Steady Galloping /Unsteady Galloping and Vortex-induced Vibration of Bluff Bodies associated with Mitigation of Karman Vortex Shedding

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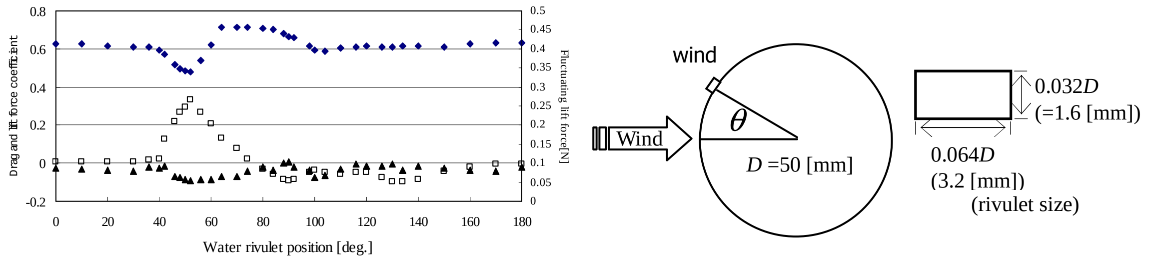
1. Introduction

In this paper, the definitely important role of Karman Vortex (KV) Shedding on characterizing bluff body aerodynamics is investigated. First, galloping instability generated by mitigation of KV is discussed by some typical examples obtained by wind tunnel tests. Second, vortex-induced vibration of circular cylinder is investigated by use of forced vibration tests by changing forced amplitude.

2. New findings on the galloping appearance by KV mitigation

Associated inclined cable aerodynamics, including rain-wind induced vibration(RV) and dry-state galloping(DG), particular position of artificial upper water rivulet can drastic changes of aerostatic/dynamic characteristics, including stationary lift and drag KV shedding intensity and appearance of galloping instability. As far as yawed cable with yawing angle of β=45˚, when rivulet position is approximately θ=50˚, C_D remarkably decreases and C_L increases and fluctuating lift caused by KV shedding is significantly reduced, then galloping occurs as indicated in Fig.1, 2[1]. Furthermore, yawed cable with β=45˚ shows galloping-like response appears depending on the cable end conditions, those are free end, with end-plates and with walls and suitable-size windows as shown in Fig.3. Depending end conditions, KV shedding intensity changes, that is most intensive is with end-plate, and next is free ends and weakest is with walls and windows. Galloping response becomes weak and unstable, as KV intensity increases as shown in Fig.4. In particular, it should be remarked that the unsteady amplitude of galloping for with free-end condition and from its time-history data, amplitude becomes large with high correlation if KV shedding mitigated.[2] The mitigation of KV is thought to be caused by axial flow in near wake of yawed cable, which plays similar role with a splitter plate. Critical Reynolds number (Re_{cr}) of yawed/ inclined cable can excite galloping [3] Similar experiments at critical Reynolds number, yawed cable with rough surface and yawing angle β=45˚ shows KV shedding mitigation and steady lift caused by asymmetrical flow fields and unstable response appearance. Besides, at Re_{cr}, the flutter Scanlan derivative[4] of H_1^* becomes positive, which means the possibility of galloping. On other hand, three different types of symmetrical bodies, those are circular cylinder with symmetrically located two protuberances, of which location is characterized by θ, two rectangular cylinders with B/D=1.28 side-by-side arranged with gap, S, in between them and single rectangular cylinder with B/D=0.5 in longitudinally periodical fluctuating flow, of which intensity $\sigma u/V$ is approximately 1% and frequency, f_p, is synchronized to four times of KV shedding frequency, f_k, that is f_p=f_k. Or circular cylinder with two protuberances, at particular protuberance position, that is approximately θ=50˚, KV is mitigated and C_D decreases and stationary C_L appears, in spite of symmetrical body, and divergent-type galloping occurs as shown in Fig.5. For two rectangular cylinders, smaller gap S/D than the critical gap ratio of S/D=1.0 KV is mitigated and C_L appears as shown in Fig.6. Theses drastic characteristics can be obtained as almost same results by LES analysis and in this analysis clearly shows the asymmetrical flow field. However, in this case of S/D<1 though, KV is mitigated because of gap-flow, galloping does not appears since intensive skewed separated gap-flow reattaches on side surface. For single rectangular cylinder in fluctuating flow, during symmetrical synchronized vortex shedding, KV is mitigated, then cross flow tends to appear on the other hand, during KV shedding, this response tend to decreases.



