 | 121.11 | 1.08; 2.12; 3.20; 4.27; 5.31 | 6942 |
| **T29-CVG24** | 80 | 123.94 | 20.56 | 104.0 | 120.89 | 1.07; 2.08; 3.17; 4.25; 5.32 | 6568 |
| **T30-CVB12** | 80 | 117.21 | 22.93 | 104.0 | 116.74 | 1.09; 2.11; 3.20; 4.23; 5.31 | 6739 |

**Note:** (*) Averaged from the acceleration monitoring data from the period 2019, 1st – 15th April.

(**) Tension forces at the completion after tuning completion from lift-off records.

In the reverse direction, the basic equation of the taut string wire below (1) could be used to estimate the cable tensile based on the identified modal natural frequencies from the monitoring data (Table 1).

$$T = \frac{4mf_n^2L^2}{n^2} \quad (1)$$

Where $m$ is the mass of cable; $f_n$ is the $n^{th}$ natural frequency; $L$ is the free length of the cable and $T$ is the cable tension. The results were compared to the lift-off data performed on site at the completion of the tension tuning and adjustment (Table 1). The errors are less than 5% for the six (06) studied longest cables as showed the figure 2 confirmed the efficiency of the modal natural frequency identification process.

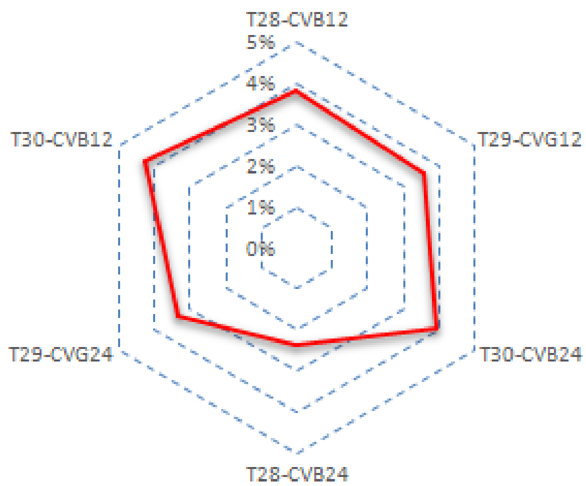


***Fig. 2–Absolut error (+/-) between the calculation values of cable tension from the vibration monitoring data and the lift-off forces after the completion of the tension force tuning procedure***

# 3 Cables wind-induced vibration assessment

### *3.1 Mechanisms of wind-induced vibration*

There are several mechanisms that can potentially leads to vibrations of stay cables. Some of these types of excitation are more critical or probable than others. Vortex excitation, rain/wind combining, and wake galloping were considered in this study.

#### *3.1.1 Rain/Wind Induced Vibrations*

High amplitude of cable vibration could be caused by a combination of rain and moderate wind at low frequencies. Wind tunnel tests have shown that water rivulets forming at the upper and lower surfaces of the cable in rainy weather were the essential components of this aerodynamic instability [8, 9].

The water rivulets moved as the cable oscillated and changed the effective shape of the cable, causing cyclical changes in the aerodynamic forces which led to the wind feeding energy into oscillations. Using realistic cable mass and damping values, the test data obtained by Saito et al. [10] are useful in helping to define the boundary of instability for rain/wind oscillations. Based on their results, rain-wind oscillations can be reduced to a harmless level when the Scruton number follows the criteria of (Eq. 2) in case of effective helical cable surface modification such as in Bach Dang bridge [7]. This criterion can be used to specify the amount of damping that must be added to the cable to mitigate rain/wind vibrations (Figure 5).

$$\frac{m\zeta}{\rho D^2} > 5 \tag{2}$$

#### *3.1.2 Wake Galloping*

Wake galloping is described as an elliptical movement caused by vibrations in drag and cross-wind forces for cables in the wake of other elements, such as towers or other cables. This occurs at high wind speeds and leads to large amplitude oscillations.

The Scruton numberis an important parameter with regard to wake galloping effects:

$$S_c = \frac{m\zeta}{\rho D^2} \tag{3}$$

An approximate equation for the minimum (critical) wind velocity $U_{cr}$ above which (Figure 4b), instability could be expected due to wake galloping effects has been proposed [11, 7]:

$$U_{cr} = c.f.D\sqrt{S_c} \tag{4}$$

where $f$ is the natural frequency; $D$ is the cable diameter; and $c$ is the constant which has an approximate median value of 40 for circular sections [7].

