Lecture Notes in Civil Engineering

Volume 54

A Further Study on Stay Cable Galloping under Dry Weather Condition

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Abstract. Wind-induced cable vibrations can be classified into several types such as buffeting due to wind gust, vortex-induced vibration, classical galloping with iced cables, wake galloping, parametric excitation, Reynolds number related drag instability, rain–wind induced vibration, high-speed vortex excitation and dry galloping. Among these vibration types, vortex induced vibration and buffeting due to wind gust are generally small amplitude while the last three types are mainly related to stay cables with larger amplitude vibration and the rain–wind induced vibration is the one most frequently observed on site of bridge. Furthermore, mechanism of rain–wind vibration has been fully elucidated in recent years, and some effective control methods have been successfully applied in practice. In particular, dry galloping is still less understood and it would require research that is more intensive. Hence, the aim of this paper is to elucidate the cable vibration characteristic in no rain condition (called "Dry galloping") by wind tunnel test. Finally, the detail of its generation mechanism will be investigated and discussed.

Keywords: stay cable vibration, dry galloping, Scruton number effect, generation mechanism

1 Introduction

Thanks to advanced construction technology and development of building materials, cable-stayed bridge length is being broken time by time. Due to the increase of main span, cable length becomes longer and more vulnerable to wind's attack. Common vibration types are rain-wind-induced vibration, cable galloping in dry weather (dry galloping-DG), vortex-induced vibration and wake galloping. In general definition, dry galloping is classified as one of the wind-induced large amplitude vibration phenomena in no rain condition, usually occurs at high-reduced wind speed. Though there are reported field observations of large amplitude violent cable motions [1-5], no site measurement was conducted for further clarification of possible cause. Recently, some studies showed the existence of dry galloping by wind tunnel test and observation field. Nevertheless, its characteristics have not been fully understood. Nakamura et al. [6] indicated that the galloping generation mechanism is interruption of communication between upper and lower separation flows. Because of communication of two separated

C. Ha-Minh et al. (eds.), *CIGOS 2019, Innovation for Sustainable Infrastructure*,
Lecture Notes in Civil Engineering 54,
https://doi.org/10.1007/978-981-15-0802-8_27

flows can tend to make pressure on upper and lower surfaces of cable become no difference, this lead to change the earodynamic force exciting on cable. In the experiments of Cheng et al.[7], both divergent type of motion and limited-amplitude vibration at high-reduced wind speed were also recorded. The former has similar response as galloping while the latter occurs only in limited range of wind speed with restricted amplitude. Jakobsen et al. (2012) concluded that inherent flow pattern unsteadiness in the critical Reynold number range and its interaction with wind turbulence and inclined angle are significant in forming DG conditions [9]. In the existing studies, characteristics of cable dry galloping have been elucidated to some extent. In addition, the flow field around cable for dry galloping still suspected and unclear. Therefore, to fulfill the literature for dry galloping, further investigation should be carried out. In this paper, wind-induced response of a circular cable was first measured at various angles against the wind, the characteristic of cable dry galloping and its generation mechanism will be elucidated.

2 Wind tunnel test for dry galloping

2.1 Reproduction of dry galloping

Wind tunnel test were carried out under no precipitation to investigate the cable dry galloping. A cable model was fabricated by a high-density polyethylene tube. Diameter and length of the cable model are 158mm and 1,500mm, respectively. The cable model was supported by two coil springs in the vertical 1DOF direction. Cable attitude is defined by the vertical angle α and horizontal angle β as shown in Figure 1. Test was conducted with three vertical angles: α = 9, 25 and 40 degrees and horizontal angles: β = 0, 15, 30, 45, 60 degrees. Other test conditions such as mass, damping, frequency are shown in Table 1.

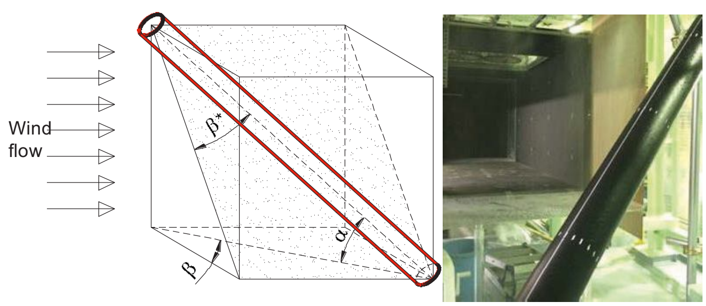


Fig. 1. Set up of cable model

The wind tunnel test results are summarized in Figure 2. Generally, dry galloping took place in many cases. The arrows in Figure 2 show the diverging characteristic of cable at a constant wind speed. Divergent vibration occurred only at some wind attack angles in the subcritical Reynolds number region (6×10^4 - 1.2×10^5). This experimental result is consistent with previous studies [5][8] that dry galloping can occur at wind flow angle from 15°-60° and high wind speed range above 10m/s. As mentioned above, current experiment conduct with low Scruton number range from 3.26 to 11.22. In the other expression, current cable model is sensitive to wind excitation. Therefore, dry galloping seems to take place easily. From these results, it should pay attention that cable dry galloping is one of large wind induced vibration, which can cause divergent galloping.

