ON GALLOPING INSTABILITY OF STAY CABLES OF CABLE-STAYED BRIDGES

Masaru Matsumoto
Professor Emeritus of Kyoto University, Kyoto, Japan

ABSTRACT

Aerodynamic response, including rain and wind-induced vibration (RWIV) and dry state galloping (DG), of stay cables of cable-stayed bridges are studied from the points of generation mechanism. It has been verified that water rivulet formation (WR), axial flow (AF) in a wake of inclined cable and critical Reynolds number (Recr) can excite individually and cooperatively can excite aerodynamically inclined cable, that Karman vortex (KV) has essentially affected these excitation mechanism caused by these factors, WR, AF and Recr and, as a summary, that aerodynamic response of stay cables is “unsteady galloping” (UG).

1. INTRODUCTION

Recent cable-stayed bridges have lengthened their main span length with more than 1000m, including Sutong Bridge (1088m China) and Stone cutters Bridge (1018m China) and Russky Island Bridge (under construction 1104m Russia). Their lengths of stay cables are more than 600m. Stay cables are extremely low frequency and low damped structures, in consequence, they are significantly and sensitively excited by wind effect. Since Hikami[1] had reported firstly in the world this particular wind-induced vibration aided by precipitation in 1986, rain-wind induced vibration (RWIV) and dry-state galloping (dry galloping) of stay cables of cable stayed bridges have been observed at a lot of long spanned cable stayed bridges in the world. Their amplitudes are too large and frequencies of vibration events are too much to produce serious damages, in particular, at connecting joint parts to girders. Wind-induced vibration of stay cables truly become crucial issues in design of bridges. In order to establish effective and reasonable countermeasure to suppress their vibration, ones
should verify the precise generation mechanism of these stay cable wind-induced vibration. However, their generation mechanisms are not clarified, even though huge number of studies on cable aerodynamics (Matsumoto et al.[2,11], Verviewe[12], MacDonald[13], Larose[14], Chen[15], , Katsuchi et al[16], Kimura et al.[17]) because of complicated phenomena between fluid and structures. Matsumoto [2, 3] has pointed out three major factors, those are formation of upper water rivulet, axial flow in near wake and critical Reynolds number, play definitely substantial role for generation mechanism of wind-induced vibration of stay cables. Each of these factors can excite aerodynamically inclined cable individually and/or cooperatively(Matsumoto et al[11]). Observed violent vibration of stay cables in the fields must be galloping. Galloping has been widely known to be cross-flow divergent type fluid-induced vibration, that is bending flutter, and its generation mechanism is thought to be caused by negative slope of lift coefficient associated to pitching angle, that is known as den Hartog Criterion[18]. Parkinson[19] and Novak[20] successfully explained the non-linear response characteristics of galloping of square cylinder by use of Krylov- Bogoliivoff method, basing on quasi-steady theory. On the other hand, Nakamura and Hirata[21] reported that the other type galloping exists, that is so called “Low-Speed Galloping(LSG), which cannot be explained by den Hartog Criterion. LSG can be observed for bluffer rectangular cylinders with B/D (B:along-wind length, D;cross flow length) less than 0.75 and at lower reduced velocity range than Vr<1/St. (Vr=V/f0D and St:Strouhal number). Its generation mechanism is explained by Nakamura and Hirata[21] as deformation of flow by body motion not affected by past flow field, it means without fluid memory. On negative slope of lift coefficient, dCF/d\(\alpha\), the particular flow fields around bluff body, those are “inner circulatory flow”(Bearman and Trueman[22]) and “the flow which generates reattachment type pressure”(simply flow with reattachment type pressure”)(Nakamura and Tomonari[23]) should play definitely important role. On the other hand, negative slope of lift coefficient, dCL/d\(\alpha\)<0, can be observed at the stalling pitching angle of thin airfoil. The reason of local negative slope of lift force is flow separation from airfoil, and formation of separation bubble on its surface. Rinoue[24] studied on the separation bubble characteristics, those are short bubble and long bubble, corresponding on properties of lift coefficient – pitching angle diagram. Furthermore, research group of Central Research Institute of Electric Power Industry, Japan, has studied on the aerodynamic behavior of transmission line with snow, and they verified that the negative slope
of lift is caused by flow reattachment, then galloping can be excited in relation to den Hartog Criterion. (Shimizu et al.[25], Matsumiya et al.[26]). Nakamura and Hirata[21] studied on the galloping instability of rectangular cylinders with various side ratios, B/D without and with splitter plate (SP) in a wake. They explained the role of SP is interruption of two shear layers in near wake, mitigation of Karman vortex (KV) shedding and sequential flow undulation generated cylinder motion. Matsumoto[27] studied on the effect of SP in awake on aerostatic forces of rectangular cylinders with various side ratios. Furthermore, aerodynamic forces associated to aerodynamic damping, that is Scanlan derivative (Scanlan and Tomko[28]) H1* has measured for these rectangular cylinders. Though bluff rectangular cylinders, with B/D =0.5, 0.4. and 0.3, with SP, their lift coefficients slope indicate positive (dCF/dα>0), all of their H1* is positive (H1*>0) at wide reduced velocity range. Taking into account that H1*>0 means cross flow vibration, that is galloping, can be excited. This galloping cannot be apparently explained basing on den Hartog Criterion. This kind of galloping is, in consequence, not QG. Nakamura and Hirata[21] also reported the appearance of galloping for these rectangular cylinders with SP. Therefore, another type of galloping should be generated under the particular flow field around bluff body. According Nakamura’s explanation, this galloping is definitely caused by the flow undulation affected by body motion in the past time, that is fluid-memory. Since this galloping is absolutely generated by unsteady body motion, in consequence, it might be called as unsteady galloping (UG), in contrast to QG. In this note, complicated aerodynamic behavior of inclined stay cables of cable stayed bridges is explained in relation to QG and UG taking account into flow fields generated by upper water rivulets, axial flow in near wake and critical Reynolds number, individually or cooperatively.

