ABSTRACT

YiBin Yangze River Bridge is regarded as a typical example in this paper. Characteristics of cables of this bridge are investigated by the statistical method to determine the model parameters for wind tunnel tests. A series of wind tunnel tests are carried out to explore the effect of wind speed, inclined angle, yaw angle, rain precipitation and structural damping ratio on the rain-wind induced vibration of cables in cable-stayed bridges. The results show that cables are prone to rain-wind induced vibration in the combination of $\alpha=25^\circ \cdot 30^\circ$ and $\beta=25^\circ \cdot 30^\circ \cdot 35^\circ$ at the predominate wind speed of about 12m/s; lighter rain can promote the rain-wind induced vibration of cables; and the rain-wind induced vibration is sensitive to the structural damping ratio.

KEYWORDS: CABLE-STAYED BRIDGE, INCLINED CABLE, RAIN-WIND INDUCED VIBRATION, WIND TUNNEL TEST, AERODYNAMIC CHARACTERISTICS

Introduction

In 1984, rain-wind induced vibration of cable stay (abbreviated by rain induced vibration) was first observed on Meiko-Nishi cable stayed bridge with a span of 405m in Nagoya, Japan [Hikami et al. (1988)]. During the later 20 years, researchers home and abroad explore the wind-rain induced vibration problems through theoretical analyze [Wang et al. (1988), Peil et al. (2003) and Gu et al. (2004)], wind tunnel experiment[Xu et al. (2006), Zhou et al. (2006) and Gu et al. (2005)] and field measure[Main et al. (1999) and Chen et al. (2005)].Since several factors are contributed to this phenomenon, such as wind velocity, wind direction, rain precipitation, cable diameter, cable surface material, cable vibration frequency and atmosphere turbulence intensity, mechanism about rain induced vibration is not recognized unitized until to now. Study on rain-wind induced cable vibration is still a hot aspect in the world. Combining the results of field measure, wind tunnel experiment and theoretical analyze in the past 20 years, characters of rain-wind induced cable vibration can be described as following.

(1) Rain-wind induced cable vibration mostly occurs on bridge located in level terrain or constructed above sea due to the low atmosphere turbulence identity in those places. It rarely happen when inflow turbulence identify is relatively high.

(2) Rain-wind induced vibration mainly emerge on cables with smooth PE rope surface, 80~200mm diameter( or 140~225mm diameter presented by some researchers),and 6×104~2×105 Reynolds number. Large and less diameter cables scarcely confront the process.

(3) Vibration appear chiefly as low order modes, but the fourth order mode vibration was also reported. Rain induced vibration is not easy to happen or amplitude is relatively small when natural frequency of cable stay is high.
(4) When cable stay and horizon plane included angle \( \alpha \) is among 20° ～ 50°, possibility of rain induced vibration is enhanced.

(5) When cable stay plane and inflow included angle \( \beta \) is among 20° ～ 60°, possibility of rain induced vibration is great.

(6) Cables in tower leeward side (cables downdip along average wind direction or project of up water way along average wind direction is positive) is easy to vibrate. The phenomenon that one cable plane vibrate while the other do not do appear usually.

(7) Vibration starting wind velocity is arranged between 6.0 and 18.0m/s (or 8.0 ～ 15.0m/s), and converted wind velocity \( U_c \) is 20～90 respectively. Cables scarcely confront the process under large and less wind velocity.

(8) Rain precipitation affects rain induced vibration to some extend. Vibration of cables with different space shapes, diameters, surface types also have various rain precipitation conditions.

(9) Up water way oscillates circumferentially along cable stay surface during rain-wind induced cable vibration. It can be concluded that form of up water way is the necessary condition of rain induced vibration to some degree. But there are reports about rain induced vibration without up water way or rain precipitation.

(10) Rain vibration is hard to appear when cable stay Scruton Number \( S_c \) \( (S_c = \frac{m\zeta}{\rho D} \sqrt{\frac{S_e}{S_b}}) \) greater than 10 or damping ratio bigger than 0.5%.

(11) Rain-wind induced vibration is a kind of vibration in plane principally. But it is also accompanied with vibration out of plane which made the oscillation trace as ellipse shape.

(12) Although mechanism about rain induced vibration is not recognized unitized at present, certain measures have been taken to depress the vibration, main aspects of which are adapting damper or changing cable surface status.

Synthetically, rain-wind induced cable vibration is a violent oscillatory motion of cables in certain space shape induced by integrated function of wind and rain under certain wind velocity range. It is one of the most violent vibration form of cable stay known now.

Taking YiBin Yangze River Bridge as the engineering background, rain-wind induced vibration characters of cable stay are investigated systematically by the wind tunnel tests[Li et al. (2005a)]. YiBin Yangze River Bridge is a 184m+460m+184m cable stayed bridge with two towers and PC beams. Density cable system is used and have 152 pairs cable stay totally with scallop set.

