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Study on the Role of Karman Vortex on Galloping of Bluff Bodies

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ABSTRACT

In this paper, galloping instability, which is one of self-controlled cross-flow vibrations, is studied in relation to mitigation of Karman vortex(KV) of bluff bodies. Particular wind tunnel tests, have been carried out to clarify the role of KV shedding on stationary lift, and drag force, vortex-induced vibration, galloping. It has been verified that galloping can be excited by KV mitigation. Furthermore, because of non-stationary property of intensity of KV shedding, cross-flow response indicates unsteady amplitude which is called here as "unsteady galloping". Through a series of wind tunnel tests, it has been clarified that on aero-statics and aero-dynamics of bluff bodies are significantly and complicatedly affected by intensity of KV shedding.

1. INTRODUCTION

It has been widely known that Karman vortex(KV) shedding should be definitely important key charactering factor of bluff body dynamics. Since Karman reduced in 1911 the stable condition of spatial arrangement of alternative vortices on two lines, a huge number of studies on KV shedding related to bluff body aerodynamics. However, many unsolved subjects remain on complex KV properties and its effect on bluff body aerodynamics. Cross f-low response and flow pattern of circular cylinder have been precisely studies by Laneville[1], Williamson[2] and recently Zasso[3] near resonant reduced velocity, that is $Vr=(1/St)$, two different motion-induced vortices, 2P mode vortices, which correspond to KV, and 2S mode vortices as shown in Figure 1[2]. As shown, at near resonant reduced velocity, response, typical hysteresis response and the amplitude diagram seems to be characterized by the boundary of 2S mode and 2P mode. It clearly implies that complicated aerodynamic behavior should be related to KV shedding characteristics. Recently the rain-wind induced vibration (RV) and dry-state galloping (DG) stay cables of cable-stayed bridges becomes great concerns because of its sever vibration. In fact, serious damages of cable supported part including installed damping devices[4]. In particular, it has been pointed out that substantial role of Karman vortex (KV) on the generation mechanism of DG[5]. It has been clarified by wind tunnel tests that when artificial protuberance which is simplified-model of water rivulet formed on cable surface, is attached on the particular position, KV shedding is significantly mitigated, galloping instability, in consequence, appears as shown in Figure 2(for non-yawed circular cylinder)[6]. It has been studied that the intensive axial flow, playing similar role with splitter plate in a wake, in near wake of yawed circular cylinder can mitigate KV shedding, then galloping instability appears[7]. Furthermore yawed circular cylinder shows the unsteady galloping with unsteady amplitude corresponding to unsteady intensity of KV shedding. On aerodynamics of rectangular cylinders, it has been known that cylinders with particular side ratios B/D is less than 0.75 or larger than 2.8 up to 4, galloping appears[8]. It should be noted intensity of KV shedding of these cylinders are enough weak. For cylinders with larger than 2.8, the separated flow from leading edge re-attaches on side surface and for cylinders with less than B/D=0.75, intensity of KV shedding is enough strong. Furthermore, Okajima et al[9]. appointed that the important role of KV on self-excited in-line response of circular cylinder near one forth of resonant reduced velocity, that is $1/4St$.

The substantial role of KV on Galloping of rectangular cylinders with various side ratios has been implied by Nakamura[10]. He classified Galloping into high speed galloping (HG) and low speed Galloping (LG).The particular flow condition with small sinusoidal and longitudinal stimulation with particular frequency f_p, of four times or KV shedding frequency f_k. This flow is simply named as "$4f_k$ pulsating flow". Knisely, Matsumoto[11] particular pulsating flow two different flow fields intermittently appear, those are intensive KV shedding flow and the symmetrical vortex shedding synchronized with coming flow frequency. The former flow can produce large drag and the later flow can decrease.

