Effects of Upper Rivulet During Rain-wind Induced Vibration

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Abstract: Rain-wind-induced Vibration (RWIV) appearing on cable stayed bridges involves complicated fluid and structure interactions and its mechanism is not fully understood. It is believed that the upper-rivulet which is often seen when the RWIV occurs plays an important role. In this study, the effects of the upper rivulet to the aerodynamic forces on the cable and flow pattern around it were numerically investigated. Different azimuths of the attached upper rivulet ranged from 0 to 60° were involved. The result showed that as the rivulet located at different position the boundary layer changed a lot and the forces on the cable and the flow patterns of the wake behind the cable were so that changed.

Key words: Rain-wind induced vibration, large eddy simulation, flow pattern, Strouhal number, cable stayed bridge, rivulet attached cable

INTRODUCTION

Rain-wind Induced Vibration (RWIV) is a kind of instability that appears on cable stayed bridges under rainy weather even with a low wind speed. Hikami and Shiraishi (1988) first reported this phenomenon. They observed the upper and lower water rivulets on the surface of the stayed cable when RWIV happened. Matsumoto et al. (1995, 2003) classified RWIV into three types, the “galloping” type, the vortex shedding type and their mixed type. They believed that the most important incentives for RWIV were firstly the “upper water rivulet” and/or “axial flow” and secondly the three-dimensionality of conventional Karman vortex shedding along the cable axis. Having realized the importance of the rivulets, many researchers tried to interpret such an inducement. Rivulets effect was experimentally studied by Bosdogianni and Olivari (1996) where, two attached bars on cylinder surface were used to represent the rivulets and a strong increase in the amplitude of the cylinder oscillation was observed. Zhan et al. (2008) carried out an experiment for a cable with artificial rivulets in wind tunnel, in which the effects of the inclination as well as the yaw angle of the cable orientation were considered. They found that the vortex-shedding-induced vibration occurred at a very low wind speed and the Strouhal number of an inclined cable was different from that of a horizontal one. They also observed that the galloping occurred when the artificial rivulet was placed at certain positions. More experiments were carried out by Alam and Zhou (2006, 2007) to study the fluid dynamics around an inclined circular cylinder with and without water running over its surface. It was found that the rivulet running over the cylinder surface behaved quite differently depending on the Reynolds number which subsequently impacted greatly upon the fluid dynamics around the cylinder. Further experimental investigation (Alam et al., 2010) was conducted about the wake of a circular cylinder with two tripwires. By analyzing the aerodynamic forces on the cylinder for different tripwire azimuth angles, it was pointed out that a bi-stable phenomenon may be closely linked with rain-wind-induced cable vibration.

Though it is now known that the RWIV is caused by the combined interactions between rain, wind and cable-rivulet structure itself and the upper rivulet plays an important role in the interaction. However, the mechanism of this complicated fluid-structure interaction is not fully understood yet. Numerical simulation of flow around rivulet attached cable will help gaining more knowledge about this. Flow field around different kinds of bluff body and body combinations were numerically studied in the past, briefly as in So et al. (2001), Shirani (2001), Benazzza et al. (2007) and Islam and Zhou (2009) and the issue that involved cross flow past circular cylinder was mainly concerned, in most of which the aerodynamic forces and flow patterns were analyzed. However, the structure of a cylinder with an attachment on its surface which a RWIV can be modeled into, was seldom reported. One of the few was done by Li et al. (2010) who treated the oscillation of the cable as a given moving boundary. By applying the moving boundary condition into a 2-D simulation model, the transient aerodynamic

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forces of the cable with a predetermined cable oscillation was obtained. Another 2-D model was developed by Robertson et al. (2010) to evaluate the formation of a thin film of water on the surface of a horizontal circular cylinder. As it is seen, those simulated results about RWIV were restricted to 2-D. To the best of our knowledge, 3-D simulation of flow around rivulet attached cable was not seen. Accordingly, a numerical investigation about the 3-D flow around a RWIV model was carried out in this study. In the RWIV model, the cable was represented by a circular cylinder and the upper rivulet was replaced by an attached arch. The 3-D transient flow fields around the models with different rivulet attached angles were simulated using Large-eddy Simulation (LES) method. By representing the flow field around the cable when RWIV happened and analyzing the forces characteristics of the cable, it was hoped to uncover the affection of upper rivulet during a RWIV.