Table 1. Wind-tunnel test conditions

Parameters	Value
Diameter: D (mm)	158
Effective length : L (mm)	1,500
Inclination angle : α (deg)	9, 25, 40
Flow angle : β (°)	0, 15, 30 ,45, 60
Mass: m (kg/m)	9.9
Natural frequency (Hz)	0.78 – 1.02
Logarithm decrement: δ	0.005 - 0.016
Scruton number ($2m\delta/\rho D^2$)	3.3 – 11.5
Reynolds number	~ 2.1×10^5
Cable's surface	Smooth (normal)

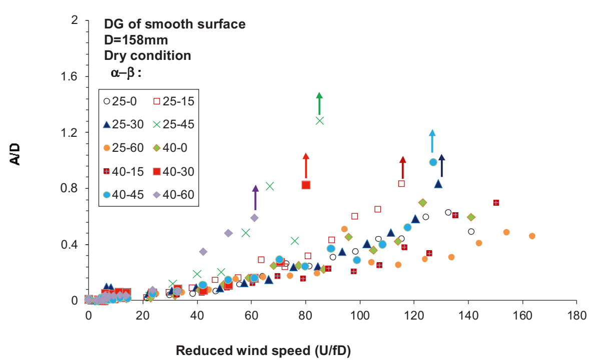


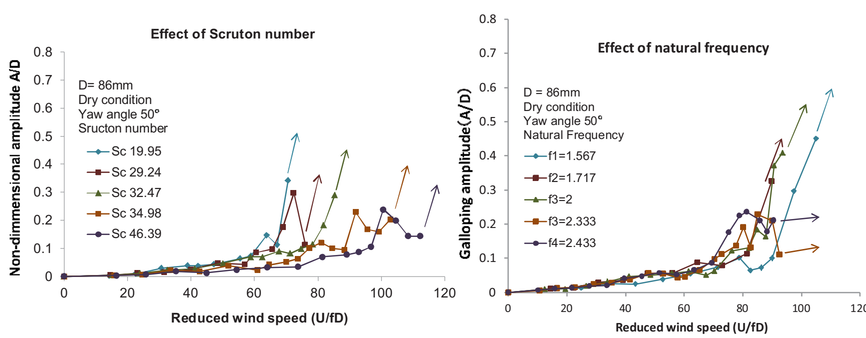
Fig. 2. Dry galloping of smooth surface cylinder

2.2 Sensitivity of dry galloping to Scruton number

In order to investigate sensibility of dry galloping to Scruton number, wind tunnel test was measured with various cases. The Scruton number was changed by increasing the mass of model. According to previous study [5], cable DG can occur horizontally in a range of yaw angle from 30°-60°, therefore current test will carried out with 50° of yawed angle. The effect of Scruton number was estimated as Figure 3a. Generally, cable dry galloping is not so sensitive to Scruton number change. Even though when increases Sc to over 45, divergent galloping still occurred at approximate 15m/s. However, when Scruton number was risen step by steps, the onset wind speed of dry galloping a little bit increased. These outcomes totally agreed with Saito et al [3] that it is quite hard to eliminate dry galloping of cable by adding more external damping or installing the external dampers. Therefore, the way to increase the stability of stay cable should be change of the cable cover to harvest higher the aerodynamic damping so that suppress dry galloping.