2. QUASI-STEADY GALLOPING

First of all, the generation mechanism of negative slope of lift coefficient, dCF/dα, has been explained by Bearman and Trueman[22] as follows. When Flow comes to rectangular cylinder with certain positive pitching angle, and separated shear layer from the leading edge of lower surface of cylinder approach without reattaching on the sharp trailing edge, then inner flow particle of closed space between cylinder surface and separated shear flow cannot be go out from this space into a wake, because of difficulty of fluid supply from wake to this space due to enough small inlet space at the trailing edge. Then the fluid
particle should return up-stream side without going out to maintain fluid volume in this closed space. Thus intensive" inner circulatory flow" is generated on lower surface. This "inner circulatory flow "can produce intensive negative pressure on lower face of cylinder, it means generation of negative slope of lift force. On the contrary, Nakamura explained the generation mechanism of negative slope of lift force by appearance of reattachment-type pressure distribution on lower surface, which indicates significantly low pressure zone near leading edge of body and significantly pressure recovery at near trailing edge, through testing by use of D-shaped cylinder which does not have sharp trailing edge but round trailing edge. Therefore this particular flow which can generate reattachment type pressure distribution should be mechanism of negative slope of lift force. However, both explanations by Bearman and Nakamura can be identical from the point of that separated flow from the leading edge approaches to the trailing edge without reattachment on side face.

Nakamura called the conventional galloping "High Speed Galloping(HSPG)" which appears for rectangular cylinders with B/D between 0.75 and 2.8 at higher reduced velocity than inverse value of Strouhal number, that is \( Vr=\frac{V}{f0D}>\frac{1}{St} \), related to negative slope of lift force coefficient, that is \( \frac{dCF}{d\alpha} \). On the other hand, Galloping which appears for bluffer cylinder with B/D less than 0.75 at lower reduced velocity than 1/St, is called as "Low Speed Galloping(LSPG)". They explained the generation mechanism of LSPG by non-fluid memory, which is instantaneously deformed flow field under less affected by Karman vortex by body motion because of KV sufficiently lower frequency than the one of body motion. They verified that the instantaneous pressure distribution on side face indicates " reattachment pressure distribution" which is generation of galloping, during cross flow motion as unsteady effect of motion, which completely differs from stationary( quasi-steady) situation. This LSPG should be Unsteady Galloping (UG) discussed below in details.