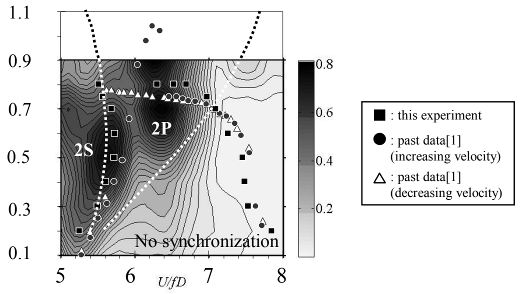
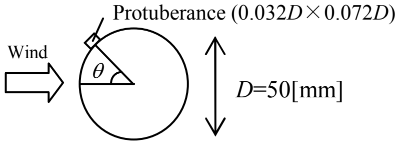
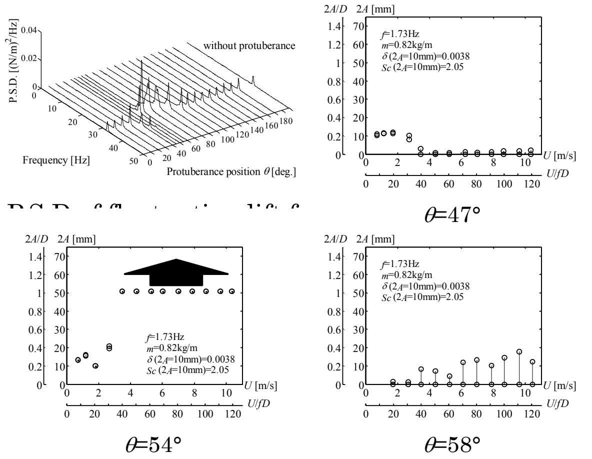


Figure 1: *Unsteady lift subject to KV frequency to centerline and its comparison with vortex mode[2] and cross-flow response of circular cylinder[1]*



a) Circular cylinder with a protuberance

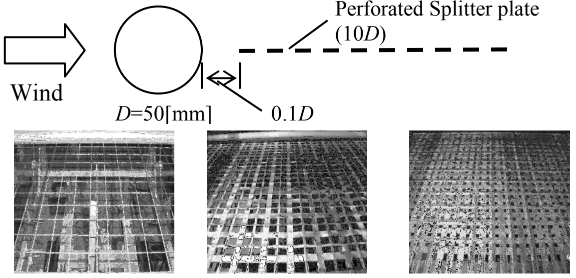


b) P.S.D. of fluctuating lift force and V-A diagrams

Figure 2: *Cross-flow response of cable model associated with KV mitigation in relation to protuberance position (β=0°, without wall, U=5.0m/s)*

2. Cross-flow response of circular cylinder when KV is mitigated by perforated splitter plates

By use of perforated splitter plate (see Figure 3) in wake with various open-ratio(OR), intensity of KV shedding was controlled.



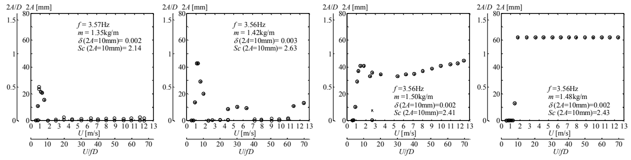
a) Open-ratio of splitter plate 90%

b) Open-ratio of splitter plate 40%

c) Open-ratio of splitter plate 10%

Figure 3: *Perforated splitter plate*

Depending on KV mitigation ratio, cross-flow vibration characteristics of circular cylinder significantly change as shown in Figure 4. As shown, KV shedding intensity, Its intensity was measured by the power at Strouhal frequency of P.S.D. of measured fluctuating lift. If OR of splitter plate is less than 80% or 70 %, KV shedding significantly mitigated. Depending on the mitigation level of KV shedding, cross-flow response significantly changes. At OR=70%, second velocity restricted response tends to appear at reduced velocity range of approximately 20 to 30, then less than OR=60%, response changes to divergent-type vibration. On the other hand, amplitude of vortex-induced vibration at low reduced velocity, approximately 5, increases with decreasing OR down to 50%. This characteristics mean that this vortex-induced vibration must be generated by not KV but motion-induced vortex which can be enhanced by KV mitigation.



O.R.: 100% O.R.: 70% O.R.: 40% O.R.: 0%

Figure 4: *Velocity – Cross-flow amplitude diagrams of circular cylinder with performed splitter plate in near wake*

3. Sensitivity of bluff body aerodynamics against external/self stimulation in relation to KV mitigation

2*D* rectangular cylinders with particular side ratios *B*/*D* of 0.75 to 2.8 generate galloping instability, whose intensity of KV measured by fluctuating lift coefficient, C_L' with Strouhal frequency , significantly is mitigated as shown in Figure 5.