**NUMERICAL METHOD**

**Physical model:** To simulate a cable with upper rivulet, a cylinder with an elliptical arch attachment is considered as shown in Fig. 1, where, D is the diameter of the cylinder, U is the velocity of the uniform incident flow, L, h and θ are the width, height and azimuth of rivulet attachment, respectively and $S_b$ represents the front stagnation point. The values of L and h are set as $\pi D/24$ and $D/20$, respectively which are comparable to those values reported by Lemaître et al. (2007).

**Governing equations:** The value $6.8 \times 10^4$ of Reynolds number based on cylinder diameter D and incident velocity U is selected which indicates that the flow is subcritical, therefore turbulent modeling must be considered. Thus Large-Eddy Simulation (LES) method is employed for the flow simulation. The filtered incompressible N-S equations in dimensionless form are:

$$\begin{align*}
\frac{\partial \tilde{u}_i}{\partial t} + \frac{\partial \tilde{u}_i \tilde{u}_j}{\partial x_j} &= 0 \\
\frac{\partial \tilde{u}_i}{\partial x_i} + \frac{\partial \tilde{p}}{\partial x_i} + 1 &= \frac{1}{Re} \frac{\partial^2 \tilde{u}_i}{\partial x_i^2} - \frac{\sigma_{i}}{\sigma_{ij}} \quad (i=1,2,3) \quad (1)
\end{align*}$$

where, $\tilde{u}_i$ are the filtered dimensionless velocity components in Cartesian coordinates along the i-th direction ($i = 1, 2, 3$ corresponding to x, y, z directions), $\tilde{p}$ is the filtered pressure, $\rho$ and $\nu$ are the density and kinematic viscosity of the fluid, respectively, $\sigma_{ij}$ is the SGS stress.

**Computational domain and discretization:** The computational domain is shown in Fig. 2. For the purpose of producing smooth and structural grid, a semi-cylinder computational zone with radius of 15D is selected in the upstream of the cylinder and a rectangular computational zone is used in the downstream of the cylinder where the outlet of the zone is set at a distance of 25D away from the cylinder center. The scale of the computational zone in the axial (span-wise) direction is set as 5D. The first layer of the grid in the normal direction to the cylinder surface is located at a distance $y^+=1$ from the cylinder, where, $y^+$ is a dimensionless length based on wall shear stress and flow viscosity.

Finite volume method is introduced for spatial discretion and the SIMPLEC algorithm is applied to uncouple the pressure-velocity equations. A second order upwind scheme is used for both velocity and pressure spatial discretizations and a second order implicit scheme is employed for the temporal part. Dirichlet boundary condition is taken at the inlet boundary, i.e., $u = 1$ and $v = w = 0$ and Neumann boundary conditions are applied at other boundaries where the normal
gradients of all variables are assumed to be zero. No-slip boundary condition \( u = v = w = 0 \) is used at the cylinder surface.

**Items:**

- Reynolds number (Re): 
  \[
  \text{Re} = \frac{UD}{v}
  \]  
  \[
  (2)
  \]

- Strouhal number (St): 
  \[
  \text{St} = \frac{fD}{U}
  \]  
  \[
  (3)
  \]

where, \( f \) is primary frequency that lift force vibrates.

**Force coefficients:** Assuming that \( F \) is the drag or lift force on the cylinder, then the force coefficient will be:

\[
C = \frac{F}{\frac{1}{2} \rho U^2 A}
\]  
\[
(4)
\]

where, \( A \) is the frontal area. In present study \( C_p \) and \( C_f \) are used to represent drag and lift force coefficients. Similarly, the surface friction coefficients \( C_f \) is defined using surface friction \( E_r \). The fluctuations of lift and drag force coefficients which are given by the root mean square values are identified with \( C_{df} \) and \( C_{lp} \).

**Pressure coefficient (C\(_p\)):** Let \( p_o \) be the far away pressure of incident flow and \( p \) be the total pressure, then the pressure coefficient is given by:

\[
C_p = 2(p-p_o)/\rho U^2
\]  
\[
(5)
\]

**VALIDATION**

Validation is carried out first with a plain circular cylinder. This part focuses on both the efficiency of numerical methods and the grid resolution independency. Four different grid systems are examined named Test-A, B, C and D listed in Table 1. Test-A, B and C have the same circumferential grid but different axial grids. Test-D has medium axial grids and less circumferential grids.

