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THE ROLE OF AXIAL FLOW IN NEAR WAKE ON THE CROSS-FLOW VIBRATION OF THE INCLINED CABLE OF CABLE-STAYED BRIDGES

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ABSTRACT

Nowadays, the violent wind-induced vibration, including "rain-wind induced vibration" and "dry-galloping", of stay-cables of cable-stayed bridges has become the most serious issue for bridge design. Up-to-date, the major factors for excitation of inclined cables have been clarified to be, for "rain-wind induced vibration, the formation of "water-rivulet" on the particular position of upper cable surface, and, for "dry galloping", the "axial flow" which flows in the near wake along cable-axis, and the effect of drag-force associated with Reynolds number", separately. However, the details of the effect of "axial flow" remain unsolved. Thus, this study aims to clarify the effect of axial flow in near wake on the aero-elastic vibration of inclined cables basing on various experiments. The mean velocity of axial flow was almost 60% of approaching wind velocity. Furthermore, the aerodynamic effect of the "axial flow" on cross-flow vibration of inclined cables is discussed in relation to the mitigation of Karman vortex shedding in near wake. Since the role of axial flow seems to be similar to the splitter plate installed in wake from the point of mitigation of Karman vortex shedding, to clarify the cross-flow response in relation to the mitigation of Karman vortex, the perforated ratio of the splitter plate was variously changed, then the similarity of effect of axial flow and the one of splitter plate was verified comparing their unsteady lift force-characteristics. In summary, it is shown that the axial flow on aerodynamic cross-flow vibration might excite like galloping similarly with the splitter plate by mitigation of Karman vortex.

INTRODUCTION

Galloping instability has been studied by former numerous researchers, and its generation mechanism is known to be related with the negative lift slope. Furthermore, From the flow field, Bearman[1] pointed out the "inner circulatory flow" generated by fluid interaction between separated shear flow and sharp-training edge on the vibrating side-surface of body, on the other hand, Nakamura[2] reported the generation of "reattachment-type pressure on the vibrating side-surface of body. In particular, Hirata[3] summarized that generation mechanism can be classified into three types, those are "low-speed galloping"(LSG), "high speed galloping"(HSG) and "with splitter plate"(WSP). LSG is caused by the significantly short wave length of separated shear layer and almost without phase lag of body motion and flow less affected from the down stream flow at low speed range, HSG is caused by the generation of "reattachment–type pressure on the vibrating side-surface of body and WSP is caused by interruption of fluid-communication, which mitigate the pressure difference between upper and lower side surfaces, between two separated shear layers in near wake. "reattachment-type pressure distribution" can be generated by that the separated flow closes sufficiently to body surface. It is known well that if flow reattaches on surface, the drastic pressure recovery appears on the surface, galloping instability can be stabilized. It can be estimated that Karman vortex would be significantly damaged or mitigated by separated flow sufficiently closes to body-surface, taking into account that Karman vortex can be generated by intensive fluid-interaction between two separated shear layers. On the other hand, regarding WSP, splitter plate can be surely damaged or destroyed Karman vortex. Furthermore, comparing fluctuating lift force coefficient, CL', generated by Karman vortex,-side ratio, B/D, of rectangular cylinders, diagrams(see Fig.1(a)) and drag force coefficient, CD, -side ratio, B/D,(see Fig.1(b)) of rectangular cylinders, it is clear that the mitigation of Karman vortex decreases drag for coefficient. The rectangular cylinders, showing galloping instability, are limited at the particular side-ratio range of

B/D=0.75 to 2.8 with small fluctuating lift coefficients. Thus from point of time-average view, the damage or mitigation of Karman vortex might be related with galloping instability.

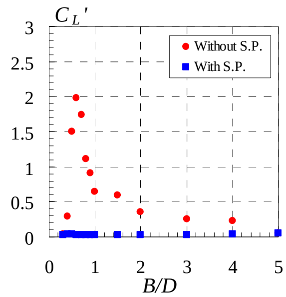

Fig.1(a) fluctuating lift coefficient, CL', v.s side ratio, B/D, of rectangular cylinders (red: without splitter plate, blue: with splitter plate)

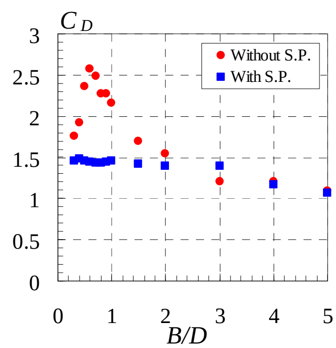

Fig1(b) drag coefficient, CD, v.s side ratio, B/D, of rectangular cylinders(red: without splitter plate, blue: with splitter plate)

Nowadays the reasonable stabilization for "rain-wind induced vibration", which is cross-flow aero-elastic vibration caused by wind and rain, and "dry-state galloping" (or shortly "dry-galloping"), which is cross-flow aero-elastic vibration without rain, of stayed cables, is one of greatly concerns for wind resistant design of cable stayed bridges. A lot of studies have been carried out for clarification of the vibration-mechanism and the establishment of reasonable countermeasure for suppression of the aero-elastic vibration.