On the other hand, the aerostatic properties of transmission line with snow have been studied by research group of Central Research Institute of Electrical Power Industry Japan verified that the negative slope of lift force was generated by the flow reattachment and formation of separation bubble. (Shimizu et.al.[25] and Matsumiya et.al.[26]) Shimizu and et.al[25] clarified that flow reattached on body surface and formation of separation bubble corresponding to appearance of negative slope of lift force by CFD analysis. Matsumiya and et.al29] reported flow fields corresponding to its aerostatic
forces.

On behavior of separation bubble near stalling angle of airfoil NACA0012, Rinoue[24] explained that short bubble, which produced more intensive negative pressure, and long bubble characterized the intensity and distance of negative pressure on airfoil surface depending on change of pitching angle, and burst event of separation bubble changed short to long bubble. These unsteady characteristics of separation bubble can also generate negative slope of lift force. In summary on negative slope of lift force of bluff bodies, there are two different kinds of flow fields, those are “inner circulatory flow” or flow field which produce the reattachment type pressure distribution, both are non-reattachment flow, and unsteady separation bubble by flow reattachment. Basing on quasi-steady theory, taking into account generation of relative pitching angle, \( \alpha_{re} = \frac{dy}{dt}/V \), due to cross-flow motion, when structural section moves downward, that is generation of positive pitching angle, intensive negative pressure on down-side surface of section generated by “inner-circulatory flow” or pressure recovery by “flow reattachment” on the upper-side surface. Both of these flows can generate downward lift force, then galloping should be excited because of coincidence of directions of motion and force.

3. UNSTEADY GALLOPING

As briefly explained above, Nakamura and Hirata [] studied on galloping of rectangular cylinder with B/D<0.8 and at low reduced velocity, that is \( V_r = \frac{V}{f_0D} < 1/\text{St} \) (St: Strouhal number), named by Low Speed Galloping (LSPG). They pointed out that its generation mechanism is particular unsteady flow which appears during cross flow oscillation of cylinder. This flow is different quasi-steady flow generated by relative angle of attack, \( \alpha_{re} = \arctan(dy/dy/V) \) and produce unsteadily “reattachment pressure distribution type” flow. It should be noted that LSPG is completely free from den Hartog Criteron, it means these bluff cylinders (B/D<0.8) show positive lift slope, \( dCF/d\alpha > 0 \), (Nakamura, Tomonari, xxx). Furthermore, they pointed out that similar unsteady flow can be observed in the case of rectangular cylinder with splitter plate (SP) in an wake as shown in Fig.4 (Nakamura and Hirata[21]).
Fig. 4 visualized flow around oscillating cylinder with B/D=0.5 at low reduced velocity (left: with a splitter plate; right: at without splitter plate) (Nakamura and Hirata [21])

Fig. 3 shows lift coefficient slope, dCF/dα, of bluff rectangular cylinders with B/D=0.3 up to 2.0 at the state of without SP and with SP. On SP its length is 15D (=900 mm, D:50 mm for all cylinders) and it is fixed at the wind tunnel wall with the gap between cylinder and SP is 0.06D (3 mm). Lift slope, dCF/dα, of rectangular cylinder without SP changes from positive to negative at B/D=0.75 decreasing B/D as shown in Fig. 3. On the other hand, under the state of with SP, dCF/dα is almost 0 or very small negative values between B/D=0.6 to 0.9. It should be noted that dCF/dα shows positive at B/D=0.3, 0.4 and 0.5. Basing on quasi-steady theory, one can evaluate that the state of with SP, rectangular cylinders with B/D=0.3, 0.4 or 0.5 at never show galloping instability, moreover, cylinders with B/D=0.6 to 0.9 must be significantly stable against galloping with enough high value as galloping onset reduced velocity.
Fig. 4 CD-\(\alpha\) diagram, CF-\(\alpha\) diagram, CF'-\(\alpha\) diagram and St(D)-\(\alpha\) diagram of rectangular cylinders with B/D=0.3 and 0.5 at the states of without SP and with SP.