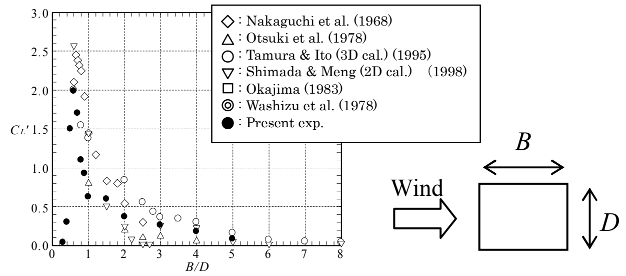


Figure 5: *Fluctuating lift force coefficient of rectangular cylinders*

In those cylinders the separated flow from leading edge is more sensitively deformed by cross-flow response itself (as self-stimulation) so that to approach the trailing edge but never re-attach to formulate inner-circulatory flow on side surface [12]or to generate re-attachment-type pressure distribution on side surface (Nakamura) which can generate negative lift slope against pitching angle in aerostatic sense or galloping in aerodynamic one than the other cylinders. On the other hand, the fluctuating lift force of stationary circular cylinder generated by vertical and sinusoidal fluctuating flow with velocity amplitude of w/V=0.03 grows with KV mitigation ratio by perforated splitter plate as shown in Figure 6.

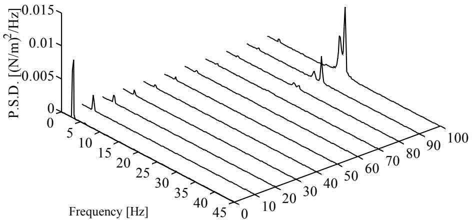


Figure 6: *P.S.D. of fluctuating lift force of circular cylinder with various open-ratio of splitter plate (U=5.0m/s)*

From these test results, significant role of KV shedding of that intensive KV shedding would have the role of protection of separated shear layer against self/external stimulation is obtained.

4. Vortex-induced vibration of circular cylinder in relation to KV shedding

Describing above, two different motion-induced vortices, those are 2P mode vortices, which correspond to KV, and 2S mode vortices, and at near resonant reduced velocity, response amplitude suddenly jumps up to larger amplitude, after that amplitude locally overshoots when velocity increases studied by Williamson and Laneville. The cross-flow response is generated by 2Pmode but by not KV, in other words, it can be said that 2P mode can suppress KV. Due to precise forced vibration tests, where wind velocity was changed by 0.01m/s step and forced vibration amplitude was changed from 0.1D up to 0.85 D (D: cylinder diameter) near the resonant wind velocity, characterized by Strouhal number. Analyzed points are up to 800. The response amplitude/velocity characteristics obtained by forced vibration test show fairly well agreement with free-vibration test results by Williamson[2] and Laneville[1]. In particular, the hysteresis response reported by Laneville[1]can be explained as follows. This response appears avoiding local existence of KV shedding. In this tests, KV intensity was measured by time-history record band-pass-filtered by Strouhal frequency or P.S.D. value at Strouhal frequency of unsteady fluctuating lift force.

5. Rectangular cylinder with *B*/*D*=0.5 in pulsating flow

The particular flow condition with small sinusoidal and longitudinal (pulsating) stimulation with particular frequency f_p, of four times oh KV shedding frequency f_k. This flow is simply named as "4f_k pulsating flow". Knisely, Matsumoto[11] reported that in this particular pulsating flow two different flow fields intermittently appear, those are intensive KV shedding flow and the symmetrical vortex shedding synchronized with coming flow frequency as shown in Figure 7.


Karman vortex (KV mode) transitional state symmetrical vortex (non KV mode)

Figure 7: Karman vortex and symmetrical vortex[11] of rectangular cylinder(B/D=0.5) in 4f$_k$ pulsating flow

The former flow can produce large drag and the later flow can decrease. The diagrams of time history of drag and lift in this 4f_k pulsating flow are shown in Figure 8.