On the vibration mechanism, major factors have been pointed out, those are (1) quasi-steady instability by lift caused by the formation of upper water rivulet at the particular position on the cable surface(Hikami[4], Matsumoto[5], Gu[6]), (2) the axial flow generated in a near wake of inclined cable as secondary flow(Matsumoto[7]) and (3) the quasi-steady instability by drag in relation to Reynolds number(Macdonald[8]). The author has pointed out that the aero-elastic vibration mechanism of the inclined cables might be related with the mitigation of intensity of Karman vortex shedding behind a cable, because these three factors of formation of upper water rivulet at the particular position, the generation of the axial flow in a near wake of inclined cable and the drag crisis at transient Reynolds number range between sub-critical and critical Reynolds number can significantly mitigate the intensity of Karman vortex shedding. (Matsumoto[9]). As far as the "axial flow", named by the author[Matsumoto] in a near wake of yawed cable, Shirakasi[10] found firstly by wind tunnel test and they call it "the secondary flow along the cylinder behind a cylinder". They also pointed out that this intense secondary flow causes the depression of vortex shedding frequency. Furthermore, the diagram of power spectrum of velocity in a wake of yawed cylinder, indicated in their paper, apparently indicates the mitigation of intensity of Karman vortex shedding.

COMPLEX FLOW AROUND YAWED/INCLINED CIRCULAR CYLINDERACKNOWLEDGMENTS

Flow tends to cross(intersect) perpendicularly the yawed cylinder.

Therefore, axial flow, which flows along cylinder axis, is generated at the front surface and the rear surface, including the front stagnation line and the rear stagnation line, respectively. Its particular flow had been visualized by Shiraklashi[10]. Fig.2 shows the visualized flow around the yawed (45 degree) circular cylinder with string-tuft.

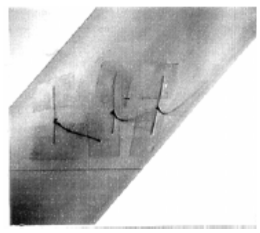

Fig.2 Visualized cross-flow by string-tuft for yawed (45degree) cylinder

As far as the axial flow has been visualized for the yawed(45 degree) circular cylinder in wind tunnel and the proto type inclined stayed cable of cable stayed bridge in the field as shown in Fig.3(a), Fig.3(b) and Fig4.

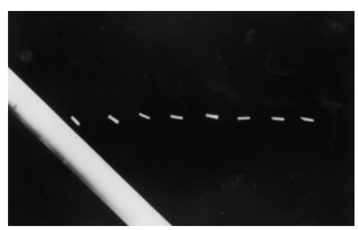

Fig.3(a) Visualized axial flow by light flags set in a wake (yawed cylinder with 45 degree)

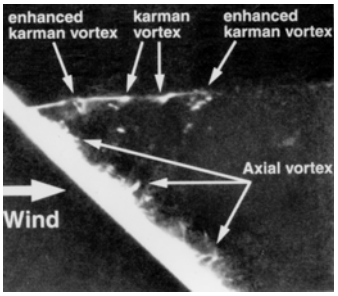

Fig.3(b) Visualized axial flow, axial vortex along cylinder axis and intermittently enhanced Karman vortex in a wake by fluid-paraffin for yawed (45 degree)

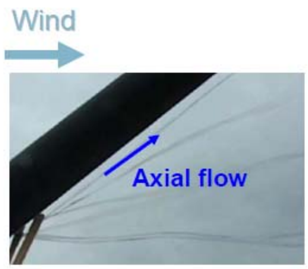

Fig4 Visualized axial flow around proto-type inclined stay cable in the field)

The velocity measurement in the near wake indicates that the intensity of the axial flow is around 60% to 80 % to approaching flow velocity(Matsumoto[7]). The intensity of axial flow measured by wind tunnel test is rather sensitively affected by the both-end condition of yawed cylinder, such as free end (without tunnel wall), with circular windows with suitable size(4D it means 4 times of cylinder diameter), 2D and so on) and the end plates. Besides, the intensity of axial flow varies along the cylinder axis from the upstream cylinder-end.[6]

It should be noted that the axial flow, which was measured at the position from upstream cylinder end by 0.64L (L:cylinder length) for 45 degree yawed cylinder with free end condition under 5m/s, indicates significantly unsteady property. The axial flow was defined as cylinder-axial component measured mean velocity, of the approaching flow direction, by X-type hot wire anemometer. The time history of lift force, fluctuating velocity in a wake and axial flow, simultaneously measured, are indicated in Fig.5(c). All these results are obtained as 8-seconds time average from their data band-pass filtered by specified frequency in PSDs indicated in Fig.5(b) (fluctuating lift) and Fig.5(b) (fluctuating velocity) by red zone which includes the frequency of Karman vortex shedding, respectively. As far as axial flow, the fluctuating velocity in wake and fluctuating lift force indicated by blue line, red line and green line individually, the positive value means the intensive axial flow and intensive Karman vortex shedding respectively. Comparing red line, green line and, blue line, obvious negative correlation between red and blue lines and fully positive well correlation between red and green lines are confirmed. This negative correlation shows that if the axial flow becomes intensive, Karman vortex becomes weak.