The equation for $U_{cr}$ suggests several possibilities for mitigation. By increasing the structural natural frequency or the Scruton number ($S_c$), the cable will be stable up to a higher wind velocity. However, due to the square root manifestation of $S_c$ in the Eq. (4), increasing the frequency is far more effective. The additional damping, on another hand, could be an effective measure to increase the damping ratio ($\zeta$) and then the Scruton number.

#### *3.1.3 Vortex excitation*

It is considered probably as the most classical type of wind-induced vibrations. The effect is characterized by limited amplitude vibrations at relatively low wind velocities. In case of a single isolated cable, vortex excitation is caused by the alternate shedding of vortices from the two sides of the cable when the wind is approximately perpendicular to the cable axis.

The wind speed (Eq.5) at which the vortex excitation frequency matches the natural frequency (f) is found using the Strouhal Number (S):

$$V_{cr} = \frac{f.D}{S} \tag{5}$$

For circular cross-section cables in the Raynolds number range 1x10$^4$ to 3x10$^5$, $S$ is about 0.2. We can see that for the natural frequency in range of 1Hz or less, vortex excitation could happen at low wind velocity. The oscillations amplitude of the cable is inversely proportional to the Scruton number. Increase the mass ($m$) and damping ($\zeta$) of the cables increases the Scruton number and therefore reduced oscillation amplitudes.

### *3.2 Enhanced damping and field testing*

Inherent cable damping ratios ($\zeta$) of the cable stayed realistically could be estimated in the range from 0.1% to 0.5% and an accurate value is difficult to predict [5]. The damping decrease as the cable length increases and in practice, the intrinsic damping of the individual coated parallel strand un-grouted cable stayed could be estimated using the empirical equation:

$$\delta_{\text{int}} = 2\pi\left(0.24 - 6x10^{-4} L\right) \tag{6}$$

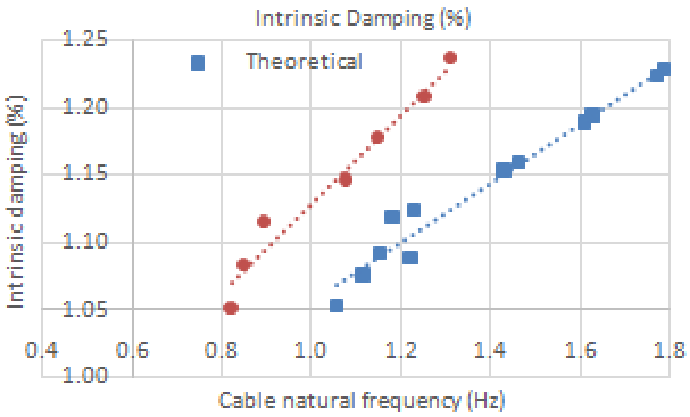


***Fig. 3–Intrinsic damping estimated for Bach Dang stay cables in comparing to the field testing of Nhat Le 2 bridge [6] for similar range of cable length (from 70m to 125m length)***

The figure 3 shows the intrinsic damping estimation for Bach Dang stay cables. The estimated damping values are in line with the field test data obtained in the Nhat Le 2 bridge [6] as well as the damping tests results from other projects.

### *3.3 Scruton number and critical velocity*

The figure 4 presents the values of Scruton number ($S_c$) in regard to the first mode natural frequency (4a) and the critical wind velocities in comparing to the design wind speed of 20m/s (4b). We observe that for cable length of more than 100m, the wake galloping instability may be expected.

From the minimum value of $S_c$ expressed in Eq. (2), and the damping ratio expressed as by definition :

$$\zeta = \frac{1}{\sqrt{1 + \left(\frac{2\pi}{\delta}\right)^2}} \tag{7}$$

The minimum required damping to mitigate the rain/wind vibration could be presented in the figure 5 in comparing to the estimated intrinsic damping values.