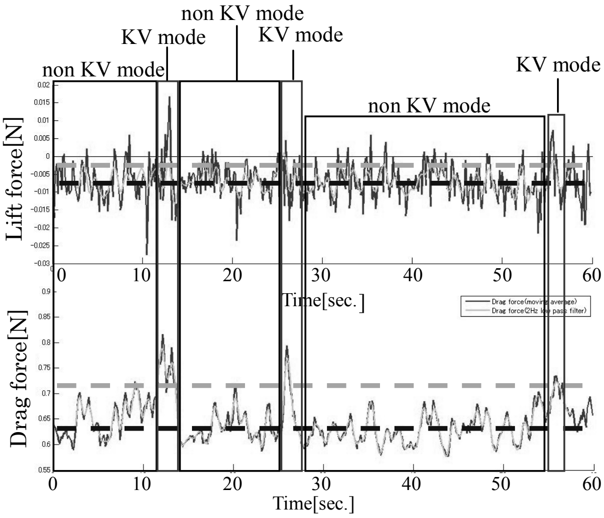


Figure 8: *Time history of drag and lift force affected by KV mitigation of rectangular cylinder with B/D=0.5 in 4f_k pulsating flow*

Depending on the mitigation of KV, it means during symmetrical vortex shedding, stationary non-zero lift appears, furthermore the cross flow self excited response tends to appear in accompany with disappearance of KV shedding, as illustrated in Figure 9.

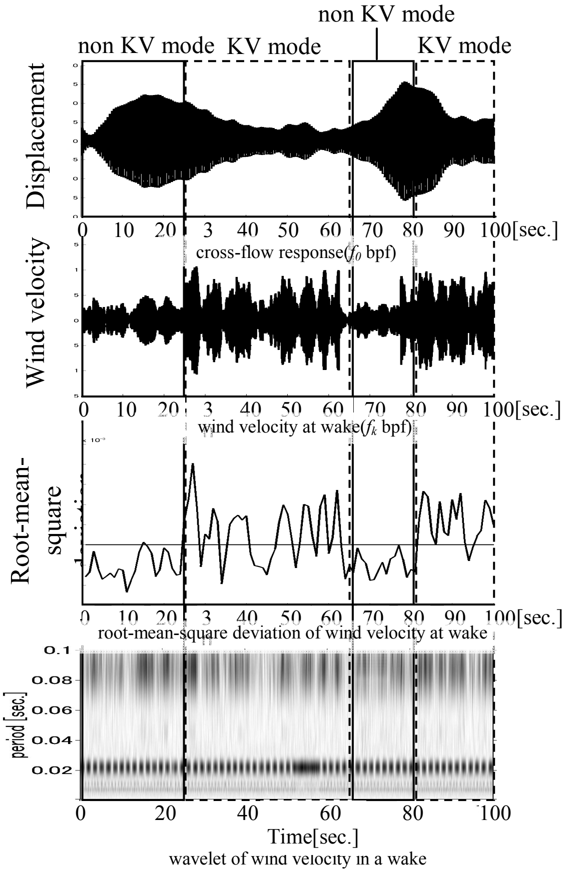


Figure 9: *Time history of cross-flow response in relation to KV mitigation (bpf by f_0), wind velocity in a wake (bpf by f_k) in $4f_k$ pulsating flow, root-mean-square deviation of wind velocity at wake and wavelet of wind velocity at wake(rectangular cylinder with B/D=0.5)*

Therefore, this cross-flow response might be a sort of Galloping, in other words this cross flow response must be self excited vibration like Galloping.

6. Side-by-side arranged two rectangular cylinders (*B*/*D*=1.28)

Side-by-side arranged two rectangular cylinders, each cylinder has *B*/*D*=1.28, was tested by changing the gap distance(*G*) from 0, which corresponds to critical side ratio, to 2*D*. As shown in Figure 10, intensity of KV mitigation changes with *G*, namely less than *G*/*D*=1, KV significantly suppressed because of intensive gap flow between two cylinders.

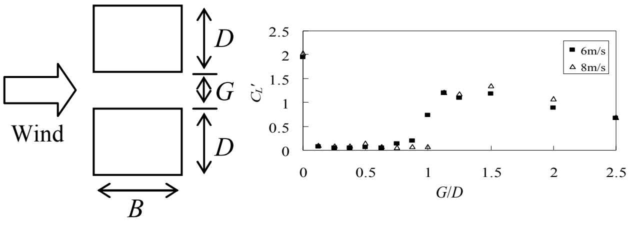


Figure 10: *Fluctuating lift force coefficient / gap (G/D) diagram of side-by-side rectangular cylinders (B/D=1.28)*

Depending on gap distance, lift, drag and cross flow response complicatedly change which is highly correlated with KV mitigation. In particular, lift and, drag *G*/*D* characteristics obtained by wind tunnel test shows good agreement with those obtained by LES analysis. For small gap, stationary lift appears because of appearance of asymmetrical flow fields which is confirmed by LES analysis as shown in Figure 11.

