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Multiple-scale investigation on aerodynamic stability of Stay Cables considering coupling effects of wind and rain

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ABSTRACT

The phenomenon of rain - wind induced vibration of cables of two different diameters is successfully re - produced using high precision raining simulator through wind tunnel test. The effects of combination of wind speed and rainfall intensity and spiraled wires countermeasure for mitigation of the vibration are investigated. The results indicate that, the mechanism of vibrations with different reduced velocities is different: vibration with high reduced velocity is more like a type of galloping, while vibration with low reduced velocity is more related to vortex-induced vibration.

1. INTRODUCTION

Rain-wind induced vibration of stay cables has attracted most research attempts in its mechanism and mitigation because of its large amplitude and frequent occurrence. Rain-wind induced vibration was firstly reported by Hikami and Shiraishi (1988) on the Meiko-Nishi cable stayed bridge 1987. Since then cable rain-wind induced vibrations have been observed on many other cable-stayed bridges. Field measurements(Yamaguchi 1999, Matsumoto 2003), wind tunnel experiments (Bosdogianni 1996, Flamand 1995, Matsumoto 1995, Gu 2005) and numerical simulations(Rocchi 2002, Li 2005, Liu 2007) are three main method to investigate rain-wind induced vibration. Among them, it is evident that wind tunnel testing method plays the most important role. However, the traditional methodology of wind tunnel experiment has been found to have some problems in refinement testing, for example, simple spraying tapes raining machine, combination of wind speed and rainfall intensity and so on. For precisely and systematically simulating various environmental combinations of wind speeds and rainfall intensities, high precision raining simulators are essential.

The mechanism of rain-wind induced vibrations is not settled. Li(2011) explored the

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characteristics of rain-wind-induced vibration from the aspect of vibration energy. The research indicates that the rain-wind-induced vibration of cables is a type of galloping with a limited amplitude induced by negative slopes of aerodynamic lift coefficients and has the properties of self-excitation and limited amplitude vibrations. Cosentino (2003) measured the unsteady pressures and water thickness by climatic wind tunnel tests. They contested that the RWIV is determined by a flow regime modification which occurs close to the critical Re range. Such flow regime fluctuations are related to the air-rivulet interference and characterized by a certain regularity which gives rise to a cumulative positive aerodynamic work and, subsequently, to the excitation. On the other hand, Matsumoto(1992, 2001, 2007) proposed the influence of the axial flow, the vortex-induced vibration at high reduced wind velocity theory and mitigation of Karman vortex theory to explain the fluid interaction between Karman vortex and axial vortex. They concluded that axial flow and rivulets at particular positions can interfere the Karman vortex shedding, mitigate the intensity of Karman vortex, and then lead to cables' aerodynamic instability. Most galloping theories ignore the influence of axial flow, which is the biggest difference with Matsumoto's theories. In the aspect of rivulet function, some reported that the oscillation and motion of water rivulets could be responsible for the rain–wind-induced cable vibration.(Flamand 1995, Verwiebe 1998 and Chen 2009), while the vortex-induced vibration at high reduced wind velocity theory and mitigation of Karman vortex theory only emphasize positions of water rivulets.

All these results indicate that the rain-wind induced vibration could include more than one mechanism. This work used the first high precision raining simulator in china and re-produced the rain-wind induced vibrations of cables of two different diameters. This vibration, for most of the time , occurs for cables with diameter between 80mm and 200mm. Small diameter of this range is not easy to vibrate. Therefore we used one 139mm-diameter cable standing for middle diameter cables, and one 200mm cable for large ones in the wind tunnel test to explore the aerodynamic instability of cables of different sizes. According to previous works, compared with large diameter cables, more wind tunnel tests of middle diameter cables(120mm~169mm) were conducted. With the development of large-span cable-stayed bridges, the consideration of the large diameter cable is necessary. In this work, the effects of combination of wind speed and rainfall intensity and spiraled wires countermeasure for mitigation of the vibration are investigated, and the mechanism of the rain-wind induced vibration is discussed according to precious works and the experiment results.

2. EXPERIMENTAL DETAILS

The stay cable testing under simulated wind and rain conditions was conducted in the efflux section of the TJ-1 Boundary Layer Wind Tunnel in Tongji University in China, which is an open-circuit wind tunnel. The exit of the wind tunnel has a round contraction section with the diameter of 2.4m, and the distance between the entrance section and the exit section is about 20 m. Wind speed lies between 0.5m/s~12.0m/s. The centers of simulated wind speed, rain intensity and the cable are all in the plane 2m away from the exit section. The model suspension frame and spatial state of cable are shown in Fig.1 and Fig.2 .

Fig.1 Model suspension frame

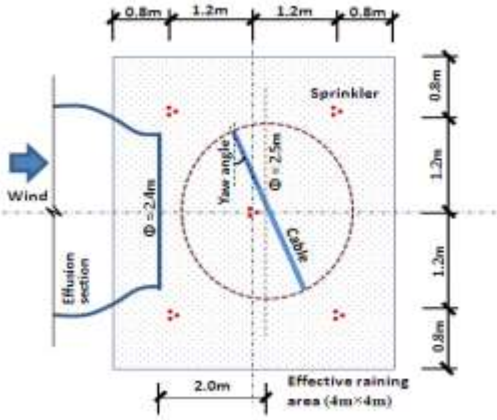


Fig.2 Spatial state of cable

Besides four springs to suspend a sectional cable model, one additional steel wire was also adopted to reduce the large axial displacement of the model in order to avoid instable vibration due to rain-wind coupling actions, and two acceleration sensors were mounted at both ends of the sectional model to measure vertical vibrations of the model. The frequency is 204.8Hz. The damping ratio of the RWIV testing system with sectional models must be kept as low as possible, and the higher damping ratio can be achieved with adding some dampers when required.

