Surface and Raindrop Effect on Aerodynamics and Wind-induced Vibration of Stayed Cables

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Abstract

Stay-cable vibrations have been observed in wind tunnel and field observation many times, the excitation mechanism remains unclear. It is pointed out that dry galloping, one type of the vibration that happens in dry condition without rainfall, have related to Reynolds number effect, while surface roughness can effect flow field around cable, so the relation between surface roughness to dry galloping need to be studied. New cables of cable-stayed bridges are covered by smooth polyethylene material. With the growth of service time, sunshine effect and dust adhesion increase the surface roughness of the cables. In rainy days, raindrop on cable surface can also affect surface roughness. In this paper, seven circular cylinders with various value of surface roughness were covered with abrasive papers and tested in fixed and elastically mounted wind tunnel tests. At the same time, free vibration tests were carried out in rainy condition. The results show that the surface roughness significantly influences the aerodynamic forces and stability in the critical Reynolds number range. With the increasing of surface roughness, the vibration amplitude become small in critical Reynolds number range. Raindrop can weaken Reynolds number effect.

Keywords: cables, surface roughness, wind tunnel tests, dry galloping, raindrop effect

1 Introduction

For the past several years, dry galloping has attracted much interest, the phenomena have been reproduced in several wind tunnel tests$^{[1-5]}$. It is pointed out that the critical Reynolds number plays an important role in their behavior$^{[2, 5-7]}$.

The critical Reynold number range was first used to describe the flow state corresponding to the drag crisis in the plot of drag coefficient against Reynolds number. In this range, a transition occurs close to or in the boundary layers on the surface of the circular cylinder. The flow state in the critical Reynolds number range can be divided into three specific regimes, pre-critical (TrBL0), one separation bubble (TrBL1) and two separation bubbles (TrBL2)$^{[8]}$.

The characteristics of aerodynamic forces in these three regimes depend on the flow transition on the boundary layer which is very thin at high Reynolds numbers. The effect of surface roughness on transition in the boundary layer can be understood from two aspects. First, surface roughness influences the formation of the boundary layer by increasing the skin friction. Therefore, the boundary layer grows more quickly on rougher surfaces. When the irregularities protrude through the boundary layer, the flow state will differ from that when the irregularities are wholly embedded within the boundary layer. Second, a rough surface induces turbulence at a similar scale to the thickness of the boundary layer. The roughness-generated turbulence may have a significant influence on the transition.

The large amplitude vibrations of the circular cylinders in the critical Reynolds number range have been explained in term of three main aspects: unsteadiness of the flow state$^{[5]}$, axial flow for inclined cylinders$^{[6]}$and imperfections of the circular cylinder$^{[7]}$.

This paper aims to reveal the effect of uniform surface roughness and raindrop on the aerodynamic forces and vibrations of cables in the critical Reynolds number range. The surface roughness was simulated by covering the cylinder with silicon carbide abrasive paper. Seven models with various values of surface roughness were tested for static aerodynamic forces with high-frequency balances at both ends and for cross-wind vibrations through a single-degree-of-freedom elastically mounted system.
2 Wind tunnel tests

The wind tunnel used in this study is a closed/open circuit type with two sections, located at Shijiazhuang Tiedao University. The large section is 4.4m in width, 3.0m in height, 24.0m in length and can reach a wind velocity of up to 30.0m/s; The small one is 2.2m in width and 2.0m in height, 5.0m in length and can reach a wind velocity of up to 80m/s. The tests of this research were carried out in the small section. The turbulence intensity in the working section is approximately 0.2%. The wind tunnel is shown in figure 1.

Wind tunnel test includes two parts: force test and vibration test. According to the investigation results, the diameters of stay cables are usually 80~190 mm, and 110~140 mm are used most. In addition, the natural frequency is generally 0~3 Hz. Therefore, depending on the requirement of blocking ratio and the size of the test section, the full-scale model was adopted in the wind tunnel test.

In the static force test, the length of model is 1.7m, which is connected to the ATI high frequency force balance through the steel pipe on both sides. The balances were fixed on the rigid frame outside the wind tunnel, which can measure 6 freedom forces and moments.

In order to eliminate the end effect, the end plate which diameter was 5 times of cable model diameter and compensation model were installed at both ends of the model. The end plate was fixed on the compensation model to avoid the aerodynamic force of end plates being measured. The static test model system is shown in figure 2 (a).