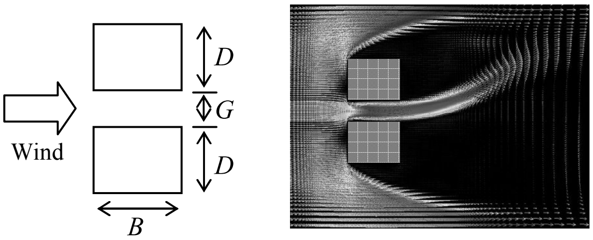


Figure 11: *Asymmetrical flow field by LES of side-by-side rectangular cylinders (B/D=1.28) at G/D=0.5*

The reason of no appearance of typical galloping even though KV is suppressed at range of less than *G*/*D*=1, is re-attachment on side surface of separated flow from leading edge, because of intensive skewed asymmetrical gap flow. For large gap the flow field around each cylinder tends to approach to those of isolated cylinder with *B*/*D*=1.28, then HG appears. *G*/*D*=1.0 seems to be the boundary of these two different flow modules, and at *G*/*D*=1.0, two different flows appears depending on wind velocity.

7. Circular cylinder with symmetrical protuberances

In case of circular cylinder with symmetrical protuberances, the particular position, approximately θ=50°, of protuberances can mitigate sufficiently KV then produce the stationary lift caused by the asymmetrical flow around cylinder.

At near this particular position of protuberances, lift slope against pitching angle shows negative, in consequence, conventional galloping appears as show in Figure 12.

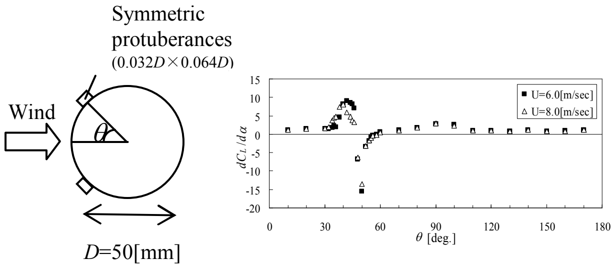
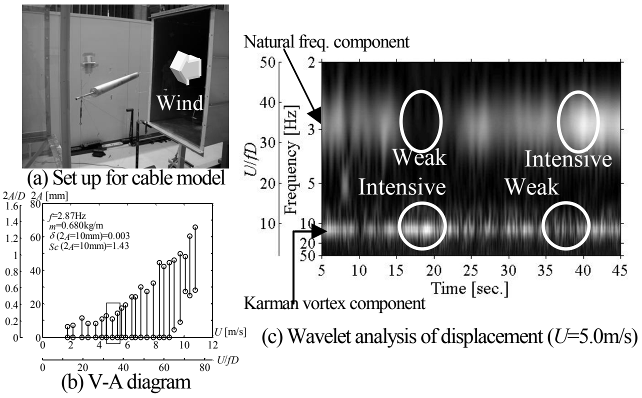


Figure 12: *Steady lift slope, $dC_L/d\alpha$ against pitching angle of circular cylinder with symmetrical protuberances*

8. Unsteady galloping of yawed circular cylinder

Furthermore, yawed (β=45°) circular cylinder with free ends, it means without end plates nor walls with windows, and with smooth surface shows galloping with unsteady amplitude, which can be called as “unsteady galloping”. The response amplitude increases when KV shedding is mitigated as shown in Figure 13 [7].



(a) Set up for cable model

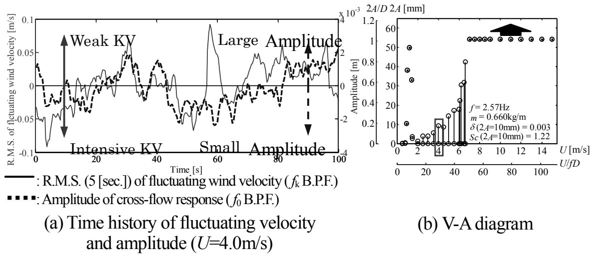
(b) V-A diagram

(c) Wavelet analysis of displacement (U=5.0m/s)

Figure 13: *Unsteady cross-flow response in relation to KV mitigation of yawed circular cylinder with β=45° (D=50mm, in smooth flow, free end condition)*

One of author have recently clarified more details that apparent mechanism of suppression or mitigation KV shedding on exciting galloping for some bluff bodies. Targeting the unsteady amplitude cross-flow response in free vibration tests shown in Figure 14, the unsteady amplitude must be caused by the intensity of Karman vortex shedding in wake.