2.3 Natural frequency's dependence

The parameters of the these tests are wind yawed angle 50^0 and natural frequencies of the cable model of 1.567Hz, 1.717Hz, 2Hz, 2.233Hz and 2.433 Hz respectively. The frequency was change by increasing the stiffness of supported springs. Figure 3b illustrates the vibration amplitudes against wind speed under different natural frequencies. It is obvious that the increase of the natural frequency of the cable, the vibration amplitude decreases considerably. Dry galloping occurred at around 12-15m/s with the low natural frequency cases, say 1.567Hz, 1.717Hz and 2Hz. However, as natural frequency increased to 2.233Hz and 2.433Hz, dry galloping was vanished up to 20m/s of wind speed. In the other expression, increase natural frequency of stay cable can suppress dry galloping.



a. Effect of Scruton number b. Effect of natural frequencies

Fig. 3. Estimated vibration amplitude with different parameters

2.4 Dry galloping generation mechanism

The fluctuating of wind velocity in the wake of the inclined cable model was recorded along the model. The circular cylinder was mounted in the wind tunnel with flow angle β=30° and inclined angle α= 25°. The hot-wire anemometer was set at 2D from the cable wake and 0.5D from cable axis as shown in Figure 4 and its position along the cable direction was varied from the upstream side to the downstream side at the distances from 2D to 7D. By this set up, the fluctuation of wind velocity will be measured at different wind speeds.

To investigate generation mechanism of dry galloping, normalized power spectrum density at different wind speeds were analyzed for wind speed fluctuation. Generally, normalized PSD is obtained by PSD multiplied with frequency and divided by standard deviation. However, frequency multiplied form is difficult to compare different frequency region, so normalized PSD will be calculated by PSD divide the standard deviation of fluctuating wind speed. According to Figure 4, Karman vortex (KV) was mitigated gradually when wind speed increased. In detail, the normalized PSD was around 0.17 at wind speed 5m/s and reduced to nearly a half at U=10m/s, and then it reached around zero at 15m/s. Typically, Karman vortex Strouhal number (fD/U) of circular is around 0.2 in case cable normal to the wind. However, Strouhal number a little bit decrease as cable orientation is yawed and inclined to the wind. In this figure, the Strouhal number was around 0.18, which is in typical range. According to former literature, it was pointed out that the generation mechanism of galloping is interruption of communication between upper and lower separated flows. Because the communication of two separated flows can tend to cancel pressure difference on upper and lower surfaces of cylinder. In addition, Karman vortex would be produced by communication of upper and lower separated flows, in another expression, the Karman vortex shedding should promote the communication between two separated flows, the interruption of this communication between two separated flows should be identical to the interruption of Karman vortex shedding. Therefore, it can be explained that mitigation of Karman vortex can excite galloping instability [5-8]. In parallel with KV interruption found here, low frequency component started dominating when incoming wind increased. Low frequency component contains much of energy can create high excitation force. There was a relationship between forming of low frequency component and interruption of Karman vortex, when Karman vortex decreased, low frequency increased. That means wake flow itself content various latent frequency (Strouhal number), as Karman vortex frequency suppressed, the other Strouhal component will be dominant. In summary, possible dry galloping's generation mechanism can be summarized as follow: when wind speed is high enough, Karman vortex will be interrupted. At this time, flow pattern will become unstable and its regularity will be lost. It leads to the flow separation will not synchronize periodically at some locations. Consequently, low frequency flow/vortices will be appeared with high energy, which can excite dry galloping.

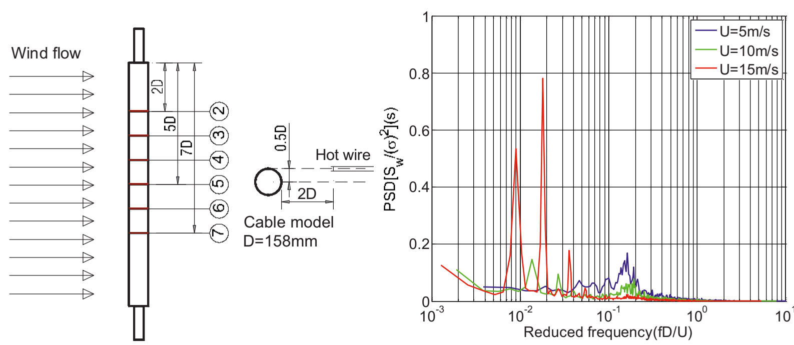


Fig. 4. Normalized PSD (Location 7D, D =158mm, β =30° and α = 25°)

3. Conclusions

In this study, cable dry galloping phenomena was investigated by wind tunnel test. The characteristics of dry galloping also clarified. Furthermore, the detail of its generation mechanism was investigated and discussed. Results obtained are as follows:

- Dry galloping has been reproduced successfully in various conditions. Both restricted response and divergent type galloping were recorded with large amplitude vibration.
- Dry galloping is less sensitive to the cable damping rather than frequency. Therefore, it is hard to suppress the dry galloping by installing the external damper.
- The generation mechanism of dry galloping strongly relates to the forming of low frequency components and interruption of Karman vortex near the wake of cable.

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