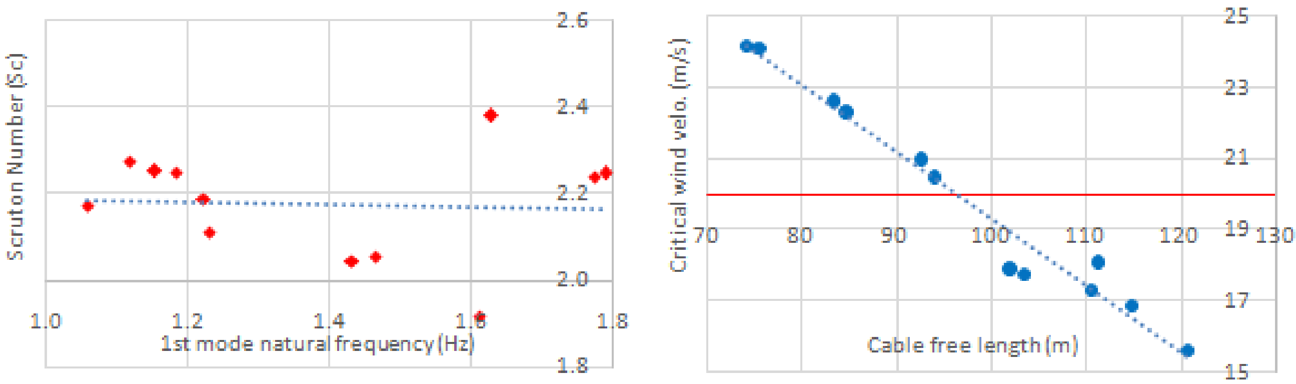


*Fig. 4–Estimated Scruton Number (4a on the left) and critical wind velocities (4b on the right)*

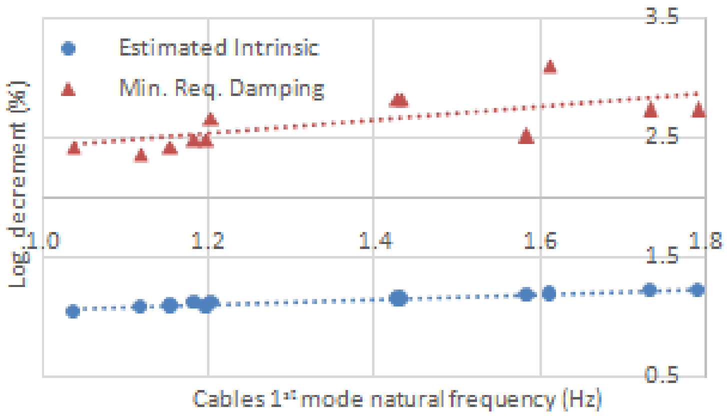


*Fig. 5–Minimum required damping to satisfy the Scruton Number criterion according to 2001, PTI [7] to mitigate rain/wind vibration*

## 4 Conclusion and discussion

A very good accordance between the identified natural frequencies based on the ambient vibration monitoring data and the theoretical values based on the cable tensions lift-off records proves that the modal natural frequencies could be confidently determined from the as-built cable tensions.

Intrinsic damping of the cables was then estimated and compared to the damping test results performed recently at the Nhat Le 2 stay cables bridge with very similar range of cables length. The estimated enhanced damping was in line with the field tests data and comparable to those given in most of International Standard for stay cable.

The determined natural frequencies and estimated intrinsic damping of the cables stay were then used for cable wind induced vibration evaluation regarding to the wake galloping and rain/wind induced vibration possibilities:

- The evaluated Scruton number $S_c$ of all the cables with more than 75m length of the Bach Dang bridge are below the critical value of instability for rain/wind oscillations according to the PTI's criterion (Figure 4a). Additional damping may be needs to completely mitigate the rain/wind vibration effect.

- For cables with evaluated critical wind velocities below the design wind speed (20m/s), wake galloping effects could be expected probably. Based on the relationship between the evaluated critical wind velocities in regard to the cable length of the bridge (Figure 4b), it could be concluded that for cables with length of more than one hundred meter, the risk of wake galloping effect should be considered.

Finally, from the Scruton number criterion, minimum damping needed to mitigate the rain/wind excitation could be determined (Figure 5). That could help for any mitigation solution study including the additional external damper system.

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