In these figures, it should be noted that CL is lift coefficient defined as structural axis.

On the other hand, flutter derivatives of these rectangular cylinders at the state of without SP and with SP, in terms of aerodynamic damping, H1* defined by Scanlan (Scanlan and Tomko[28]), has been measured by forced vibration method.

\[
\frac{dy^2}{dt^2} + 2\zeta\omega_0\frac{dy}{dt} + \omega_0^2 y = (\rho b^2 \omega_F/m)H1^*(dy/dt) + (\rho b^2 \omega_F^2/m)H4^*y \tag{1}
\]

where m: mass per unit length, \(\rho\): air density, b: half chord length (=B/2), \(\zeta_0\): heaving damping ratio, \(\omega_0\): heaving circular frequency, \(\omega_F\): flutter (galloping) frequency (=\(\omega_0\)), H4*: flutter derivative in term of aerodynamic stiffness

Therefore, H1*>0 means aerodynamic unstable effect, and if \((\rho b^2 \omega_F/m)H1^*\) is larger than \(2\zeta_0\omega_0\), galloping appears. Quasi-steady state being satisfied, following formula should be satisfied:

\[
H1^* = \frac{1}{\pi}(-dCF/d\alpha)(D/B)Vr \tag{2}
\]
As shown in Fig.5, all rectangular cylinders with B/D=0.3, 0.5, 0.6, 0.9 at the state of with SP, galloping should be excited, however their slopes of lift coefficient, dCF/d\(\alpha\), are positive. This kind of galloping cannot be explained by the conventional quasi-steady theory. This galloping should be excited by substantial unsteady interaction between fluid and motion of body. This galloping can be called as “unsteady galloping(UG)” in contrast to “quasi-steady galloping(QG)”. What kind of flow field can excite UG? When SP is installed in a wake, Karman vortex(KV) should be mitigated/weakened in near wake, but flow undulation generated by body cross-flow motion still survive even though installation of SP. (Hirata[30]) This flow undulation around oscillating body must be generated by body cross-flow motion in the past time. In another expression, this undulation flow can be said “fluid memory”. Through a series of wind tunnel tests, it can be evaluated that mitigation of both of KV and upstream influence of flow interaction between two separated shear layers in a near wake plays definitely important in enhancement of “flow undulation” or “fluid memory”, then, unsteady lift force with phase lag to excite galloping, that is H1*>0. On the other hand, rectangular cylinders with more than B/D=5 at the state of with SP, do not indicate UG anymore, because H*<0.

At the state of without SP, it has been known that galloping of rectangular cylinders with B/D more than 2.8 cannot be observed, This aerodynamic property can be observed from H1* diagrams. At the state of with SP, critical B/D is 5, it means rectangular cylinders with B/D=3.0 and 4.0 still indicate galloping instability, because of time average flows of these cylinders do not reattach on side face because of curvature of separated shear layers should be mitigated by mitigation of KV, on the other hand, rectangular cylinders with B/D more than 5, time averaged flow reattach on side face of cylinder, in consequence galloping of these rectangular cylinders is stabilized. On the other hand, Assi, Bearman and Kitney[31] reported that circular cylinders with fixed SP in a wake with length from 0.2D up to 2D show violent galloping. This galloping seems to be UG similarly with bluff rectangular cylinders with from B/D=0.3 to B/D=0.9 at the state of with SP in a wake. Kawai[32] verified by CFD analysis(discrete point vortex method) out the SP installed in a wake of circular cylinder can produce the undulating flow locked in cylinder cross-flow motion because of interruption of two separated shear layers by SP. Furthermore, another case of appearance of UG, in addition to the case of with SP, is discussed as follows.
UG could be excited at the particular situation of when flow reattaches on the surface or edge of bluff body. One can identify the flow reattachment by CL-α diagram, CD-α diagram, CL’-α diagram and St-α diagram. When flow attachment arises, the local peak (summit or canyon) of CL, accompanying with local CD canyon and the local minimum value of CL’ (fluctuating lift coefficient) caused by KV, and rapid change of St are observed. The complicated response characteristics of circular cylinder with symmetric protuberances in relation of KV mitigation is shown in Fig.9(by Matsumoto and et.al[33]).