Seven models with different surface roughness were tested in static and dynamic tests. The smooth model was made of plexiglass, and the six others were covered by abrasive papers around plexiglass.

Four vertical springs were connected at each end of the model. The springs were fixed on the rigid frame outside the wind tunnel. The model, end plates and springs made up the vibration system. The displacements were measured by two laser displacement meters installed on the outer wall of the wind tunnel. The dynamic test model system is shown in figure 2 (b). The model picture and abrasive papers are shown in figure 3.
The surface roughness are measured by SJ-410 high-precision surface scanner. Shape parameters and roughness factors for the different models are shown in table 1.

Table 1 Shape parameters for the different models

<table>
<thead>
<tr>
<th>Model</th>
<th>Abrasive paper</th>
<th>Diameter/mm</th>
<th>Roughness Pa/μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>No</td>
<td>120.13</td>
<td>0.51</td>
</tr>
<tr>
<td>M2</td>
<td>P5000</td>
<td>120.39</td>
<td>5.36</td>
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<tr>
<td>M3</td>
<td>P3000</td>
<td>120.39</td>
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<tr>
<td>M4</td>
<td>P1200</td>
<td>120.56</td>
<td>5.98</td>
</tr>
<tr>
<td>M5</td>
<td>P600</td>
<td>120.43</td>
<td>11.24</td>
</tr>
<tr>
<td>M6</td>
<td>P100</td>
<td>120.59</td>
<td>41.06</td>
</tr>
<tr>
<td>M7</td>
<td>P60</td>
<td>120.98</td>
<td>75.02</td>
</tr>
</tbody>
</table>

3 Roughness effect on Aerodynamic force

The variations of mean drag and lift force coefficients with Reynolds number and surface roughness are shown in figure 4. It can be seen that a significant feature in the critical Reynolds number range is the sudden drop in the drag force coefficient curve, known as the ‘drag crisis,’ which was observed for all tested models. In critical Reynolds number ranges, with the increasing of surface roughness, the lift force coefficients decrease correspondingly, the drop degree of drag force coefficients decrease, and the value of critical Reynolds number decrease correspondingly.

Figure 4. Drag and lift force coefficients of model in different surface roughness

4 Roughness effect on free vibration amplitude

The variations of free vibration amplitude with Reynolds number and surface roughness are shown in figure
5. Here, the vortex-induced vibration in low wind velocity was not measured and was not plotted. It can be seen that in different surface roughness, vibration amplitudes in critical Reynolds number are different, roughness can effect vibration feature significantly. For smooth cable model, the amplitude is up to 128mm. With the increasing of roughness, vibration amplitude decrease correspondingly. When roughness up to 75.02μm, no vibration was observed in critical Reynolds number range.

![Graphs showing vibration amplitude in different surface roughness](image)

Figure 5. Free vibration amplitude of model in different surface roughness

5 Raindrop effect on free vibration amplitude

The variations of free vibration amplitude with Reynolds number and surface roughness, in dry condition and rainy condition, are shown in figure 6. As the vibrations in critical Reynolds number range are so sensitive, even small change of model setting can influence the amplitude results.

It can be seen that in dry condition, the models which show different amplitude vibration in critical Reynolds number range, raindrop can influence the amplitude significantly, no obvious vibration was observed in critical Reynolds number range in rain condition.

![Graphs showing vibration amplitude in dry/rain condition](image)

Figure 6. Free vibration amplitude of model in dry/rain condition
6 Conclusion

Wind force for fixed cable models in different surface roughness and free vibration for spring-supported cable models in dry and rainy condition were measured, the effect of surface roughness on aerodynamic forces, the effect of surface roughness and raindrop on free vibration in critical Reynolds number range were investigated. 

1) In critical Reynolds number ranges, with the increasing of surface roughness, the lift force coefficients decrease, the drop degree of drag force coefficients decreases, and the value of critical Reynolds number decrease correspondingly.

2) In critical Reynolds number ranges, with the increasing of roughness, vibration amplitude decrease. When roughness up to 75.02μm, no vibration was observed in critical Reynolds number range.

3) In dry condition, the models which show different amplitude vibration in critical Reynolds number range, raindrop can influence the amplitude significantly, no obvious vibration was observed in critical Reynolds number range.

Acknowledgments

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