STALL-TYPE GALLOPING OF BLUFF BODIES

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The "stall-type galloping(STG)" of bluff bodies is studied in contrast with the well-known conventional "reattachment type pressure distribution flow Galloping (RPDFG)". STG can be excited by unsteady switching of a generation of the separated bubble(SB) on a side face of a body generated by a flow reattachment on a side face and destruction of SB, because of a flow-change to a separated type from reattachment type. Some bluff bodies similarly show the peculiar characteristics the "stall" with an airfoil at the critical stalling angle, those are a drastic change of a drag, a drastic change Strouhal number, appearance of a negative slope of the lift associated with a pitching angle, and a significant low frequency fluctuation of the flow and the lift force. The "stall" of bluff bodies appears mostly associated to the angle of attack to the flow similarly with an airfoil, but the "stall" of a circular, observed at a range of critical Reynolds number is a particular case. STG would be excited by an unsteady generation/destruction of SB, in consequence, STG would not be explained by the quasi-steady theory, and it might be characterized by a low frequency flow/vortex produced by the "stall". Some bluff bodies such as, a circular cylinder with protuberance(s), a yawed circular cylinder, a circular cylinder with a splitter plate in a wake, a snow-accreted transmission line, a rectangular cylinder with B/D=2.8, a circular cylinder at the critical Reynolds number and so on show STG.

1. INTRODUCTION

Numerous former studies on stall and related to the "stall" of airfoils in the field of the Aeronautical engineering have significantly contributed on verification of the generation mechanism and its characteristics of the "stall".   However the detail generation-mechanism of low frequency flow field during the "stall" still remains unclear. On the generation low frequency unsteady flow at the stall of stationary airfoil has been studied, the large-scale vortex caused by the unsteady bi-stable flow is shedded at changing from the long-separation bubble to the short-separation bubble at the "leading edge stall". (Rinoie[1]). The low frequency flow/vortex during the stall of an airfoil shoul be generated in relation to the "Kelvin-Helmholtz instability" (K-H instability) and the "Tommlin-Schlichiting Wave instability" (T-S Wave instability) of the separated shear flow forming the separation bubble on body surface.(Rinoie[2],Zhou[3]).Furthermore, the lift force variation with a pitching angle, drastic/ discontinuous decrease, significant decrease and gradual/smooth decrease has been observed at the case of leading edge stall, trailing edge stall and thin-airfoil stall, respectively. (Hirose[4]) In particular, the sudden change of separation bubble from the short-bubble to the long bubble should the "bubble-burst", which means disappearance of the bubble, causes the sudden decrease of the lift force.(Rinoie[1]). This bubble change by the bubble-burst is expressed by flow change from the reattachment-flow to the separated-flow/non-reattached flow. On the dynamic instability caused by the "stall", the torsional flutter has been well known. On the torsional flutter/ the stall-flutter, it has been clarified that the dynamic stall vortex generated by the pitching motion of airfoil plays an essentially important role on the torsional flutter or the stall flutter.(McAlister, Carr[5], Wang[6]). On the other hand, E.K. Armstrong et al. (1960[7]) reported the fatigue of the

blade of the compressor of aircraft caused by the flexural mode. Their report must be thought to imply appearance of the flexural oscillation by the stall of blade. This flexural oscillation can be thought to be the galloping caused by the negative slope of lift force associated to the pitching angle. It is significantly interesting that taking into account of the lift force property in terms of angle of attack, the characteristics of the low frequency fluctuation of lift and wake velocity, the flow property around the body, some bluff bodies must show the similar stall with an airfoil described above, and the cross-flow fluid-dynamic instability related to the "stall". Those are a circular cylinder with a protuberance at the particular location, a yawing circular cylinder with 45° to the flow and a circular cylinder at the range of critical Reynolds number (Matsumoto[8]), a snow accreted conductor(Matsumiya[9]) and a rectangular cylinder with the side-ratio(B/D) of 2.8.(Itou[10]) In particular, Schewe[11] studied based on the precise wind tunnel tests on the aerostatic characteristics, including time-averaged lift and drag forces, fluctuating lift force and Strouhal number, at the rang of critical Reynolds number. He indicated the peculiar low frequency property of fluctuating lift force when the non-zero time-averaged lift force suddenly appears or disappears at the specified Reynolds number. Taking into account of recent studies on the airfoil-stall described above, these aerostatic characteristics of a circular cylinder at the critical Reynolds number must be related to the "stall".   .