(a) Circular cylinder with symmetrical protuberance (each protuberance size:0.032D thickness, 0.072D width, D:diameter of cylinder(50mm)) at θ measured from horizontal line)

(b) CL-θ diagram

(c) CD-θ diagram

(c) CL’-θ diagram

(e) St-θ diagram

Fig.9 Aerostatic properties of circular cylinder with symmetrical protuberances (Matsumoto[33])

Appearance of stationary “bias flow” for geometrical symmetrical section has been observed at circular cylinder at critical Reynolds number( Schewe[34], Larose[14], Matsumoto[11], Sato[35], Liu[36]), side-by-side arranged rectangular cylinders (Alam and Zhou[37], Okajima[38], Matsumoto[39] and circular cylinder with movable (rotatable) splitter plate (Assi, Bearman and kitney[31], Cimbala and Garg[40]). On bias flow would be not discussed in this paper.
On the other hand, cross-flow responses and CL-α diagram (L is defined as structural axis, in these cases) of circular cylinder with symmetrical protuberances at the position of θ=48° (a), θ=50° (b), θ=55° (c), θ=58° (d) and θ=60° (e) are shown in Fig.11, respectively.

(a) θ=48° (SC=2mδ/ρD²=3.145)

(b) θ=50° (SC=3.144)

(c) θ=55° (SC=4.254)

Fig.11 CL-α diagrams and cross-flow responses of circular cylinder with symmetrical protuberances at θ=48°, θ=50° and θ=55°.

The lift slope and cross-flow response drastically change bounded at
around at $\theta=50^\circ$ where flow attaches, as shown in Fig.11 As far as slope of lift coefficient is observed as negative at $\theta=48^\circ$ and $\theta=50^\circ$, almost zero at $\theta=55^\circ$, $\theta=58^\circ$ and $\theta=60^\circ$, respectively. Therefore, cross-flow responses at higher reduced velocity than motion induced vibration(MIV), including unstable response at $\theta=60^\circ$, should be UG or at least hybrid type of QG and UG at $\theta=48^\circ$ and $\theta=50^\circ$.

As another example of UG, cross-flow response of circular cylinder at critical Reynolds number. Recently Liu and et.al[36] carried out significantly tough wind tunnel test at high wind velocity up to 80m/s in order to realize subcritical, critical and transient critical Reynolds numbers. At critical Reynolds number, $3.3\times10^5$- $4.4\times10^5$, steady lift, up to $CL=1.6$, suddenly appears in variation of Reynolds number caused by bias flow. Drag crisis appears like step. It is interested in the appearance of cross-flow response at two narrow Reynolds number zones, corresponding to two particular Reynolds number zones where drastic change of $CL$ appears. A similar cross-flow response of circular cylinder at critical Reynolds number has been reported by Kimura and et.al[17]. This cross-flow seems to be UG, because cross-flow vibration cannot produce exciting force basing on quasi-steady explanation. At critical Reynolds number, It has been verified that flow reattaches and separation bubble can be generated by CFD analysis by Basu[41] and high Reynolds number wind tunnel test by Sato et.al[37].In particular, Sato reported that the separation bubble was formed at one side face, it means un-symmetrically.

Thus, UG of bluff body can be excited under the “undulation of separated flow” synchronized to body motion less affected by KV, that is significantly “mitigated KV” by such as installation of SP in a wake, or at the condition near “flow reattachment”. However, un-cleared subjects still exist in the generation mechanism of UG, more precise research should be needed.

4. RWIV (RAIN AND WIND –INDUCED VIBRATION) AND DRG (DRY-ATATE GALLOPING) OF INCLINED STAY CABLES

As described at 1.Introduction, the fundamental factors are “axial flow” in near wake of yawed/inclined cable, formation of “upper water rivulet” on cable surface and the state of critical Reynolds number.

4.1 The Role of Axial Flow(AF)

First of all, the effect of “axial flow” is explained. Fig.15(a) and (b) show
visualized “axial flow” of proto-type inclined cable in the field and yawed cable model in wind tunnel. Fig (a) and (c) are visualized by light strings, and light flags respectively.