The resulted force coefficients and Strouhal number are presented in Table 2, where some results from literature are also presented for comparison. It is seen that the value of \( C_p \) with fine axial resolution (Test-C) is close to the experimental results with similar Reynolds number, i.e., only 1.6 and 4.9% lower than that of Lam et al. (2003) and Alam et al. (2010), respectively. The value of \( C_p \) with moderate axial resolution (Test-B) is also close to the experimental data, i.e., 5.8% lower than that of Alam et al. (2010). A much higher \( C_f \) value may be obtained when the axial resolution is coarse which suggests that such low axial resolution should be avoided. A slight lower circumferential resolution (Test-D) is tested and the \( C_p \) is very close to that of Lam et al. (2003). This slight reduction of circumferential grid resolution will help reducing computational cost. The comparison of \( C_p \) for different tests with the experimental data indicates similar trend. Basing on the vortex shedding frequency which is given by applying FFT onto time varying lift force coefficients, the values of \( St \) from the tests show well agreement with those from the literature. Considering both the calculation expense and accuracy, a mesh system with fine grid in XY plane and moderate grid in Z direction are adopted for further simulation.

**RESULTS AND DISCUSSION**

Aiming to both investigate the effect of orientation angle of the rivulet attachment on the flow pattern around cylinder, four different attached angles where, \( \theta = 0^\circ, 30^\circ, 45^\circ \) and \( 60^\circ \) are examined. The forces on the cylinder and flow field around the cylinder are analyzed.

**Forces and Strouhal numbers:** Mean drag force coefficients, \( C_d \), fluctuations of drag and lift forces, \( C_{df} \) and \( C_{lp} \) are shown in Fig. 3. It is seen that, the trend of \( C_p \) varying with \( \theta \) is quite similar to the results of Alam et al. (2010). It is also found that rivulet makes \( C_p \) much lower than that of plain cylinder when attached angle \( \theta \) is below \( 45^\circ \). When \( \theta = 45^\circ \), \( C_p \) is slightly larger than that of \( \theta = 30^\circ \). At \( \theta = 60^\circ \), \( C_p \) becomes to 1.616 which surpasses that in plain cylinder situation and this value is more than twice that of smallest one at \( \theta = 30^\circ \). \( C_{df} \) of rivulet attached cases is close to that of plain cylinder except when the attached angle is \( 60^\circ \). When \( \theta = 60^\circ \), \( C_{df} \) goes to many
times higher than that of plain cylinder. $C_{l2}$ also shows a
sudden change at $\theta = 60^\circ$ and its value is about twice
larger than that of plain cylinder.

The frequency spectrums of lift force via FFT
calculation are shown in Fig. 4 and the primary peak
frequency corresponds to the Strouhal Number. When
$\theta = 0^\circ$, St is close to that of plain cylinder. While the
attached angle is equal to $30^\circ$, there is no peak frequency
where the spectrum density is of priority, instead in a
frequency band from 0.1907 to 0.2308 the density keeps at
a similarly high level. The largest St of steady case
appears at $\theta = 45^\circ$ with the value of 0.2349, then St
drooply drops 30% to 0.1644 at a higher attached angle
of $60^\circ$. This trend is quite similar to the experimental
results of Alam et al. (2010), where two tripping rods were
symmetrically placed at the cylinder face mainly to analyze
how the rods position affected the flow field and forces
onto the cylinder at various Reynolds number.

**Pressure and surface friction:** Basically aerodynamic
forces acting on cylinder can be distinct in two parts the
pressure and the friction. Their distributions on the
cylinder face will help revealing forces vibrations among
cases. For the convenience of description the 3D
cylindrical surface in Cartesian coordinate is converted
into 2D rectangle with circumferential direction ($\Phi$) and
axial direction ($Z$ which is normalized with cylinder
length). The circumferential coordinate origin form the
front stagnation point $S_f$ (Fig. 1) of $\Phi = 0$ with the
clockwise direction and end at the same point of $\Phi = 2\pi$.