In order to precisely simulate rainfall intensity, rain drop size and rainfall uniformity, high precision raining simulator (HPRS) was adopted in artificial raining simulation, as shown in Fig.3 and Fig.4 This HPRS of portable automatic measurement and control rainfall simulation machine ZKSB-3 was developed by Institute of Soil and Water Conservation, AS&MWR. In this refined raining simulator, a kind of special sprayers with full-jet rainfall drop simulator has been utilized. Each sprayer has three bores and can be individually controlled through three electric switches to simulate various rainfall intensities and rainfall uniformity, and to some extent, rainfall drop size. For the following stay cable RWIV testing, The rainfall intensity can be set into eight values from 10mm/h to 80mm/h.

Fig.3 HPRS rain-making simulat

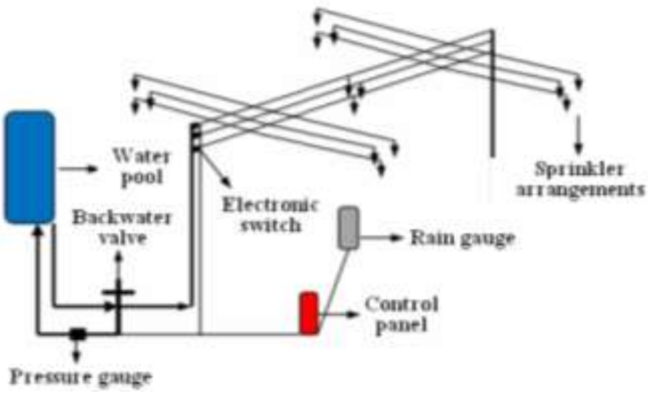
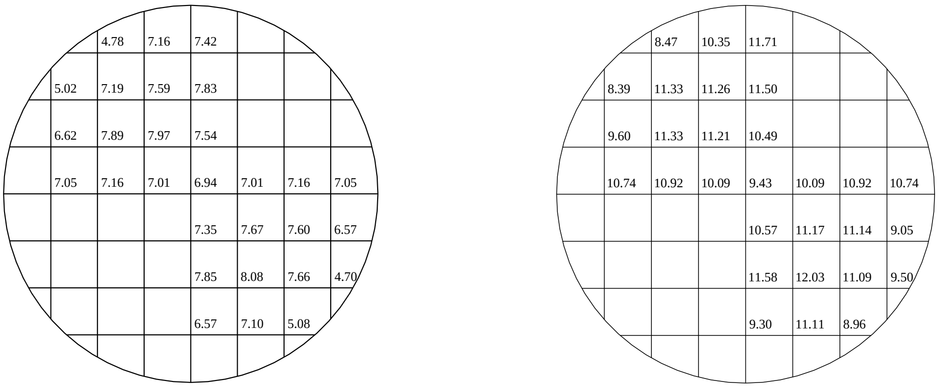


Fig.4 Schematic diagram of HPRS

Wind speeds in the working plane were measured by Xu(2011) with hotline anemometer. The testing wind speeds at the working section were set at 10m/s and 15m/s. Fig. 5 shows detailed information of wind speed distributions at the cross sections under the testing wind speed of 10m/s and 15m/s. The statistical values of wind speeds were shown in Table 3, in which, U is the mean value of wind speed, and σ is the standard deviation.



(U=10m/s) (U=15m/s)

Fig.5 distribution of wind velocity

Table 1 Wind velocity statistic data

Wind speed	10m/s		15m/s	
statistical value	Mean velocity U (m/s)	Standard deviation σ (m/s)	Mean velocity U (m/s)	Standard deviation σ (m/s)
	6.72	1.30	10.46	1.05

The stay cable models used in the testing were designed as sectional models with the length of 2m, one with a diameter of 139mm, the other 200mm. The aspect ratios is 1:1. And the cables were also designed with the prototype PE sheath, without steel wires, resulting in light-weight sectional models of stay cables. Reynolds number and Strouhal number were exactly simulated in the testing(the Reynolds number is between 1.2×10^4 and 1.34×10^5), while the simulation of Scruton numbers were not followed, which were approximately one twentieth of the prototype models for the 139mm-diameter cable and one tenth of the prototype models for the 200mm-diameter cable. Due to the reduced Scruton number, the amplitude of the model could be larger than that of the prototype. Therefore, the result of the wind tunnel test is conservative. The cable characteristics and testing conditions are shown in Table 2 and Table 3. The effectiveness of spiraled wires, one kind of vibration suppression, was also investigated as shown in Table 4.