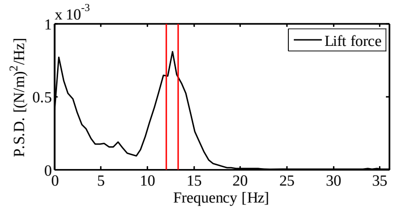

Fig5(a) P.S.D. of fluctuating lift force

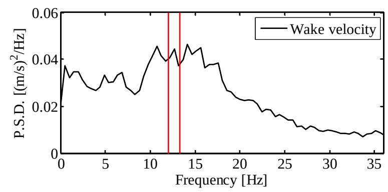

Fig5(b) P.S.D. of wind velocity
(X/L=0.64, Y/D=4.0, Z/D=0.5)

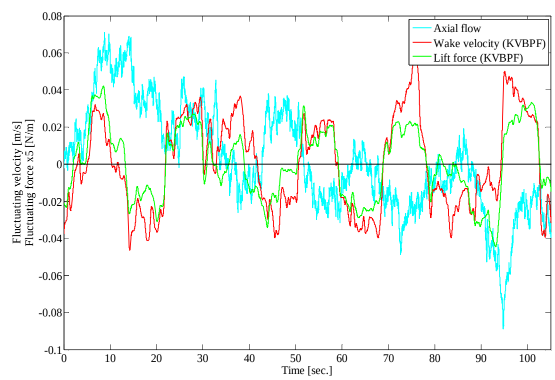

Fig5(c) Time history of axial flow velocity, wind velocity in the wake and lift force

Fig5 Axial flow effects on stationary cable model
(β=45°, D=50mm, Smooth cable, Free end,
U=5.0m/s, in smooth flow)
Hotwire Position: (G) X/L=0.64

Effect of Axial Flow on Karman Vortex

Shirakasi pointed out that Karman vortex shedding was significantly damaged for yawed cylinder[10]. The damage of Karman vortex is thought to be caused by the existence of axial flow in near wake. The same property can be observed in comparison of the power spectral density of fluctuating lift force measured for non-yawed cylinder and yawed (45 degree) cylinder as shown in Fig.6(a) and Fig.6(b). For non-yawed cylinder, the single sharp peak can be observed at the specified reduced frequency(fr) corresponding to Strouhal number, it is 0.2. On the contrary, for yawed cylinder, the sharp spectral peak at fr=0.2 disappear, Two peaks appears at rather low reduced frequency ranges, that is less than .05, and 0.15 to 0.1. The later peak seems to be caused by damaged Karman vortex, because velocity-restricted response is observed at the specified reduced velocity corresponding to these reduced frequency range.(see Fig.8(g))

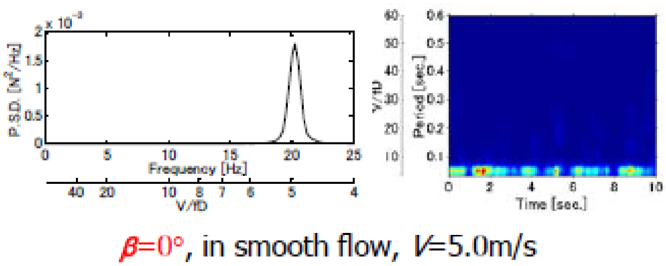

Fig6(a) PSD and wavelet-value of fluctuating lift of non-yawed cylinder

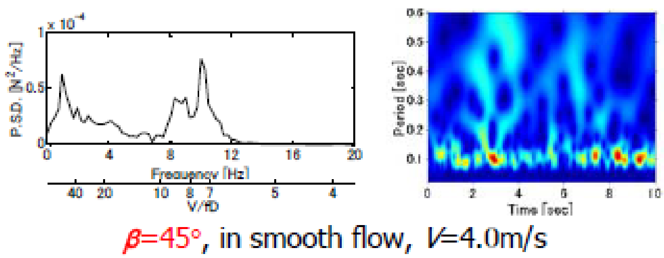

Fig.6(b) PSD and wavelet-value of fluctuating lift force of yawed (45 degree) cylinder

Artificial axial flow can excite galloping

The artificial axial flow was generated in the wake of non-yawed cylinder, which means that the flow perpendicularly comes to the cylinder axis, by blow-out of air and air-suction at the windows installed at the cylinder ends in use of the electric air-cleaner and air blow-out of the inside of cylinder through holes skewly installed on the rear surface of cylinder and distributed along cylinder axis by use of compressor(see Fig.7(a)). The relative attitude of holes and the inlet and outlet of cleaner was changed to change the pitching angle. Thus, the negative slope of lift force was obtained as shown in Fig.7(b), furthermore, the galloping instability, which onset at around Vr=40 (Vr: reduced velocity defined by V/fD), was observed in dynamic test with artificial axial flow as shown in Fig.7(c). This critical galloping velocity is similar to the one of yawed cylinder with yawing angle of 45 degree. It denotes that the axial flow should generate the galloping instability. Therefore, the aero-elastic role of axial flow should be similar with the one of splitter plate installed in near wake of cylinder.