**Cable Stay Statistic Characters and Experiment Parameters Setting**

Before experiment, cable stay inclined angle, natural frequency and ect. need to be analyzed statistically in order to elect typical system parameters and assure the representation of wind tunnel experiment outcomes. YiBin Yangze River Bridge has 304 cables stay in all. We only account one of the two cable planes due to symmetry. Because No.0 cables are vertical and impossible to face rain-wind induced vibration. Statistics below only considers 148 cables without No.0 cables.

**Inclined Angle**

Cable stay inclined angles along bridge span are described in Figure 1 and its statistical quantity can be seen in Figure 2. From Figure 2, cable stay inclined angles mainly focus between 25° and 50°, of which 25° ～ 35° inclined angles take a dominant place. Cables with big inclined angle occupy a minor part of whole bridge and possibility of them to vibrate under wind and rain is small. Moreover, they are usually close to tower and have small length leading to high natural frequency (see Figure 3). Even if rain-wind induced cable vibration occur, amplitudes of them are relatively slight. According to cable stay inclined angles
attributions and disadvantages of big inclined angle cables, three types of inclined angle cables ($\alpha = 25^\circ, 30^\circ, 35^\circ$) are adapted to test representatively.

Natural Frequency

Natural frequencies of all cables are calculated using theoretic expression while finite element method is employed to check typical conditions. Figure 3 shows the first three order natural frequency attributions along span direction. We can get that cables near towers have higher frequency. Second order natural frequencies are above level 1.2Hz and third order frequencies exceed 2Hz. Because vibration amplitude are smaller with vibration order and natural frequency increasing, this study concentrates on cable stay basic frequency safely. For cables with big inclined angle, possibility to vibration under wind and rain is small and having litter amplitude when vibrating, so only cables with inclined angle smaller than 50° (Figure 1) are accounted. Figure 4 illustrates cable stay fundamental natural frequency statistical quantity. 0.75Hz is the dominant frequency and elected as the test frequency of model.

Other Parameters

Wind passing by cable stay can hold various direction, which make wind direction angle a important role in rain-wind induced vibration wind tunnel test. Up to now, most of researches about wind characters do not take account of effect of wind direction. Additionally, there are short of measured wind direction record at bridge site area. It is impossible to gather statistics of Wind direction angle. Grounded on rain induced cable vibration feature, four wind direction angle ($\beta = 25^\circ, 30^\circ, 35^\circ, 40^\circ$) are considered in the wind tunnel model test for safety.

Cables stay of YiBin Yangze River bridge are covered by haversian canals, outer diameter of which represents outer diameter of cables. According to outer diameter, cables
can be divided into three types. Cables with 160mm diameter locate near tower and have short length. They are not easy to face rain induced vibration as a result of low natural frequency and big inclined angle. Cables with 225mm diameter are impossible to vibration under combining function of wind and rain for approaching upper limit of cable diameter of rain induced vibration and. Cables with 200mm diameter occur rain induced vibration easily relatively and have greatest quantity proportion. So, they are selected to be tested.

Measured damping ratio data of cable stay is limited now and considered about 0.1~0.3% in common.

Rain Induced Vibration Model Wind Tunnel Test

Cable Stay Model and Test Devices

Scaling factor of cable stay sectional model is 1:1 with a 2.7m length. Cable model composes of three sectors, two aerodynamic transition sectors at each end and aerodynamic action sector in the middle through rubber belt encapsulation connecting. Transition sector has a length of 0.35m, one end of which connects to action sector and the other owns a hemisphere style. Both transition sectors locate at the outside of wind tunnel outlet transiting aerodynamic forces on model smoothly and weakening the influence of end-effect. Owing to sensitivity of rain induced vibration to hydrophilicity of cable surface material, aerodynamic action sector is made of real haversian canal thus having identical surface status with true cable. It has a length of 2m located in the wind tunnel outlet and bears process of wind and rain. A rigid axle cross the center of transition sectors and action sector with springs linked to the ends. Model additional counterweight locates inner action sector and fixed on rigid axle.

Rain induced vibration of cable stay wind tunnel test devices include signal-testing system, cable stay supporting system, spring suspension system, simulated rain system and external damp system(see Figure 5).

Figure 5: Configuration of Test Equipment

Test Condition

Based on statistic characters of cable stay parameters, twelve space statuses of 200mm diameter cable are tested. Experiments are achieved in Southwest Jiaotong University XNJD-2 wind tunnel (direct wind tunnel special for rain induced vibration). Frequency and damp of
system satisfies test requirement well. System mass is about half of requirement in virtue of test device and condition limitation, which will produce securer results.