Table 2 Parameters of cable models

Diameter(mm)	Mass(kg/m)	Frequency(Hz)	Surface treatment
139	3.55	1.034	smooth，spiraled wires（height：1.5mm、2.0mm、2.5mm）
200	6.6	1.067	smooth，spiraled wires（height：2.0mm、2.5mm、3.0mm）

Table 3 Test conditions for cables without spiraled wires

Diameter (mm)	Yaw angle (°)	Inclined angle (°)	Frequency (Hz)	Damping (%)	Wind speed (m/s)	Rainfall intensity (mm/h)
139	20~40	25~35	1.033	0.1,0.3,0.37,0.5	2~10	0~80
200	10~40	25~35	1.099	0.09	1~10	0~80

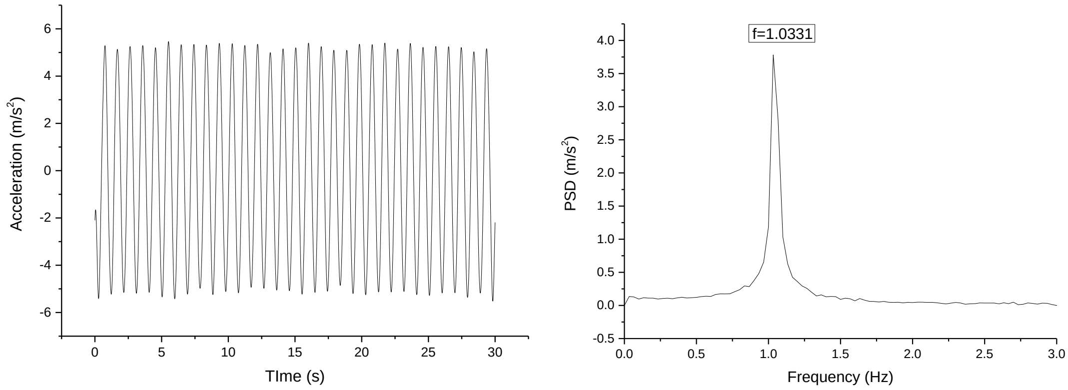
Table 4 Test conditions for cables with spiraled wires

Diameter (mm)	spiraled wires height (mm)	Yaw angle (°)	Inclined angle (°)	Frequency (Hz)	Damping (%)	Wind speed (m/s)	Rainfall intensity (mm/h)
139	1.5 2.0 2.5	25	25	1.033	0.1	2~10	0~80
200	2.0mm 3.0mm	25	25	1.099	0.09	1~10	0~80

3. SELECTED TEST RESULTS

3.1 Results of139mm-diameter cable

According to the field measurement and wind tunnel tests, rain-wind induced vibration only occur with particular spatial states. In our tests, cables vibrated severely when the yaw angle β was 25° and inclined angle α was also 25°. The rain-wind induced vibration occurred with constant amplitude, and the frequency was consistent with the cable's nature frequency. One typical time-history and PSD curves of acceleration are shown in Fig.5 . Fig 6 and Fig.7 show the change of the measured maximum amplitude over rainfall intensity and wind speed respectively. Therefore we can find that, the maximum displacement amplitude of rain-wind induced vibration happened when wind speed is 8m/s and the rainfall intensity is 20mm/h.



a) Time-history　　b) PSD curve

Fig.6 Time-history and PSD curves of acceleration with rainfall intensity 10mm/h（α=25°, β=25°, U=9m/s, ξ =0.1%）

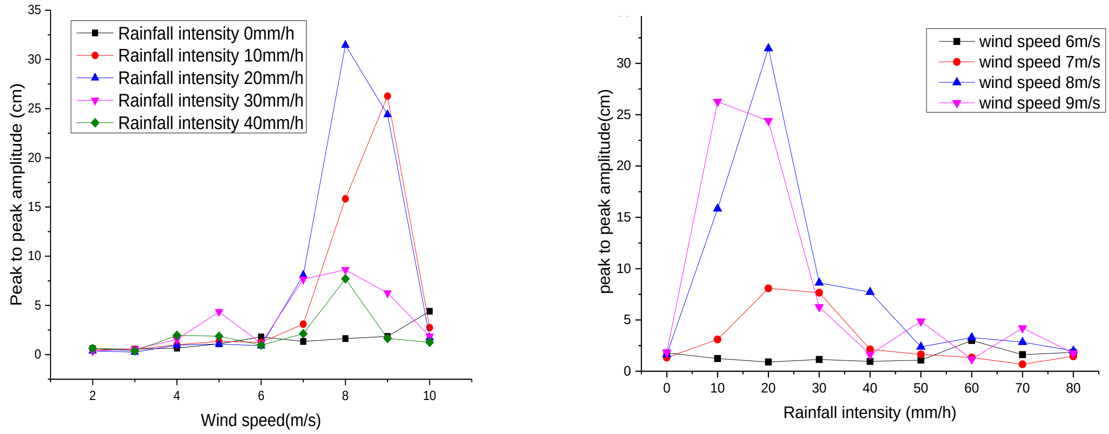


Fig.7 Influence of wind velocity　　Fig.8 Influence of rainfall intensity

The result of the cable with spiralled wires is shown in Fig.2(b). No evident vibration occurs with spiralled wires higher than 1.5mm at rainfall intensity 20mm/h..From the experimental results, it can be seen that the rain-wind induced vibration occurs only in a particular rainfall intensity range. The 139mm-diameter cable is susceptible to light rain. Furthermore, for different rainfall intensity, the cable's vibration wind speed range is different, so is the maximum vibration amplitude. High rain could suppress the vibration.

It was observed that there was no celar upper rivulet for low wind velocity. When wind velocity is over 7m/s, one clear upper rivulet appears. When wind velocity is 8m/s, cables vibrate severely with low rainfall intensity and the regularly oscillating upper rivulet. Cables' vibration is suppressed when rainfall intensity approach 40mm/h. Lower rivulet was observed for most wind velocities.