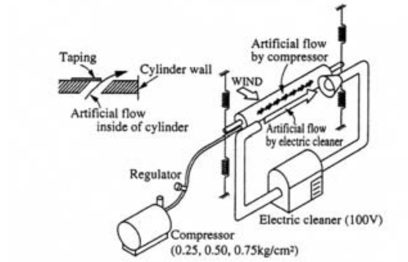

Fig.7(a)Artificial axial flow generation System

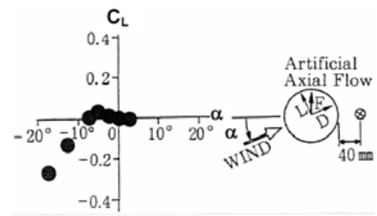

Fig.7(b) lift force coefficient v.s. angle of attack (by artificial axial flow)

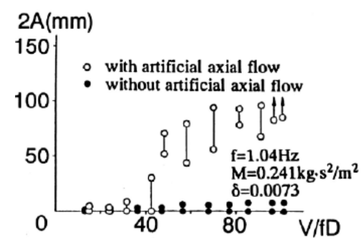

Fig.7(c) Cross-flow response by artificial axial flow

Analogy of axial flow and splitter plate

There is apparent similarity on the damage or suppression of Karman vortex shedding in between the axial flow and a splitter plate installed in a wake. But, a solid splitter plate with sufficient length has been known that Karman vortex can be completely suppressed, however, the axial flow in near wake generated by yawing angle of cylinder can damage or sufficiently modify Karman vortex as describing above. This means that the axial flow forgives the fluid interaction between two separated shear layers to certain extent. Therefore, forgiving the fluid interaction of two shear layers, the particular splitter plate with 30% perforated plate and limited length of 4D has been installed in a wake of non-yawed cylinder as shown in Fig.7(a). The power spectral densities of fluctuating lift forces of these two cases, for non-yawed cylinder with perforated splitter plate under velocity of 5m/s and yawed cylinder with 45 degree under velocity of 4m/s, for the stationary state are compared in Fig.8(d)and Fig.8(e). In both PSD diagrams, there are two mild peaks at two different frequency ranges. Their diagrams are globally similar, though some different shape exists in detail. Furthermore, as shown in Fig.8(b) and Fig.8(c), the low frequency component, which corresponds to the first peak at lower frequency range in PSD diagram of lift force, intermittently appears. The cross flow responses are compared in Fig.8(f) and Fig.(g). There is discrepancy between their velocity-amplitude diagrams, however, galloping instability appears in both cases though the galloping onset reduced velocity are not identical. Through these test results, in summary, it can be pointed out that suitable mitigation of Karman vortex can change the Strouhal number and excite the galloping instability at high reduced velocity range.

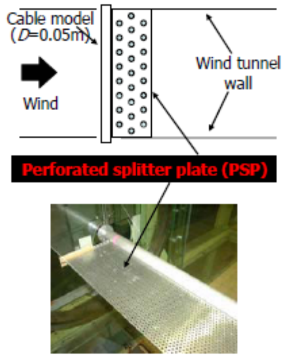

Fig.8(a)Installed perforated splitter plate (with 30%opening ratio) in a wake of non-yawed cylinder

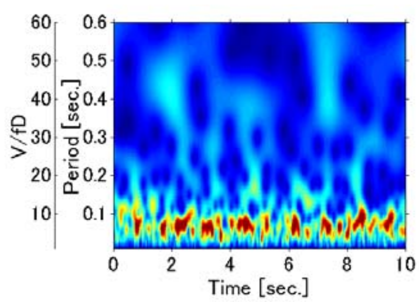

Fig8(b)Wavelet-value of fluctuating lift of non-yawed cylinder with perforated splitter plate

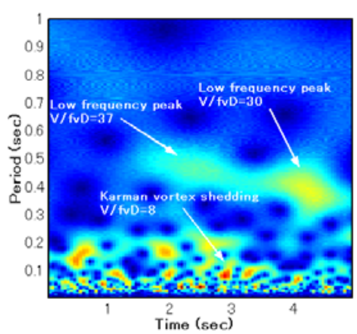

Fig8(c)Wavelet-value of fluctuating lift of yawed 45 degree) cylinder

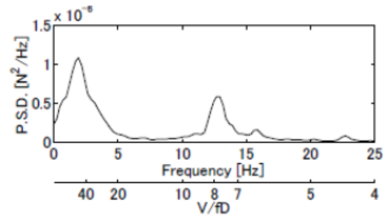

Fig.8(d)PSD of fluctuating lift of non-yawed cylinder with perforated splitter plate