![Prototype cable in the field](image1)

![Yawed (β=45°) cable model](image2)

Fig.15 visualized “axial flow” in a near wake of inclined/yawed cable (Matsumoto[9])

The intensity of this axial flow of yawed circular cylinder with β=45° is almost 40% to 60% of on-coming flow velocity, depending on the boundary condition of both cylinder-ends, such as in free jet without end plates, by penetration through an open circular windows on wind tunnel wall with size 3D or 4D.

The “axial flow” must interrupt fluid interference between two separated shear layers from cylinder, something like bleeding, air-curtain or SP. Various splitter plates with perforation-ratio and its length have been investigated in the way of “try and error” to simulate “axial flow” of yawed circular cylinder with β=45° by comparing unsteady lift force of yawed cylinder and non-yawed with SP. Finally, it is verified that a perforated splitter plate with 30% perforation, with 4D length and with gap of 0.1D between cylinder and SP for non-yawed cylinder(β=0°) might suitably simulate “axial flow” of yawed cylinder with β=45°. Therefore, cross flow response of yawed/inclined circular cylinder at the range of around critical Reynolds number must be UG.

![Perforated splitter plate (PSP) with 30 % opening ratio with 4D length](image3)
(b) PSD (Left figure) and its wavelet value (right figure) of yawed ($\beta=45^\circ$) cylinder

(c) PSD (Left figure) and its wavelet value (right figure) of non-yawed cylinder with 30% PSP

Fig. 18 Analogy of unsteady lift forces of yawed cable and non-yawed cable with PSP (Matsumoto [9])

(a) Non-yawed ($\beta=0^\circ$) with PSP (30%)  
(b) Yawed cylinder with $\beta=45^\circ$

Fig. 17. Comparison of PSD of fluctuating lift force and its Wavelet value and their cross-flow response of non-yawed ($\beta=0^\circ$) cylinder with PSP (30%) and yawed ($\beta=45^\circ$) cylinder. (At the case of (a), $f_0=4.538\text{Hz}$, $m=4.75\text{Kg/m}$, $\delta_0=0.00216$ (at $2y_0=0.2D$), $Sc=7.168$, and the one of (b), $f_0=2.096\text{Hz}$, $m=0.509\text{Kg/m}, \delta=-0.00373$ (at $2y_-=0.2D$), $Sc=1.138$) (Matsumoto[9])

Furthermore, on unsteady cross-flow response of yawed ($\beta=45^\circ$) at
subcritical Reynolds number, at lower reduced velocity than onset reduced velocity, Vrcr., of divergent-type UG significantly large amplitude appears when KV is mitigated, on the contrary, when KV is intensive, response amplitude becomes small, as shown in Fig.18.

(a) Test view of Yawed (β=45°) cylinder(left photo) and cross flow response of yawed(β=45°) cylinder (right figure)

(b) cross flow response at U=4m/s Band-pass filtered by f0 (2.4-2.8 Hz)(top blue data) and fluctuating velocity in a wake (U=4m/s) Band pass filtered by KV frequency (fK=8.0-10.5)(measured position x/L=0.25, y/D=1.0, z/D=1.25) (bottom red data)

(c) STD subtracted by its mean value of STD in 100sec of fluctuating velocity time-averaged by 5.0sec (fK B.P.F) :red-solid line, and STD of response amplitude B.S. filtered by f0 (f0B.P.F.), subtracted by its mean value in 100 sec: blue broken line

Fig.18 unsteady response of yawed (β=45°) circular cylinder at V=4m/s corresponding unsteady KV intensity

Unsteady intensity of axial flow might cause unsteady KV intensity. Because of amplified cross-flow response appears in relation to suppression of
KV, this unsteady response at $V=4\text{m/s}$ is thought to be of a sort of UG.