When Karman vortex shedding becomes weak, response amplitude becomes large. Figure 15 shows the cross correlation coefficient function between cross-flow response amplitude (broken line), which larger amplitude is positive, and fluctuating velocity component (solid line), which weaker is positive, associated with Karman vortex shedding frequency, which is measured by hot-wire anemometer in wake.



(a) Time history of fluctuating velocity and amplitude (U=4.0m/s)

(b) V-A diagram

Figure 14: *Unsteady cross-flow response in relation to KV mitigation of yawed circular cylinder with β=45° (D=54mm, in smooth flow, model-end condition: with walls and windows)*

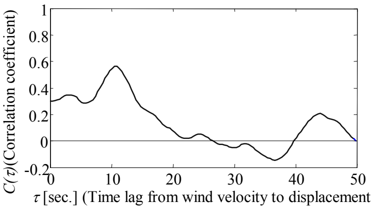


Figure 15: *Cross correlation coefficient between R.M.S. of fluctuating velocity subject to KV shedding and cross-flow response amplitude of yawed cable with β=45° (D=54mm, in smooth flow, with walls and windows)*

As shown, maximum correlation value is 0.57 as positive value. This is sufficiently large value when taken into account extremely complicated flow field around yawed cable. Through these test results, it is clarified that the increasing of amplitude of unsteady galloping highly correlates with mitigation of Karman vortex shedding.

9. Generation mechanism of galloping when KV mitigated

Nakamura classified galloping of rectangular cylinders into Low-speed galloping (LSG) and high speed galloping (HSG) bounded by resonance Karman-vortex excited vibration which occurred at *Vrcr*. Nakamura explained from the pressure measurement of body surface during free vibration and flow visualization as follows The mechanism of LSG is motion-induced flow which is induced by quicker cylinder-motion than KV shedding frequency in consequence is less affected by KV shedding. Then the lower separated flow approaches to body lower surface on the other hand, upper separated flow moves far away from body upper surface during downward motion of body. In consequence down lift is generated. Which is LSG mechanism[10]. Furthermore, he pointed out that the galloping generation-mechanism of conventional divergent-type galloping is interruption of communication between upper and lower separated flows. Because communication of two separated flows can make pressure difference on upper and lower surfaces of cylinder zero. This interrupting communication between two separated flows can be accomplished by following three cases. (1) a long downstream splitter plate, (2) vanishing effect of wake undulation at low wind velocity related with LSG and (3) critical geometry at high wind velocity which can produce a reattachment-type pressure distribution caused by separated-flow/edge interaction related with HSG[8]. On the other hand, Okajima [9] pointed out that self-excited vibration can be produced if vortex shedding is mitigated in relation of in-line response near $Vr=1/(4St)$. He called it in-line galloping and pointed the important role of wake breathing due to synchronized symmetrical vortex shedding, Taking into account of that KV shedding should be generated by fluid-dynamically interaction or communication between two separated shear layers, in other words, intensity of KV shedding can be measure of or scale of communication of two separated shear layers. Therefore, the mitigation of KV means the same physical meanings of interruption of communication of two shear layers.

10. Conclusion

Conclusion through a series of wind tunnel tests can be summarized as follows:

1. Separated shear layer of bluff bodies must be protected against various stimulations by intensive KV shedding.
2. Mitigation of Karman vortex surely promotes self-excited cross-flow response, including divergent galloping.
3. Mitigation of Karman vortex shedding must be identical to interruption of communication between two separated shear layers.
4. Karman vortex shedding is not always stationary but many cases it shows non-stationary characteristics. Depending on the intensity of Karman vortex shedding, unsteady galloping which indicate non-stationary response amplitude.
5. If Karman vortex shedding can be suppressed, unsymmetrical flow field appears for even though symmetrical body to flow, in consequence, non-zero lift force can be produced.
6. The hysteresis response of vortex-induced vibration of circular cylinder near resonance velocity formally reported can be caused by local existence of Karman vortex shedding in Velocity/Amplitude diagram.

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