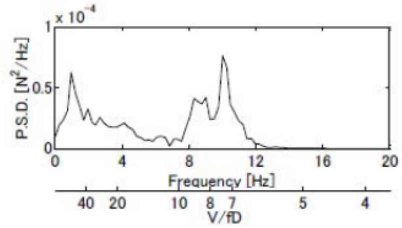

Fig8(e)PSD of fluctuating lift of yawed (45 degree) cylinder

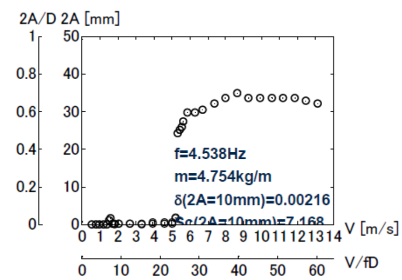

Fig.8(f)Cross-flow response of non-yawed cylinder with perforated splitter plate

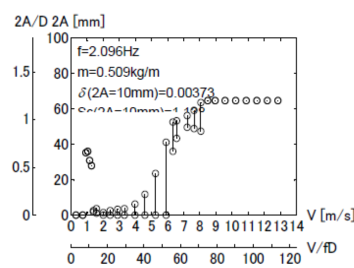

Fig.8(g) Cross-flow response of yawed (45 degree) cylinder

Galloping appearance caused by mitigation of Karman vortex shedding

It is implied that galloping can be excited by mitigation of Karman vortex at high reduced velocity in former section. In order to get more information on this issue, the effect of mitigation ratio of Karman vortex on the cross–flow response have been studied by changing the opening ratio of the splitter plate installed in a wake. The splitter plate has 14D (700mm) length and full span width of cylinder, L and the position was horizontally fixed to the wind tunnel walls and in the line behind the center of cylinder. The gap between cylinder and splitter plate 0.1D(5mm). The opening ratio was changed by closing the thin steel rod frame by tape from 0%(it means solid splitter plate) to 100%(state without splitter plate), as shown in Fig.9a, by pitch of 10%. The PSD of fluctuating lift force and the peak value of PSD of the lift force, corresponding to the frequency of Karman vortex shedding, of the stationary cylinder with the perforated splitter plate with various opening ratios are shown in Fig.9(b) and Fig.9(c), respectively. It is known that intensity of Karman vortex is extremely sensitive to the opening ration of splitter plate, it means for less than around 70% opening ratio, Karman vortex can be sufficiently suppressed. The cross-flow response diagrams for different opening ratios are indicated in Fig.9(d1) to Fig.9(d11). Several interesting information are obtained from these results. First, the decreasing the opening ratio of splitter plate, it means increasing the ratio of suppression of Karman vortex, the galloping instability increases at higher reduced velocity than the resonance reduced velocity characterized by Strouhal number, that is Vr=around 5. Secondly, looking at the maximum amplitude of vortex-induced excitation at reduced velocity of around 5 for the range of opening ratio of 100% to 40%, decreasing of opening ratio of splitter plate, the maximum amplitude increases. The response diagram of the cylinder with perforated splitter plate with 30% shown in Fig.8(f) differs from the one with the perforated a splitter plate with same opening ratio of 30%. The reason is thought to be different length of splitter plate, different shape of perforation and different Scruton number, but, globally description, in between two response diagrams, there is similarity of disappearance of response after vortex-induced excitation less than the reduced velocity of around 20, then the reappearance of response at higher reduced velocity. Taking into account of almost suppression of Karman vortex for less than 70% opening ratio, as describing above, this result clearly indicates that this vortex-induced excitation is not caused by Karman vortex but by motion-induced vortex in relation to shear layer instability issue(E.Naudasher&Rockwell [12]). Thirdly, this vortex-induced excitation must be trigger of galloping instability. Lastly, Karman vortex must be the stabilized vortex related to shear layer instability issue by the stimulation from the alternative vortex shedding in a wake, therefore it is thought to be like twin brother with motion-induced vortex related to shear layer instability at around the reduced velocity of 1/St.

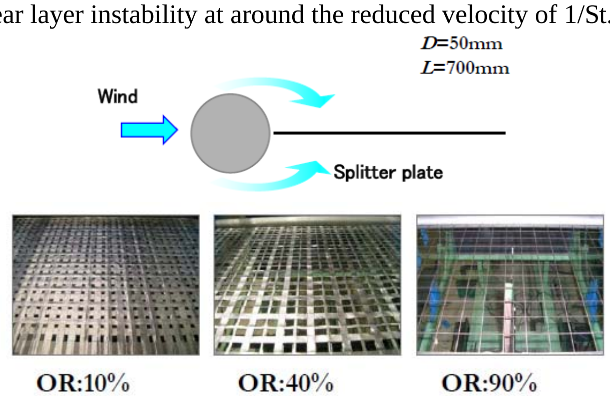

Fig.9(a) perforated splitter plate installed in a wake of non-yawed cylinder

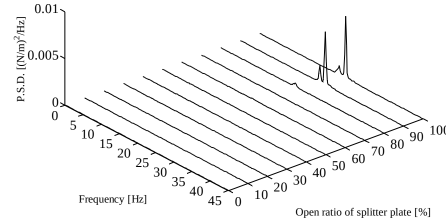

Fig.9(b) PSD of lift of non-yawed cylinder with perforated splitter plate with various opening ratios