□;Drag force coefficient, □;Lift force coefficient, ▲;Fluctuating lift force

Fig.1 Aerodynamic characteristics of circular cylinder with symmetric protuberances in various positions.(in smooth flow)

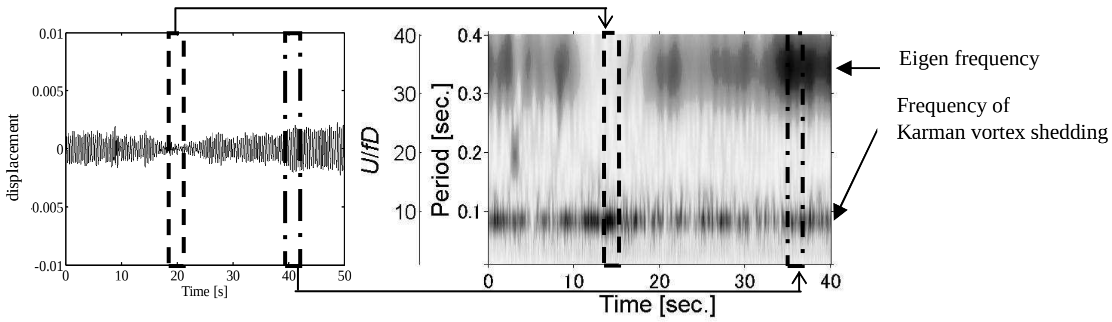
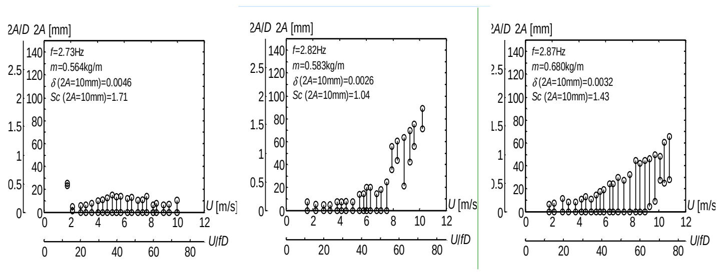


Fig.2 Relationship between galloping and Karman vortex(β=0°, without wall)

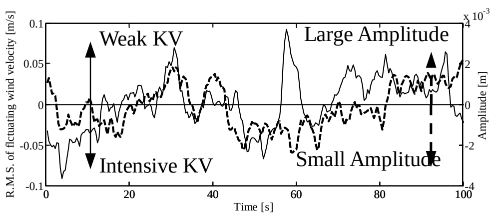


Without wall and with end plate

Without wall

With wall imstalled Windows(ϕ=170mm)

Fig.3 Velocity – Amplitude diagrams(β=0°, D=50mm, in smooth flow)



—: R.M.S. (5 [sec.]) of fluctuating wind velocity (f_k B.P.F.)

···: Amplitude of cross-flow response (f_0 B.P.F.)

Fig.4 Time history of fluctuating velocity and amplitude(β=45°, U=4.0m/s, D=54mm, Sc=1.22, in smooth flow, 200mm window)[2]

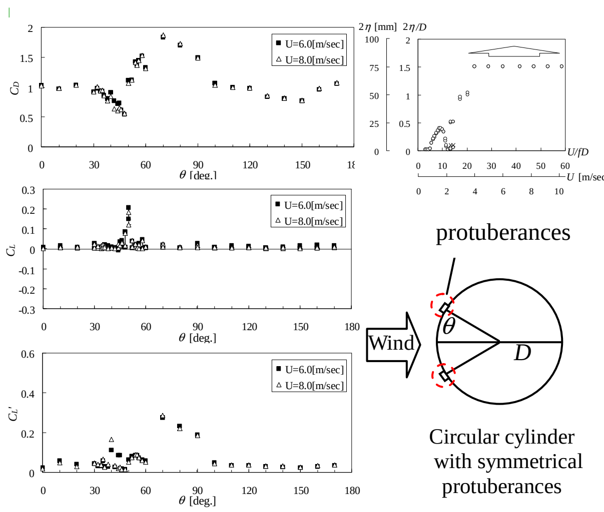
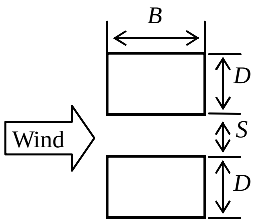
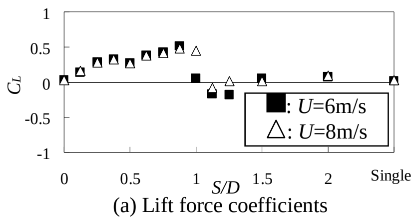