The influence of damping was investigated by adding some dampers when required. The maximum vibration amplitude change with damping is shown in Fig.8 . The vibration disappears with 0.5% damping. Therefore, increasing damping is an effective way to suppress the rain-wind induced vibration.

The spiraled wire is another effective measure to suppress rain-wind induced vibration. For the cable models with three heights spiraled wires, no evident vibration occurs at any combination of wind speed and rainfall intensity as shown in Fig. 9. Therefore, spiraled wires can totally suppress the rain-wind induced vibration, and a 1.5mm-heigth spiraled wire is high enough.

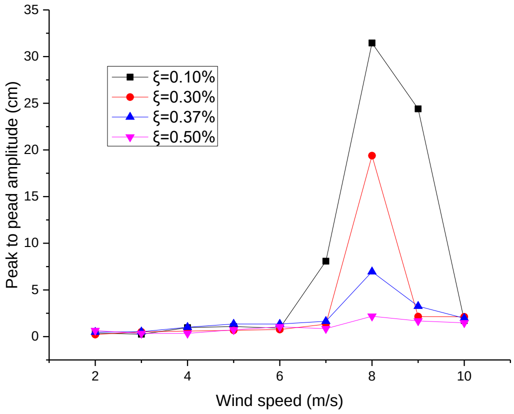


Fig.9 Influence of damping ratio

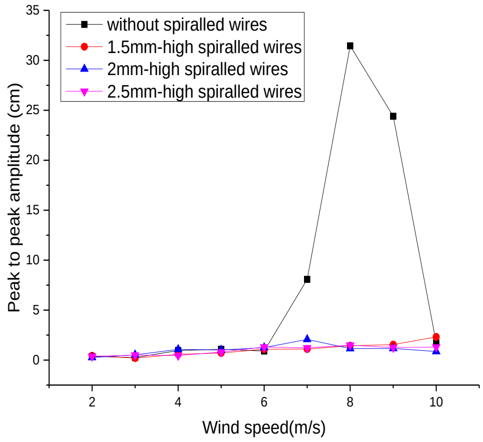
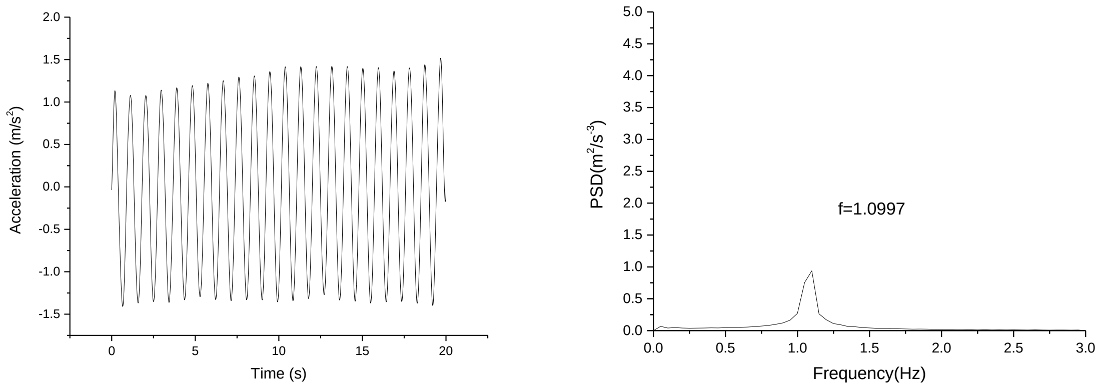


Fig.10 Influence of spiraled wires

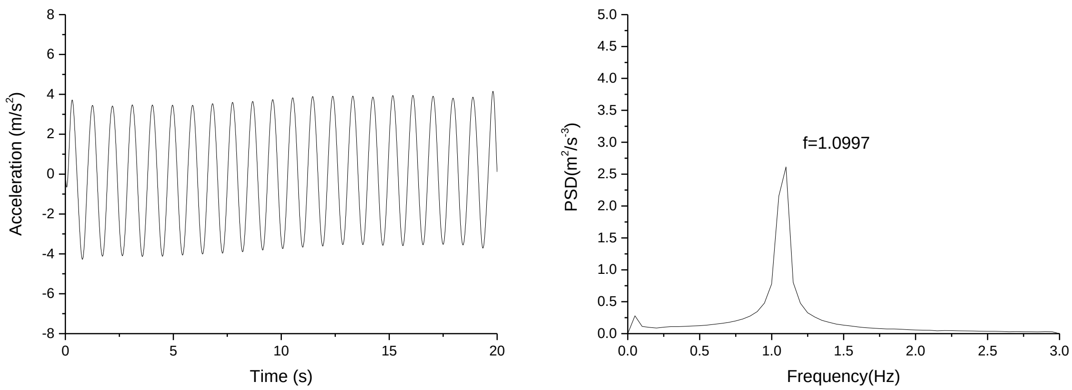
3.2 Results of 200mm-diameter cable

For a 200mm-diameter cable, one literature reports that under the spatial state that β= 25° , 30° , 35° and α= 25°,30°, the cable is susceptible to vibrate with central wind speed 12m/s and light rain. Due to the wind tunnel condition, the cable's vibration when wind speed is about 12m/s was not reproduced. However, the evident vibration occurs when wind speed is 2m/s under β= 25°and α= 25° regardless of the rain. Fig. 10 and Fig.11give the time-histories and PSD curves of acceleration at rainfall 20mm/s and 60mm/h respectively. Fig.12 and Fig.13 show the changes of the measured maximum amplitude over rainfall intensity and wind speed respectively. According to the measured amplitude results, the cable's vibrate regularly with wind speed 2m/s. The vibration amplitude increases with rain. When the rainfall intensity is over 70mm/h, the amplitude decreases and becomes the same with that without rain. No clear upper rivulet was observed for low wind speed. Only the water film formed in the surface.