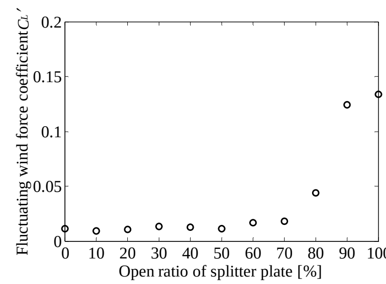

Fig.9(c) Maximum (peak) value of PSD of lift force of non-yawed cylinder with perforated splitter plate with various opening ratios

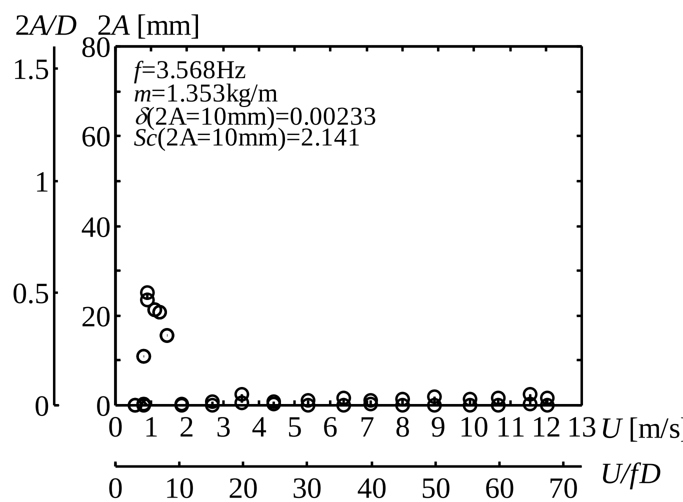

Fig.9(d1) Cross-flow response with perforated splitter plate with opening ratio of 100%

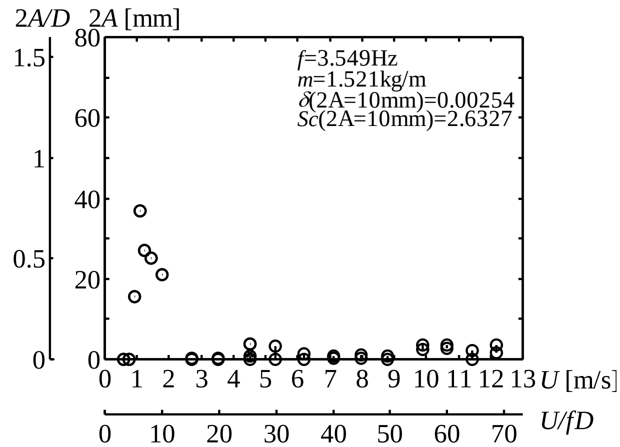

Fig.9(d2) Cross-flow response with perforated splitter plate with opening ratio of 90%

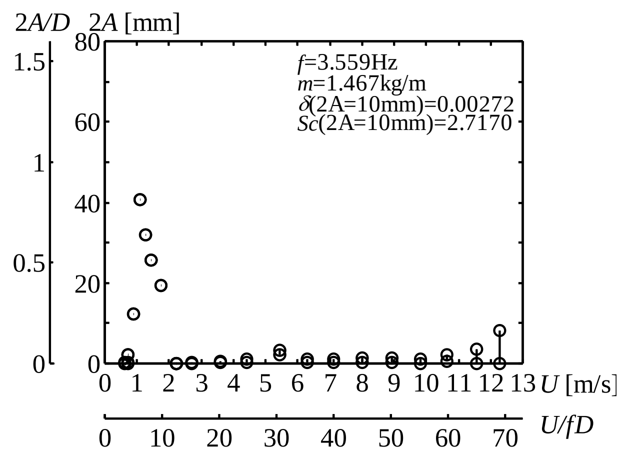

Fig.9(d3) Cross-flow response with perforated splitter plate with opening ratio of 80%

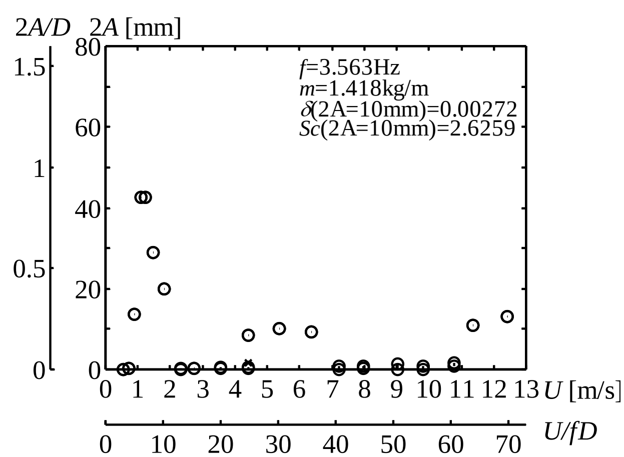

Fig.9(d4) Cross-flow response with perforated splitter plate with opening ratio of 70%