For plain cylinder, it can be seen from Fig. 5 that both
$C_p$ and $C_f$ distribute symmetrically about the back
stagnation line ($\Phi = \pi$). When there is a rivulet
attachment, $C_p$ suddenly drops at the rivulet position
(Fig. 6a). At $\theta = 0^\circ$, $C_p$ distribution is almost symmetric and
its symmetry is wrecked as $\theta$ grows up. When $\theta = 30^\circ$,
pressure quickly recovers a little then withdraws to
minimal value at $\Phi = \pi/2$, after that recovers again and
keeps average at trailing zone of the cylinder. While $\theta =
45^\circ$, $C_p$ comes up to average level directly behind the
rivulet. And $C_p$ distribution looks quite different at $\theta =
60^\circ$ comparing other cases with lower $\theta$, not only $C_p$.
distribution at trailing edge zone is unbalanced which means the upper side ($\pi/2<\Phi<\pi$) is slight lower than the down part ($\pi<\Phi<3\pi/2$) but also its value is smaller than previous cases. This directly leads to the sudden increase of $C_p$. For the frictional coefficients (Fig. 6b), letting aside for the rivulet neighborhoods, $C_f$ distributions at back-and-down part ($\pi/2<\Phi<2\pi$) vary not much via cases. When the rivulet is at the most forward, both steady and oscillating cases have almost the same configuration as plain cylinder.

Wake dynamics: Wake dynamics is very important in bluff flow investigation and it will help revealing not only the forces and vibrating properties of cylinder but also reaction of cylinder to fluid field. Wake dynamics of plain circular cylinder have been studied a lot and different regimes are classified as $Re$ varies. As Williamson (1996) reviewed: after laminar and wake transition regimes, the flow underwent shear-layer transition regime in a long range of $Re$ (1,000--200,000) where in present work it locates; then as $Re$ continuously grew, boundary layer
transition regime took place. However, when the rivulet is attached on plain cylinder, the boundary layer will be greatly changed, on concerning affection of rivulet to near wall region and the wake, both instantaneous and mean wake properties of the cylinder are investigated via different ways in this section, including pressure, velocity, vortex and vortex shedding frequency.

**Instantaneous flow field:** Iso-surface of vortex gives general information of flow formations, where vortex ($\omega$) can be made dimensionless through $\omega^* = \omega D/U$. Iso-contour of instantaneous vortex in stream-wise ($\omega_x^*$) and axial direction ($\omega_z^*$) are shown in Fig. 7. The axial vortex surfaces seem to be easier to break down in plain or low attach angle steady cases (Fig. 7a-d) and keep formational longer distance down to further field with larger attach angle (Fig. 7e) which means the later one have stronger vortices especially at the same side where the rivulet locates. The pattern of stream-wise vortices appears as hairpin in most cases. The “hairpin” are more stable when $\theta$ is low (Fig. 7a-c). Once $\theta$ exceeds 45° “hairpin” fractures easily which is probably because of larger disturbance caused by the rivulet attachment. Obviously the scales of the “hairpin” which demonstrates the scales of near wake, are different varying with cases and an much easier way to get those information is from vortices core distributions (right-down corner in Fig. 7). Comparing with other cases when cylinder is plain and steady (Fig. 7a) the trans-flow length ($L_t$) of vortices core zone is narrow. Apparently vortices burst point along the cylinder face is put back compared with other cases. In Fig. 10b $L_T$ is larger but the stream-wise length ($L_\omega$) of vortices core zone hardly changes. As $\theta$ increases (Fig. 7c-d) vortices congregate to the center line, $L_T$ get smaller but still over that of plain cylinder. When $\theta$ reaches to 60° (Fig. 7e), vortices suddenly diffuse around and $L_T$ nearly doubles compared with previous case. Rather than that the vortices cores come out and reattach to the cylinder face behind rivulet attachment $\theta = 45^\circ$ (Fig. 7d), when $\theta = 60^\circ$ (Fig. 7e) the vortices zone behind rivulet radiate backward.

**Mean flow properties:** Forces and Strouhal number are closely connected with near wake parameters that include: formation length of mean recirculation region, recirculation bubble shape and wake width etc. The bubbles are recognized by the iso-surface of mean stream wise velocity ($U_{zmean}$) with zero value. Three dimensional bubbles of different cases are shown in Fig. 8, where the right-down corner of each case gives stream wise slice through cylinder center line with negative $U_{zmean}$ in blue color. It is seen that the bubble along the axial direction is uniform.
Fig. 8(a-e): Iso-surface of mean stream wise velocity $U_{x_{min}} = 0$. Right down corner: stream wise slices through center lines of cylinders where blue zones show negative $U_{x_{min}}$.

Fig. 9(a-e): Contours of $U_{k_{min}}$ (non-positive) on axial cross section.