Effect of Cable Inclined Angle and Inflow Direction

Cables vibration in different inflow angle $\beta$ and cable inclined angle $\alpha$ are presented as Figure 6-9. When $\beta=25^\circ$ (Figure 6), amplitude regularities with wind velocity in three inclined angle are not well and cable vibrates slightly at $\alpha=35^\circ$. When $\beta=30^\circ$ (Figure 7), cable vibration is not obvious at $\alpha=35^\circ$ while amplitude regularities with wind velocity are well in other two inclined angles. When $\beta=35^\circ$ (Figure 8), cable vibrates obviously in all three inclined angles. When $\beta=40^\circ$ (Figure 9), cable vibrates slightly.

In sum, rain induced vibration is easy to happen under the combination of $\alpha=25^\circ \cdot 30^\circ$ and $\beta=25^\circ \cdot 30^\circ \cdot 35^\circ$. Mean square root amplitude can reach 214mm and maximal single edge amplitude can go up to 406mm. Rain induced vibration center vibration starting wind velocity is about 12m/s. According to literatures [Li et al. (2005b)], return period of wind velocity calculated is 0.154 year (based on 31.9m/s designed wind velocity at cable stay center height position), which is equal to 6~7 times per year.

Table 1: Cases of Wind Tunnel Test for Rain-Wind Induced Vibration

<table>
<thead>
<tr>
<th>No.</th>
<th>Inclined angle ($\alpha$)</th>
<th>Inflow angle ($\beta$)</th>
<th>Wind velocity</th>
<th>Rain precipitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25°</td>
<td>25°</td>
<td></td>
<td></td>
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<tr>
<td>2</td>
<td>25°</td>
<td>30°</td>
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<td>3</td>
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<td>10</td>
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<td>12</td>
<td>35°</td>
<td>40°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td></td>
<td></td>
<td>Velocity range is From 6m/s to 15m/s. Increment is 1 m/s below 10m/s, which is 0.5 m/s when vibration is obvious.</td>
<td>Adjusting rain precipitation at each wind velocity level in different conditions to promote forming up water way.</td>
</tr>
<tr>
<td>14</td>
<td>Comparing 10 types of rain precipitation at 12m/s wind velocity when $\alpha=25^\circ$ and $\beta=30^\circ$ in order to inspect the effect of rain precipitation on vibration amplitude.</td>
<td>Comparing 3 types of damp at 12m/s wind velocity when $\alpha=25^\circ$ and $\beta=30^\circ$ for the sake of exploring the effect of damp on vibration amplitude.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 6: RMS of Cables at the Yaw Angle $\beta=25^\circ$

Figure 7: RMS of Cables at the Yaw Angle $\beta=30^\circ$
Effect of Rain Precipitation

Ten types of rain precipitation at 12m/s wind velocity when $\alpha=25^\circ$ and $\beta=30^\circ$ are tested (see Figure 10). Cable vibrates slightly without rain precipitation. When water pressure arrives at 0.02MPa, amplitude comes to a peak. Further raising water pressure (equal to increasing rain precipitation), amplitude decreases sharply. It is tough to measure actual rain precipitation under wind. However, ten types of rain precipitation introduced in the text must contain light rain, moderate rain and heavy rain in term of rainfall state (Figure 10). The tests demonstrate that it is facile for cables to vibrate under slight rain or even drizzling rain while oversize precipitation restrain rain induced vibration of cables.

Effect of Cable Damp

Three types of damping ratio at 12m/s wind velocity when $\alpha=25^\circ$ and $\beta=30^\circ$ are tested by installing liquid dampers(see Figure 11). Results show that rain induced vibration of cables is susceptible to damping ratio and amplitude drop remarkable with damping ratio rising.

Conlusions

Through statistic analyze, cable stay inclined angles mainly focus between 25° and 50°, of which 25° ~ 35° inclined angles take a dominant place. Three inclined angle types of cables ($\alpha= 25^\circ$, 30°and 35°) are adapted to test representatively. 0.75Hz is the dominant frequency among basic frequency and elected as the test frequency of model. Cables with 200mm diameter occur rain induced vibration easily relatively and have greatest quantity proportion. Cables with 200mm diameter are selected to be tested.
Grounded on the test parameters described above, we can gain the results as following by systematic model rain induced vibration wind tunnel test.

(1) Rain vibration is easy to happen under the combination of $\alpha=25^\circ, 30^\circ$ and $\beta=25^\circ, 30^\circ, 35^\circ$. Mean square root amplitude can reach 214mm and maximal single edge amplitude can go up to 406mm.

(2) Rain vibration center vibration starting wind velocity is about 12m/s. Return period of this velocity is 0.154 year and the probability to occur is $6 \sim 7$ times per year.

(3) It is facile for cables to vibrate under slight rain or even drizzling rain while oversize precipitation restrain rain induced vibration of cables.

(4) Rain induced vibration of cables is susceptible to damping ratio and amplitude drop remarkable with the damping ratio rising.

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