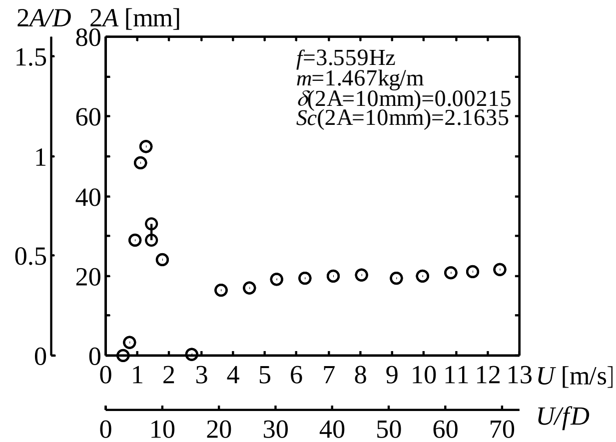

Fig.9(d5) Cross-flow response with perforated splitter plate with opening ratio of 60%

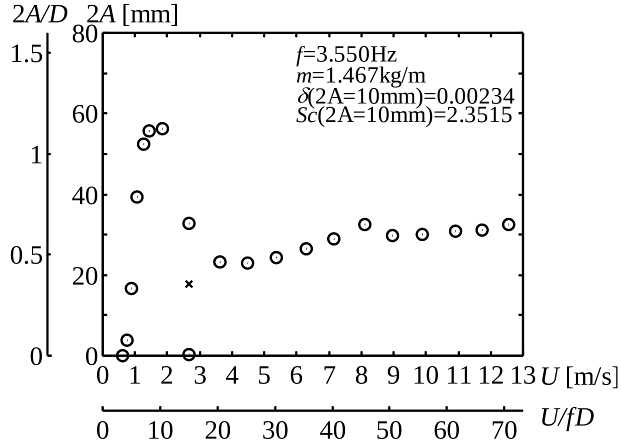

Fig.9(d6) Cross-flow response with perforated splitter plate with opening ratio of 50%

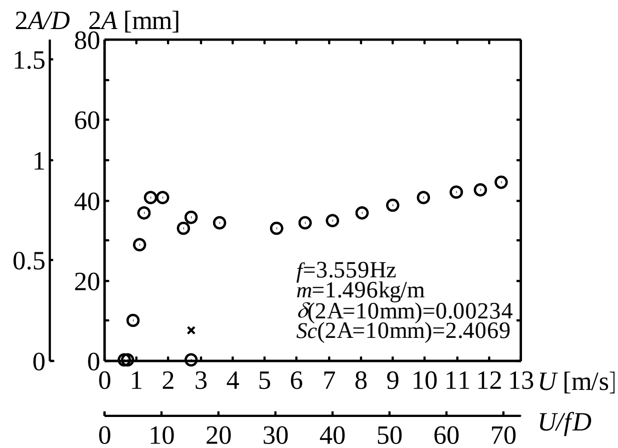

Fig.9(d7) Cross-flow response with perforated splitter plate with opening ratio of 40%

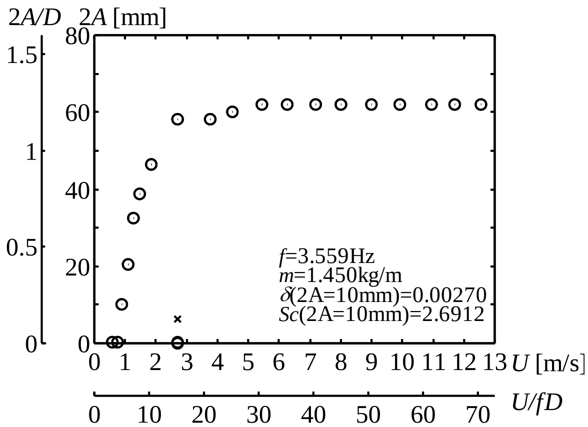

Fig.9(d8) Cross-flow response with perforated splitter plate with opening ratio of 30%

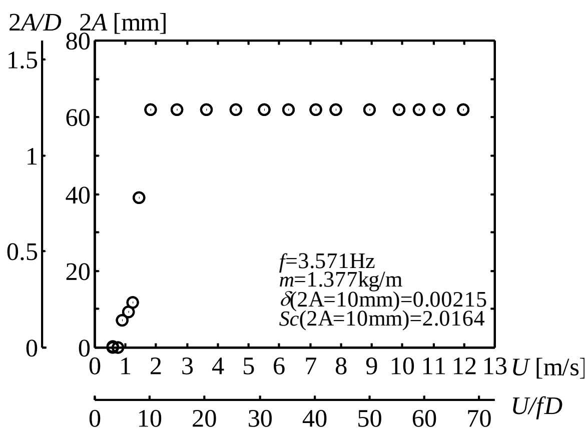

Fig.9(d9) Cross-flow response with perforated splitter plate with opening ratio of 20%