The formation length ($L_f$) which expresses the stream wise scale of the recirculation region, can be defined as the distance from the most downstream point on zero value bubble face to the central line of cylinder. Zdravkovich (1997) pointed out that larger $L_f$ corresponded smaller $C_{D}$, $C_{L}$ and $C_{T}$, or vice versa. In this work $L_f$ is gotten from the axial cross section of $U_{k_{min}}$ contour shown as Fig. 9. For convenient description normalized value $L^{*}_{f} = L_f/D$ is used instead. $L^{*}$, varies a little except decreasing suddenly at $\theta = 60^\circ$ where $C_D$ dramatically increases as recited previously and according to Table 3 it reduces nearly 30% at $\theta = 60^\circ$ comparing with other attached angle. $U^{*}_{x_{min}, min}$ which represents the minimum ratio of $U^{*}_{k_{min}}$ to $U_i$ is also listed in Table 3 for comparison. It exposes that the largest value of $U^{*}_{x_{min}, min}$ appears when $\theta = 60^\circ$, at which it is nearly 40% larger than that of steady cylinder with smaller attached angle.
Fig. 10(a-e): Contours of $U_{rms}$ on axial cross sections

Fig. 11(a-e): Separation, reattaching and Boundary layer status: (S1, S2—up, down separation point; R—reattaching point; l—origin of laminar boundary transition)

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<th>Table 3: Details of wake parameters</th>
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<tr>
<td>Plain</td>
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<tr>
<td>$L_r^*$</td>
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<tr>
<td>$U_{rms, max}$</td>
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<tr>
<td>$W_{w}$</td>
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<tr>
<td>$U_{rms, max}$</td>
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<td>S1</td>
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<td>R</td>
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Width of the wake, $W_w$, is another important parameter and it can be defined in different ways. One way used by Alam et al. (2010) is to take the lateral separation between the two maximum concentrations of root mean square velocity in stream wise ($U_{rms}$). $U_{rms}$ contours on axial cross sections are shown in Fig. 10. The maximum $U_{rms}$ and $W_w$ are normalized using $U$ and $D$ and they are represented with $U_{rms, max}$ and $W_{w}$ of which the values are list in Table 3. Basically larger $W_w$ corresponds bigger $U_{rms, max}$ could be summed up. The max and the least appear at $\theta = 60^\circ$ and plain case, respectively which $W_w$ of the former is about 50% over than that of the later. Comparing the results here with those in Alam et al. (2010)'s experiment, good consistence of $U_{rms, max}$ is received except at $\theta = 60^\circ$, where in present study the value is much higher.

**Boundary separation:** Boundary separation and transitions in boundary layer is shown in Fig. 11, where $S_1$ and $S_2$ represent two separation points. $R$ marks the
reattaching locations, details of these angles that are defined with clock-wise direction front stagnation point are listed in Table 3. The down separation points, $S_d$, are not much varying, locating at near $260^\circ$ in most cases. The upper separation points, $S_u$, are nearly the same when $\Theta$ is $0^\circ$ or cylinder is plan. At $\Theta = 30^\circ$ or $45^\circ$ the boundary first separates at the rivulet position, then reattaches and separates again thereafter. The difference between those reattachments is in the former case a laminar flow reattaches on the cylinder face while in the later the reattachment point the flow goes to transition already. This makes $S_d$ of the latter case appears several degrees ahead that of the former case. At $\Theta = 60^\circ$ the flow separates and goes to transition at the rivulet position which enlarges the wake behind the cylinder, therefore a large $C_w$ comes out.

CONCLUSIONS

Numerical simulations about RWIV were carried out in this work using LES method. The effects of upper rivulet position, $\Theta$, to the flow pattern and to the forces acting on the cable are investigated. The results show that the existence of upper rivulet changes boundary separation and boundary layer transition. When the rivulet locate at the most front of the cable, the boundary layer is quite similar to that of the plain cylinder, thus similar flow pattern and aerodynamic forces are obtained. As $\Theta$ goes little higher, the boundary layer separates at the position of the rivulet, then reattaches to the cable and the reattached boundary layer keeps laminar until it separates again. Similar situation of separation-reattaching-separation recurs as $\Theta$ goes even larger, except that boundary turns to transition as past the rivulet before reattaching, thus the position that the flow separate again comes a little earlier. Then when $\Theta$ is large enough, the boundary layer separates and makes transition directly after the rivulet. These properties of the boundary layer contribute to the different flow patterns and force properties of cable with various rivulet azimuths, where especially at $\Theta = 60^\circ$, the force coefficients enlarges dramatically and Strohal number reduced a lot reasonably. Under the limitation of computational resource, only few rivulet attached angles are simulated. Further investigation with detailed attached angles should be conducted when larger computational resources are available.

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