### 4.2 The Role of Upper Water Rivulet

Artificial single rivulet is used to clarify the role of rivulet on non-yawed ($\beta=0^\circ$) circular cylinder. Rivulet is this rectangular shape with 0.062D in length and 0.032D in width and its position was change from $\theta=0^\circ$ (at front stagnation point) to $\theta=180^\circ$ (at center point of rear face of cylinder). $CL(\theta)$, $CD(\theta)$, $CL'(\theta)$ and $St(\theta)$ were measured at various rivulet position. As shown in Fig.19, protuberance position sensitively characterizes them. From these characteristics, “flow reattachment” occurs at $\theta=50^\circ$, as explained before, those are showing local peak of $CL$, local minimum $CD$, significant mitigation of $KV$ and drastic change of $St$ at $\theta=50^\circ$. Furthermore, it should be noted that position of “flow reattachment” is identical in both cases of single protuberance and symmetrical ones. Fig. 20 shows PSD of fluctuating lift force. It is clarified that complicated and drastic changes of $KV$ characteristics at near “flow reattachment” at $\theta=50^\circ$. Galloping appears at high reduced velocity at $\theta=54^\circ$, corresponding negative slope of $CF$, therefore this galloping might be almost QG with less effect of UG.

![Graphs showing CL-\theta and CD-\theta diagrams](image1)

![Graph showing L'(fluctuating lift force caused by KV)-\theta diagram at V=8m/s](image2)
Fig. 19 CL, CD, L' and St depending on protuberance position of non-yawed (β=0°) circular cylinder with single protuberance (Matsumoto[11])

Fig. 20 PSD of fluctuating lift force of non-yawed (β=0°) circular cylinder with single protuberance

On the other hand, aerodynamic derivative, H1*, are shown in Fig. 21 at various protuberance positions, θ=40°, θ=46°, θ=48°, θ=50°, θ=52°, θ=54°, θ=56°, θ=58°, θ=60°, θ=70° and θ=90°. As explained before, H1*>0 means aerodynamically unstable, that is appearance of cross-flow vibration. Therefore, from these H1* diagrams, non-yawed (β=0°) circular cylinders with single protuberance at the position of θ=50°, θ=52°, and θ=54° should show galloping. As discussed before, galloping at θ=50° at least should be UG. The other galloping at θ=52° would be hybrid type of QG and UG.

(a) without protuberance (rivulet), θ=40°, θ=46°, V, θ=48°, θ=50° and θ=52°
(b) $\theta=54^\circ$, $\theta=56^\circ$, $\theta=58^\circ$, $\theta=60^\circ$, $\theta=70^\circ$, $\theta=90^\circ$

Fig.21 Aerodynamic derivative, $H1^*$, of non-yawed ($\beta=0^\circ$) circular cylinder with various protuberance positions. (2y0=10mm(0.2D), fy=2.0Hz)

4.3 The Role of Reynolds Number

Unsteady galloping of non-yawed/inclined cable might be excited because of formation of separated bubble on cable surface at near Re$\nu$ as explained before, but for yawed/inclined cable unsteady galloping becomes more aerodynamically unstable as shown in Fig.13(Kimura and et. al[17]). This is thought to be why cooperative effect of formation of separation bubble and axial flow on aerodynamic instability.

5. CONCLUSIONS

Conclusions of this study on inclined stay cable aerodynamics are as follows:
1. Galloping of bluff body can be classified into “Quasi-steady Galloping (QG)” and “Unsteady Galloping (UG)”. 
2. Den Hartog criterion is not always necessary to excite UG. 
3. When wake undulation generated by Karman vortex(KV) is mitigated, unsteady flow generated by body-motion around body plays definitely essential role for UG excitation. 
4. Stay cables of cable stayed bridges can be aerodynamically excited by three major factors, those are “formation of rivulet” on cable surface by rain effect, “axial flow “ in a near wake of inclined/yawed cable and “Reynolds number “, in particular at near critical Reynolds number. 
5. These factors can excite mainly UG, but rivulet formation at particular position can generate significant negative lift-forces slope, that is $dC_F/d\alpha<0$, QG can be, in consequence, excited.
6. Unsteady cross-flow response of yawed/inclined cable at lower reduced velocity than critical reduced velocity of divergent type galloping, should be a sort of UG, generated by unsteady of KV intensity caused by unsteady axial flow.

As Further study, effective and practical countermeasure to stabilize aerodynamic response of inclined cables is definitely needed.

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