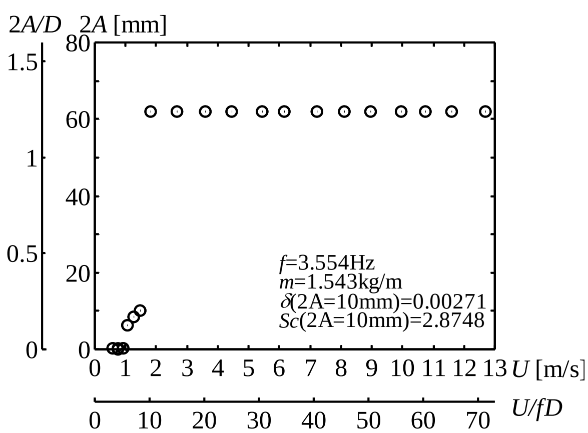

Fig.9(d10) Cross-flow response with perforated splitter plate with opening ratio of 10%

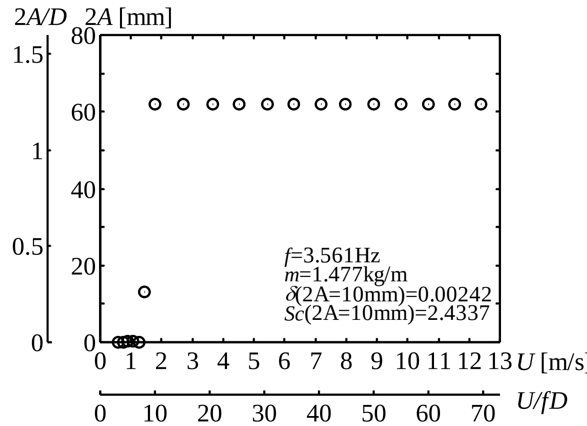

Fig.9(d11) Cross-flow response with perforated splitter plate with opening ratio of 0%

UNSTEADY CROSS-FLOW RESPONSE V.S. UNSTEADY KARMAN VORTEX SHEDDING

The yawed circular cylinder with 45 degree supported by coil spring (see Fig.10(a)) shows the cross-flow vibration with unsteady amplitude because of unsteady intensity of axial flow as explained in Fig 5(c). The unsteady response with unsteady amplitude is observed at lower velocity range than the galloping onset-velocity. As shown in Fig. 10(b). Fig.10(c) indicates the time-history of amplitude which is obtained by being band-pass filtered by the natural frequency, f0, subtracted by the mean amplitude, and the value of 8second mean value subtracted by 8sec RMS value of fluctuating velocity which is band-pass filtered the frequency of Karman vortex at V=4m/s. As shown in Fig.10(c), the amplitude of cross-flow response increases if Karman vortex becomes weak in a wake. Thus it can be verified that the unsteady amplitude of cross-flow response might be caused by unsteadiness of the intensity of axial flow, in another expression, unsteadiness of intensity of Karman vortex shedding.

Fig10(a) free vibration system of yawed circular cylinder (45 degree) in smooth flow

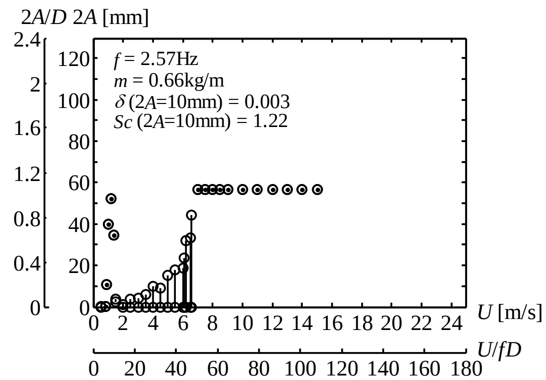

Fig.10(b) cross-flow response of yawed circular cylinder (45degree) in smooth flow

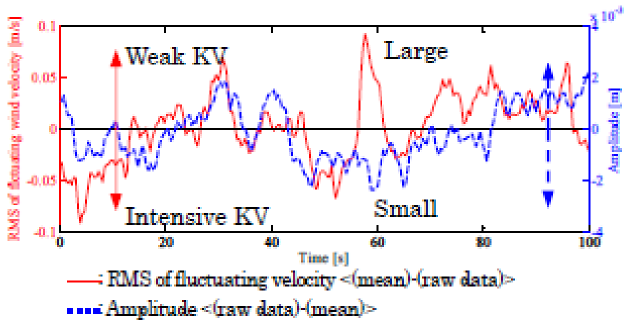

Fig.10(c) time-history of amplitude (blue-line) subtracted by mean value, of cross-flow response band-pass filtered by natural frequency, f0, and the value of raw data subtracted by 8 second RMS value (red line) of band-pass filtered fluctuating velocity in a wake by the frequency Karman vortex, fK, (cylinder with the yawing angle of 45 degree, V=4m/s)

Conclusion

The concluded remarks obtained in this study are summarized as follows: Galloping can be excited by the generation of axial flow behind the yawed circular cylinder, because of damage or mitigation of Karman vortex shedding in the near wake. The axial flow of inclined cables possesses the non-stationary property caused by non-stationary intensity of Karman vortex shedding. It has been clarified that depending on unsteady change of intensity of axial flow generated behind yawed circular cylinder, the intensity of Karman vortex changes, in consequence the magnitude of cross-flow response changes. It is implied that damaged Karman vortex might excite cross-flow vibration including galloping. However, the further study is definitely required to verify the detail mechanism of Karman vortex on galloping.

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