2. CONTRAST BETWEEN THE CONVENTIONAL GALLOPING OF BLUFF BODIES AND THE STALL-TYPE GALLOPING

Conventional galloping of bluff bodies, such as rectangular cylinders with the side-ratios between B/D=0.8 to B/D=2.8, is generated by the particular flow around bluff body, so called as "reattachment-type pressure distribution flow". (Nakamura[12]) It should be noted that this particular time-averaged flow generating the galloping, never reattaches on body-side face. Den Hartog condition has been often used for judgement of galloping instability, that is when $dCFy/d\alpha=dCL/d\alpha+CD<0$, galloping can be excited.   This particular flow making $dCFy/d\alpha= <0$ is observed at the lower face of a body at the positive angle of attack. In consequence, the time average lift force is down-ward, it means the negative lift, at the range of positive pitching angle.   In contrast, the negative slope of lift , $dCFy/d\alpha=dCL/d\alpha+CD<0$,   regarding the stall-type galloping, can be characterized by the separation bubble formation/ disappearance at the upper side face of body when angle of attack of the flow is positive. Therefore, the time-average lift force should be positive. Also the flow substantially reattaches on the upper side face to produce a separation bubble. In conclusion, the "stall" provides $dCFy/d\alpha<0$. The "separated bubble" plays, in consequence, definitely important role to excite the "stall-type galloping".

3. WIND-INDUCED VIBRATION OF STAY CABLES OF CABLE-STAYED BRIDGES

Recent the main-span length of cable-stayed bridges become more longer than 1,000m, including the Sutong Bridge(1088m China), the Stone cutters Bridge (1018m China) and the Russky Island Bridge(1104m Russia). Their length of the stay cables is more than 600m. The stay cables are extremely low frequency- and low damped- structures, in consequence, they are sensitively excited

by the wind. Since Hikami[13]'s finding, in 1986, of the peculiar wind-induced vibration under the condition of the precipitation. He named this cable-vibration as the "rain-wind induced vibration(RWIV)". Nowadays RWIV of the stay cables of many cable stayed bridges have been observed in the world. Because of serious damages caused by their large amplitudes and frequent occurrence, RWIV become the crucial issues in the design of cable-stayed bridges. Moreover, the violent cable vibration has been observed at the some cable-stayed bridges without rain. This kind of cable vibration has been named as "Dry Galloping (DG)". (Larose[14], Macdonald[15]) How to suppress RWIV and DG of stay cables must be substantial issue for safety design of cable stayed bridges. Based on many field observations of RWIV, the occurrence conditions of RWIV have been mostly summarized as (1) Polyethylene lapped cable, (2) wind direction to the cable-plane: at the range of yawing angle of 30°~60° (measured from cable plane)   (3)wind velocity range ; at the range of   5m/s~30m/s   (4) cable vibration frequency; at the range of 0.5Hz~3Hz   (5) low turbulent wind: low intensity of turbulence;   Iu <10%, (6) low structural damping of cables; δ<0.01. The sequential studies on cable wind induced vibration clarified that major factors of RWIV and DG are (1) formation of the upper rivulet on cable surface at particular position determined by the balance of wind pressure, cable surface roughness,   tensile force of water on cable surface and water-rivulet gravity.   (2) the axial flow, that is secondary flow along the cable-axis, generated in the near wake, (3) the critical Reynolds number effect on cable aerodynamic properties. Matsumoto.[16to25],   Verviewe[26],   MacDonald[15],   Larose[14],   Chen[27],   Katsuchi[28], Kimura[29], Georgakis[30], Liu[31], Flamand and Benidir[32]) Matsumoto [8], Jakobsen[14]. The major countermeasures to suppress RWIV are installation of dampers, cross-tie and helical fin or indented cable surface. Particular attention should pay that the Scruton number (Sc=2mδ/ρD2: m:mass of cable unit length, δ: logarithmic damping decrement od cable , ρ:air density, D:cble :diameter) is no effect on DG suppression by Macdonald[15] and Kimura[29]. The clarification of the generation mechanism of RWIV and DG is absolutely expected to establish more reasonable and effective countermeasures for safety maintenance and design of existed and to be constructed cable stayed bridges, respectively.