a) Time-history b) PSD curve

Fig.11 Time-history and PSD curves of acceleration without rain（α=25°, β=25°, U=2m/s, ξ =0.09%）



a) Time-history b) PSD curve

Fig.12 Time-history and PSD curves of acceleration with rainfall intensity 60mm/h（α=25°, β=25°, U=2m/s, ξ =0.09%）

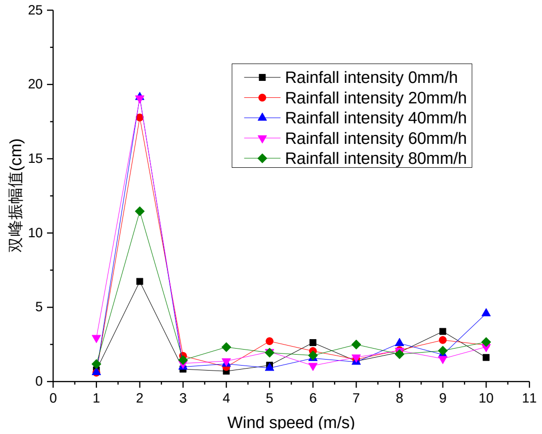


Fig.13 Influence of wind velocity

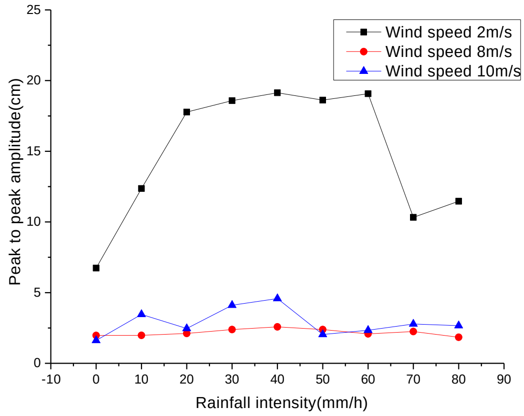
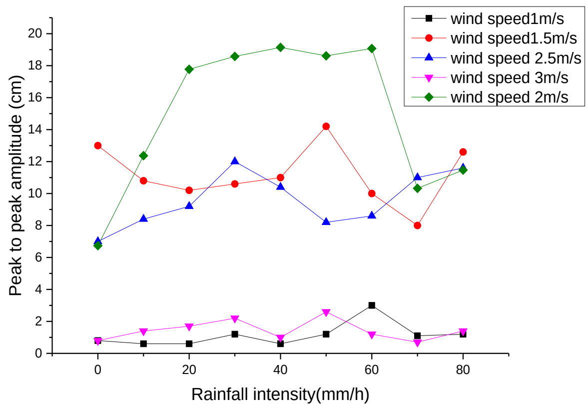


Fig.14 Influence of rainfall intensity

The measured maximum amplitudes of cables with spiralled wires are shown in Fig.14 . The effectiveness of two heights spiralled wires are almost the same. In the rain, the vibrations are significantly suppressed. However, the cable models keep vibrate regularly with an amplitude as large as that without rain.



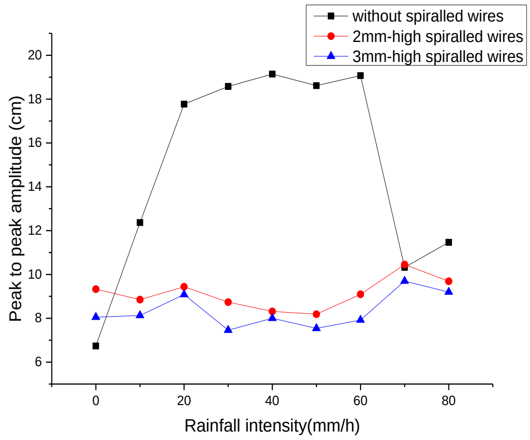


Fig.15 Influence of spiraled wires

Fig.16 Influence of wind velocity around 2m/s

More tests with wind speed between 1m/s and 3m/s(step 0.5m/s) were conducted to investigate the vibration around 2m/s. The results are shown in Fig.15. The cable vibrates regularly without rain at wind speed of 1.5m/s, 2m/s, 2.5m/s. And when wind speed is 2m/s, the amplitude of the vibration increases with rainfall intensity between 20mm/h and 60mm/h. At other wind speed,1.5m/s and 2.5m/s, the amplitudes fluctuate with the rainfall intensity at a low level.The maximum displacement of this cable, appearing at wind speed 2m/s and rainfall intensity 40mm/h, is smaller than that of the 139mm-diameter cable. When the spiralled wires are applied to suppress the vibration. the increase at the wind speed of 2m/s with artificial rain vanishes.