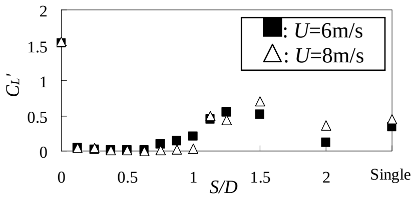
Fig.5 Aerodynamic characteristics and Velocity – amplitude diagrams (θ=50˚) of circular cylinder with symmetric protuberances in various positions. (in smooth flow)



Side-by-side arranged two rectangular cylinders with B/D=1.28



(a) Lift force coefficients



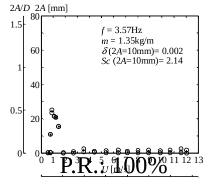
(b) Fluctuating lift force coefficients

Fig.6 *CL* (lift coefficient), *CL'* (fluctuating lift coefficient)– *S*/*D* diagrams for side-by-side arranged two rectangular cylinders

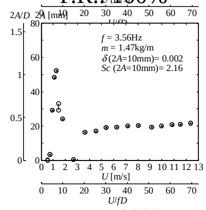
3. Effect on Cross-flow response of circular cylinder by KV mitigation

Cross-flow response of circular cylinder complicated changes depending on KV mitigation level. KV control was carried out by use of perforated splitter plate in wake of circular cylinder.

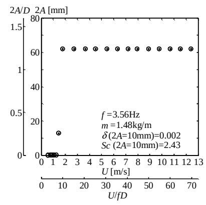
KV shedding significantly mitigated by perforated splitter plate with perforation ratio (P.R.) of 80 % or 90%. Less than P.R=60 or 70 %, KV shedding can be mitigated by almost around 10 % in comparison with no splitter plate(P.R.=0%). Increasing P.R., KV shedding can be more mitigated. In corresponding mitigation level of KV shedding, cross flow response complicatedly changes as shown in Fig.7. It should be noted that the maximum amplitude of vortex-induced vibration at near resonant reduced velocity gradually increase in increasing P.R. up to 50 %, in another words, in more mitigation of KV shedding to around 10% -mitigation. This mechanism is described later at the section of vortex-induced vibration of circular cylinder in relation to KV. At less P.R. than 50%, this vortex-induced vibration tends to be included in divergent –type galloping at high reduced velocity range At less than P.R. of 70 %, cross-flow response starts to be generated at high reduced velocity range. This simple experiment implies that KV mitigation can give remarkable effect on cross flow response. The mechanism of appearance of galloping, if KV is mitigated, just identify with the Nakamura'study [5] in which the galloping mechanism is caused by the mitigation/interruption of two separated shear layers.



P.R.: 100%



P.R.: 60%



P.R.: 0%

Fig.7 Velocity – Amplitude diagrams (β=0°, D=50mm, in smooth flow)

4. Quasi-steady/divergent-type galloping and unsteady galloping

It has been well known that KV shedding from stationary body is not stationary, it means the intensity varies in time domain. Therefore, it is natural to suppose KV intensity is not stationary under suitably mitigated state. Depending on the change of KV intensity, amplitude of cross-flow response also varies. The cross-flow response with unsteady amplitude is called as unsteady galloping. On the other hand, if KV is completely and in stationary suppressed, stable galloping with stable amplitude or divergent-type galloping could occur.

5. Vortex-induced vibration characteristics of circular cylinder

Circular cylinder model has 50[mm] diameter and .1000[mm] length and with smooth surface. All tests were carried out in smooth flow. The comparison of *Ur*- *A* diagram obtained from forced vibration test and free-vibration test [6] is indicated in Fig.8. As shown, both response characteristics show fairly good agreement except for overshooting response reported by Laneville at reduced velocity of around U/f_0D=3.77-8.16. Furthermore, Fig.9 indicates the unsteady lift component filtered by characteristic of frequency band $f_k \pm 0.2$[Hz](f_k: frequency of Karman vortex shedding) including Karman vortex (KV) shedding frequency. As shown, significant amplified zones with existence of KV appears at around (($2\eta/D$<0.1, *Ur*=5.1),

($2\eta/D$= 0.6 - 0.7, Ur = 5.3 - 5.4) and (($2\eta/D$)>0.85, Ur=5.7-6.0). Taking into account the definition of lock-in phenomenon means KV shedding frequency, f_k, is involved to body vibrating frequency, f_0, that is $f_k=f_0$ during response appears. Thus, at reduced velocity range where vortex-induced response appears, existence of KV with f_k, absolutely indicate that this response is not lock-in phenomenon but motion induced vibration or self-excited vibration. In another words, there is no lock-in phenomenon. First intensive zone in Fig.9 should correspond resonance of forced vibration frequency to KV shedding frequency. Therefore response with small amplitude at this particular velocity is merely resonance phenomenon which appears when external force frequency coincides to natural frequency of vibrating system. Second intensive zone in Fig.9 is the most significant, because **cross-flow response seems to avoid this zone**, when compared to V-A diagram reported by Laneville. Therefore, this locally KV-amplified zone thought to be cause the appearance response sudden jump, in another words appearance of unstable limit cycle amplitude as shown in Fig.10. Furthermore, it should be noted that first-zone and second-zone locate on the boundary between 2S mode and 2P mode. Therefore, the motion-induced vortex mode can switch by more or less KV effect. Looking at higher reduced velocity range where response terminates, KV appears. KV appearance suppresses cross-flow response, which is same mechanism of appearance of galloping self excited vibration when KV mitigated [7] However, the mechanism of appearance of KV at second-zone and third zone is not verified. It seems that this KV appearance at particular zone would be complicated interaction between 2P and 2S mode vortices but for the detail further investigation should be needed.