4. RESULT ANALYSIS

In this work, cables with two different diameters are susceptible to vibrate regularly and significantly. However, the condition of wind speed and rainfall and phenomenon of vibration are different. For a 139mm-diameter cable, the vibration amplitude reaches a maximum at wind speed 8m/s and rainfall intensity 20mm/h, and there is regularly oscillating upper rivulet on the cable surface. No evident vibration occurs without rain. For a 200mm-diameter cable, the vibration occurs when the wind speed is around 2m/s without rain, and the amplitude increases largely with the rainfall intensity between 20mm/h and 60mm/h. During the vibration, no clear and complete upper rivulet forms on the surface. The maximum amplitude of the 200mm-diameter cable is smaller than that of the 139mm-diameter cable. According to Xu(2011)'s wind tunnel test, one cable can vibrate under two environmental conditions. One condition is low wind speed and high rainfall intensity. Another one is high wind speed and low rainfall intensity. The former one's amplitude is smaller than the later one's. Therefore, the mechanism for the regular vibration under different environmental conditions could not be completely identical.

Matsumoto(1992) found that stay cable would vibrate severely in a rainless weather, and this kind of vibration was not like traditional galloping or buffeting. They investigated this phenomenon by adding axial flow and then proposed axial flow theory to explain the mechanism of rain-wind induced vibration. Later, Matsumoto(2001, 2007) proposed that vortex-induced vibration and Karman vortex mitigation could be responsible for the cable vibration. The aerodynamic instability of inclined cables would occur by the fluid interaction between Karman vortex and axial vortex, and the upper water rivulet may enhance this instability.

The 139mm-diameter cable's vibration at wind speed 8m/s corresponds to galloping as many literatures concluded. And when the spiralled wires are applied, the vibration vanishes completely. Therefore, it could be the coupled motion between the cable and oscillating rivulet that leads to the vibration. Its mechanism can be explained as a type of amplitude-limited galloping.

However, the 200mm-diameter cable's vibration might be different. The smooth cable section is circular, and its central wind speed of vortex-induced vibration is determined by the Strouhal Number, $St=fvD/U$. The vortex-induced vibration wind speed is around 1m/s for a 200mm-diameter cylinder. The cable vibrates regularly without rain at wind speed of 1.5m/s, 2m/s, 2.5m/s. One of the reasons is that vortex-induced vibration occurs. However, at wind speed 1m/s, the energy of the wind is too deficient to excite vibration. Another reason could be the cable's vibration is influenced by the axial flow as Matsumoto proposed and visualized. The axial flow may mitigate Karman vortex shedding, and enhance the very low frequency component about 1Hz. Additionally, the cable's vibration amplitude increases with rain at wind speed 2m/s. Reported by Zhao(2014), rain can suppress the vortex-induced vibration. In this work, the cable's vibration become more severe with rain, which is in contrast with previous work. Therefore, the vibration could be different from traditional vortex-induced vibration.

At wind speed 2m/s, the Strouhal Number is 2Hz. According to Matsumoto's theory of the fluid interaction between Karman vortex and axial vortex. In this work, if the shedding frequency of the axial vortex is 1/2 of the shedding frequency of Karman vortex, the Karman vortex along the main flow is enhanced every second vortex shedding as illustrated in Fig. 16. Therefore, the low frequency component that is consistent with the cable's natural frequency would be dominant in the wake. Furthermore, Liu(2008) found that from a uniform wind field test, the intensity of axial flow varies with artificial rivulets. Therefore, cables' surface state can influence the axial flow, which may then influence the cable's aerodynamic instability. Additionally, the surface wet state of the cable with water film might result in some Reynolds number effects that leads to the vibration with increasing amplitude. To be concluded, the 200mm-diameter cable's vibration is caused by both axial flow and rain, and is more related to the fluid interaction and vortex shedding than galloping. The vibration of cables with spiralled wires is largely suppressed. It may be result from the damage of water film which can promote or enhance the aerodynamic instability.

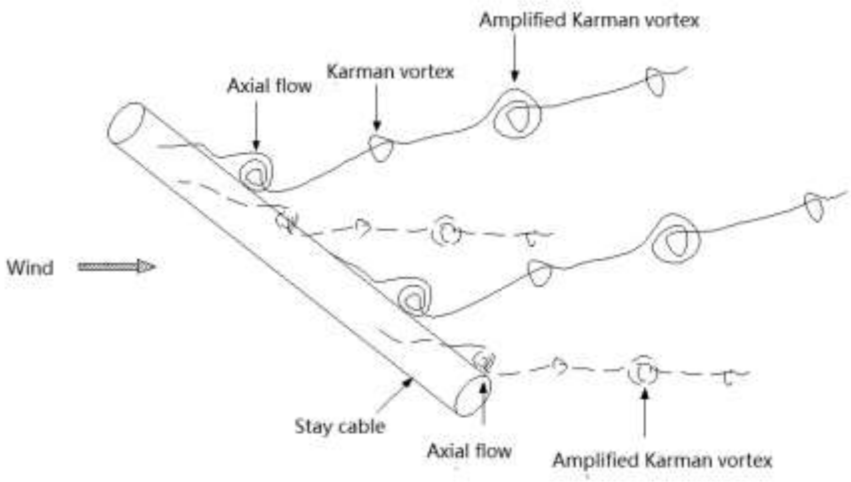


Fig.17 Illustration of axial vortex and Karman vortex

In conclusion, cables' vibrations under different wind speed may result from different mechanism. The 139mm-diameter cable vibration at wind speed 8m/s is a type of galloping, while the 200mm-diameter cable vibration at wind speed 2m/s is more related to vortex shedding, which results from the fluid interaction between Karman vortex and axial vortex. However, more effort is needed to further clarify this phenomenon. Furthermore, the 139mm-cable's vibration can be completely suppressed by 1.5mm-height spiralled wires, while the spiralled wire effectiveness is limited for 200mm-diameter cable. Therefore in practical engineering, the mechanism of cables' vibration should be first clarified and then corresponding measures can be made.

5. COMPARISION WITH FIELD MEASUREMENT

Zuo(2010) summarized characteristics of wind- and rain-wind-induced vibrations observed from two cable-stayed bridges, the Fred Hartman Bridge and the Veterans

Memorial Bridge, during long-term full-scale measurement efforts. He identified three type of wind-induced vibrations of cables. That is Karman-vortex-induced vibration, rain-wind-induced vibration and large-amplitude dry cable vibration. He found that the stay AS16, of which the diameter is 0.141m that is consistent with our 139mm-diameter cable and the frequency is 1.26Hz, is susceptible to the rain-wind-induced vibration, and the stay AS24, of which the diameter is 0.194m that is consistent with our 200mm-diameter cable and the frequency is 0.57Hz, is susceptible to the rain-wind-induced vibration and large-amplitude dry cable vibration.

The field measurement results of rain-wind-induced vibration are shown in Fig.17. The black open circles in the graphs represent the speed and attack angle of the wind during the events when rainfall was recorded, and the solid light-coloured circles represent the instances of these rain-wind events where the stays exhibited vibration amplitude of more than 5% of their diameter at frequencies much lower than the nominal Strouhal frequencies. Specifically, stay AS16 exhibited large-amplitude vibrations only when the attack angle was around or <90°, while for stay AS24, the vibrations occurred over a much wider attack angle range of approximately 40°-160°. The author believed it is primarily due to the different inclination angles of stay AS16(α=45.91°) and stay AS24(α=21.11°).

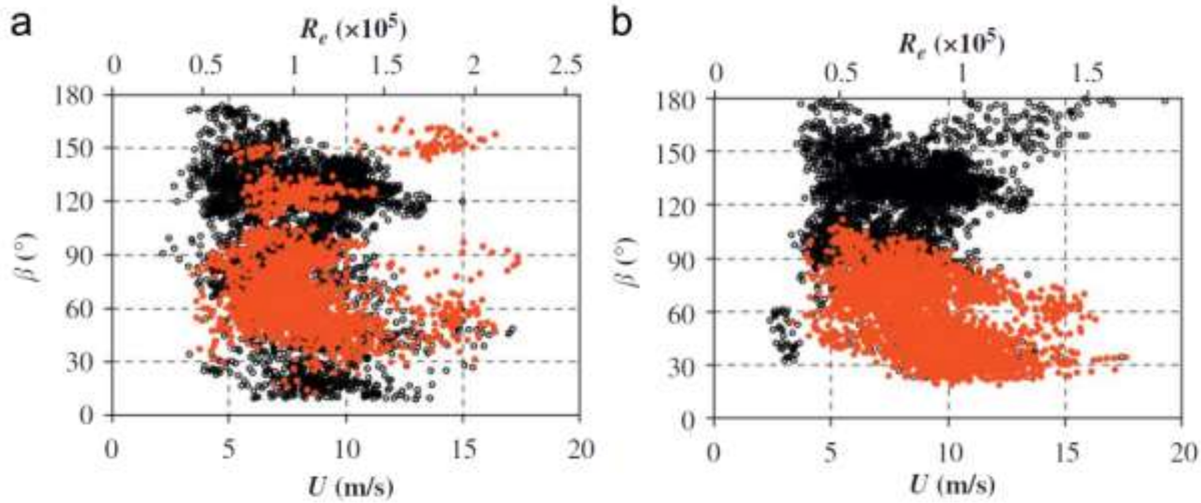


Fig.18 Ranges of wind speed and attack angle for rain-wind-induced vibration of stays (a) AS24 and (b) AS16

Fig.19 and Fig.20 show nodal major-axis displacement amplitudes of recorded steady-state rain-wind-induced vibrations and dry-cable vibrations of stay AS24. The amplitude of the vibrations is represented by the diameter of the circles, and the dimension of the cable diameter (1D=0.194m) is included for reference purposes. For stay AS24,large-amplitude dry-cable vibrations occurred when the attack angle is around or <90°, and the required wind speed appears to increase when the attack angle deviates from 90°. These characteristics are similar to the corresponding characteristics of rain-wind-induced vibrations as shown in Fig.19(a) and Fig.20(a). Comparison of Fig.19(b) with Fig. 20(b) indicates that dry-cable vibrations occurred over a similar reduced velocity range as rain-wind-induced vibrations do. These similar characteristics shared by large-amplitude vibrations with and without rainfall for stay AS24 suggest the potential of a close connection between rain-wind-induced vibration and this class of large-amplitude dry-cable vibration.