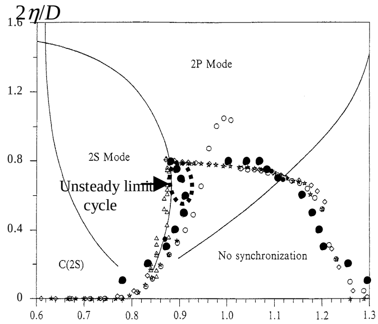


Fig.8 Comparison of Velocity-Amplitude diagram H_1^*=0 (·)and test result [5]

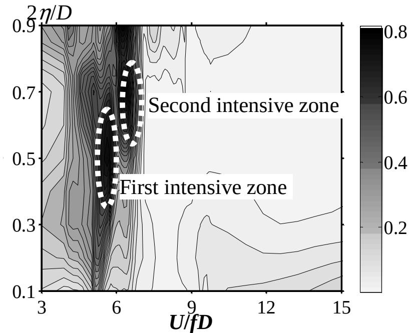


Fig.9 Velocity-Amplitude of C_L' caused by KV diagram

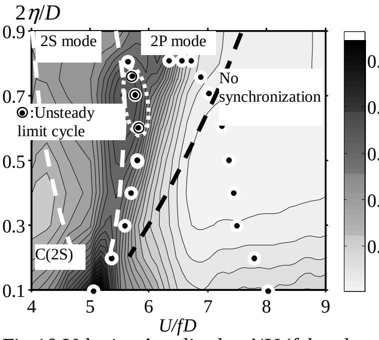


Fig.10 Velocity-Amplitude-u'/U (f_k band pass filter) diagram and velocity at H_1^*=0 for each amplitude

Conclusion

In conclusion KV shedding stabilize against self-excited vibration such as galloping, therefore, if KV would be mitigated by certain reason, galloping could appear. Its generation mechanism is caused by interruption of communication between upper and lower separated flows by KV mitigation. Inclined cable aerodynamics could be related to KV mitigation by formation of upper water rivulet, axial flow in near wake and critical Reynolds number. In order to reduce drag force, some devices or geometrical shape- modification have frequently used, including helical fin, strakes or wire installation on stay-cables or transmission cable or chimney, however taking into account the discussions in this paper, more detail study should needed.

Reference [1] M. Matsumoto, T. Yagi, T. Oishi, Q. Liu, "Motion-effect of water rivulet on rain-wind induced vibration of inclined stay-cables", in Proc. of the 6th Int. Symp. on Cable Dyn., 2005, [2] M. Matsumoto, T. Yagi, H. Hatsuda, T. Shima, M. Tanaka, "Sensitivity of dray-state galloping of cable stayed bridges to scruton number", in Proc. of the 7th Int. Symp. on Cable Dyn., 2007, [3] S. Cheng, P.A. Irwin, J.B. Jakobsen, J. Lankin, G.L. Larose, M.G. Savage, H. Tanaka, C. Zurell, "Divergent motion of cables exposed to skewed wind", in Proc. of the 5th Int. Symp. on Cable Dyn., 2003, [4] R.H. Scanlan, J.G. Belveau, K.S. Budlong: "Indicial Aerodynamic Functions for Bridge Decks", Jour. Eng. Mech. Division, Proc. ASCE., Vol.100, 1974, [5]Y.Nakamura,"The Aerodynamic Mechanism of Galloping",Trans. of the Japan Soc. For Aeronautical and Space Science, Vol.36, No.114, 1994 [6] C.H.K. Williamson, A. Roshko: "Vortex formation in the wake of an oscillating cylinder", *J. of Fluids and Structures* 2, 1988, [7] M. Matsumoto, T. Yagi, H. Hatsuda, T. Shima, M. Tanaka, "Sensitivity of dray-state galloping of cable stayed bridges to scruton number", in Proc. of the 7th Int. Symp. on Cable Dyn., 2007,