a b

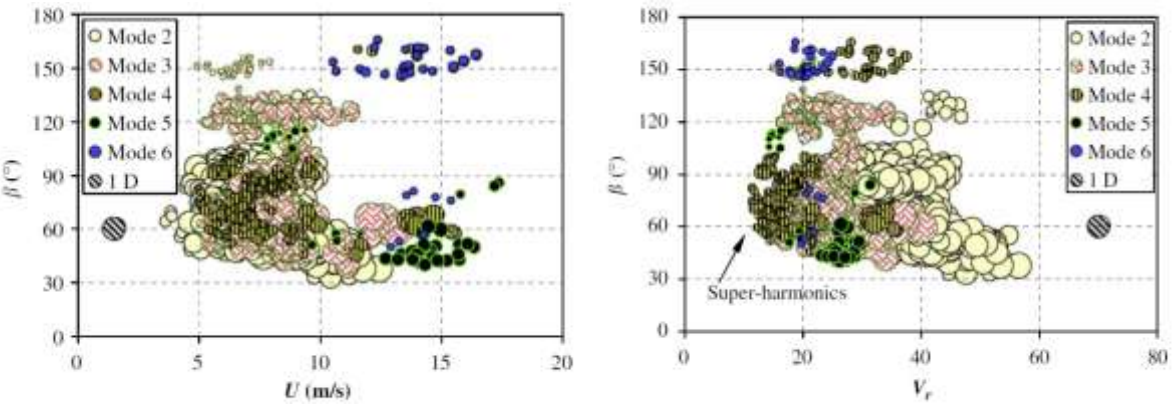


Fig.19 Amplitude vs. (a)wind speed (b) reduced velocity and attack angle for rain-wind-induced vibration of stay AS24

a b

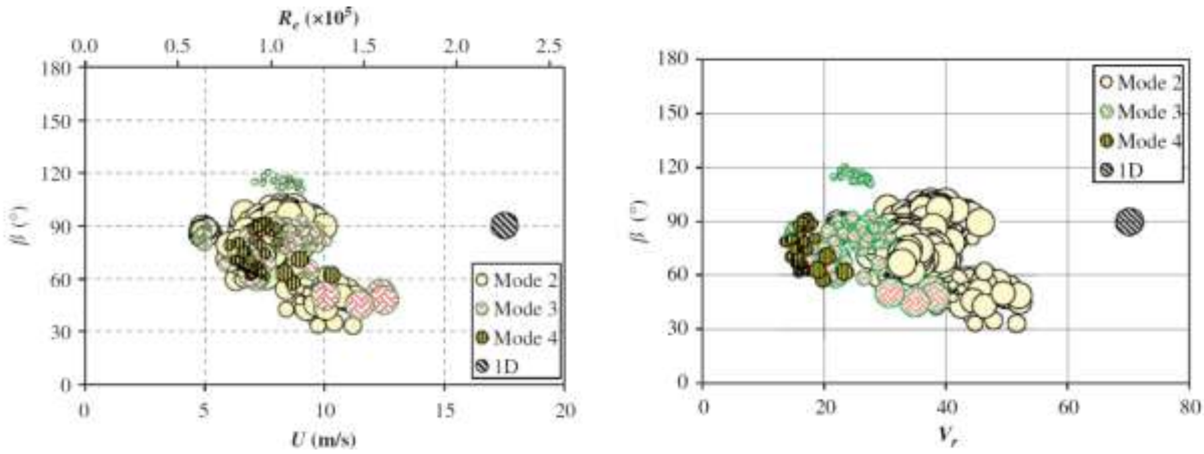


Fig.20 Amplitude vs. (a)wind speed (b) reduced velocity and attack angle for a type of dry-cable vibration of stay AS24

In our experimental results, the 200mm-diameter cable also is also susceptible to both rain-wind-induced vibration and large-amplitude dry-cable vibration at β=25°, which is equal to β=75° in Zuo's definition. At this attack angle when the two vibrations occur, the wind speeds are between 5m/s and 10m/s, and the reduced velocities are between 16 and 42 according to Zuo's field measurements. These two vibrations occur over a same range of wind speed which is around 2m/s and reduced velocity which is around 10 in our experiments. The discrepancy between Zuo's field measurements and our experiments may interpreted by two reasons. First, the sectional mode only has one frequency, which is different from AS24's modes. Fig.19(b) and Fig. 20(b) show that different modes of vibration cluster are in different regions of wind speed and direction. Therefore, the frequency difference may contribute to the discrepancy. Second, the simulation of Scruton number of the 200mm-diameter cable was not followed, which was one eleventh of stay AS24. The cable may vibrate at lower wind speed with the reduced Scruton number.

From Zuo's field measurements and our experimental results, it is clear that rain-wind-induced vibration and large amplitude dry cable vibration share many characteristics on spatial state, the occurrence conditions and vibration responses for a 200mm-diameter cable. It can be suspected that the rain-wind-induced vibration may in fact be due to a mechanism that inherently exists for inclined and/or yawed cables regardless of the presence of rainfall, and that the role of the rainfall is to promote or stabilize this mechanism(or both) at lower reduced velocity. Due to our assumption in chapter 4, the large-amplitude vibrations, with or without rainfall, might be due to a type of vortex shedding that is different from the classical Karman vortex shedding.

6. CONCLUSIONS

This work used the high precision raining simulator and re-produced the rain-wind induced vibrations of cables of two different diameters in wind tunnel. The effectiveness of spiraled wires countermeasure were also investigated. From the test results, cables can vibrate under different environmental conditions. The maximum amplitude of rain wind induced vibration occurs in a different wind speed and rainfall intensity combination when their diameter of cables varies. The experimental results are compared with Zou's field measurements for verification. The 139mm-diameter cable is likely to vibrate with high wind speed and low rainfall intensity, while the 200mm-diameter cable's vibration occurs at wind speed 2m/s regardless of rain.

It can be concluded that the mechanism of these two vibrations are not exactly the same. Different theories can be used to explain the vibrations of the two cables. The mechanism of the 139mm-diameter cable vibration at high wind speed may be explained as a type of galloping. The vibration of the 200mm-diameter cable is more related to vortex-induced vibration, because it can vibrate regularly without rain, which may result from the influence of the axial flow. However, the details are not clarified. More work is needed for further understanding of the mechanism of the cables.

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