4. THE "STALL" AND THE "STALL-TYPE GALLOPING" OF BLUFF   BODIES
(1) Non-yawed (β=0°) circular cylinder with protuberance(s)

In order to clarify the effect of the water rivulet on RWIV, A protuberance with rectangular shape, w/D=0.064 in width and t=0.032D in thickness (D:cylinder diameter(0.05m)) is installed to simulate a water rivulet on the face of a stationary circular cylinder. The protuberance position, θ, was changed from 0° to 180°, measured from the front stagnation point .

Time-averaged Lift force coefficient, CL, and the time-averaged drag force coefficient, CD, the fluctuating lift force, LF' caused by the vortex and Strouhal number, St(=fvrD/V: fvr:vortex shedding frequency, D: cylinder diameter, V: mean wind velocity)of the stationary circular cylinder with a protuberance associated with protuberance position, θ, measured in smooth flow and at the

subcritical Reynolds number, are shown in Fig.1. These CL, CD, Lfl' and St sensitively varies with θ, in particular, at near critical stalling angle of θcr=50°. The Flow around cylinder affected by the protuberance position would be characterized mainly based on these, as follows:

θ<30°: The almost effect of protuberance, and the flow is fundamentally separated-type.

30°<θ<50°: Separation bubble behind a protuberance gradually grows with increase of θ, and the flow is reattached-type. FL' gradually decrease with increase of θ, since the flow becomes more intensively reattached-type.

θ=50°: the most intensive separation bubble (short bubble) is formed behind a protuberance, and, the flow shows the bi-stable flow, those are a separated-type and a reattached-type.(based on St-θ diagram)

50°<θ<54°: The intensive "bubble-burst" appears following with drastic decrease of CL with increase of θ. The flow mainly is mainly a separated-type affected by the intensive "bubble-burst".

54°<θ<70°: the weak "bubble-burst" continues following with gradual decrease of CL with increase of θ. Comparatively large value of FL' corresponds on the low frequency vortex caused by the "bubble-burst". The flow is fundamentally a separated-type, but affected by a separated-type, because of small value of St.

70°<θ<100°: The flow gradually becomes the one affected by a protuberance. The flow, in consequence, is a separated type.

100°>θ: The almost effect of protuberance, and the flow is fundamentally separated-type.

As summary on the effect of protuberance on circular cylinder, the "bubble burst" can be observed near at θ=50°, then the low frequency flow /vortex appears. The bubble-burst at θ=50°can be successfully visualized by CFD analysis by Liu[33] as shown in Fig.2.
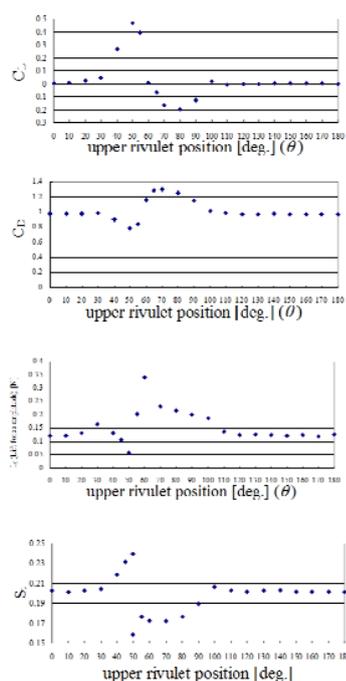
Fig.1 Lift coefficient, CL (top), Drag coefficient, CD(second), Fluctuating lift, FL'(third) and Strouhal number, St(bottom) of a circular cylinder with a protuberance
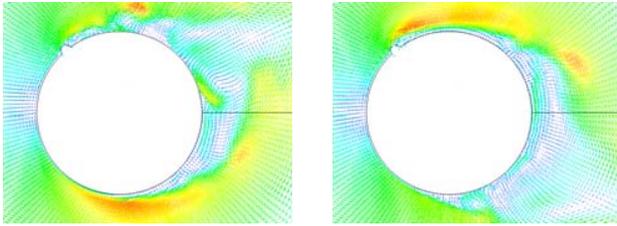

Fig.2 Unsteady flow around a stationary circular cylinder with a protuberance at stalling angle of θ=50°. Appearance of the "bubble-burst(left) "and reattachment flow during stall(right)(CFD analysis by Liu[33])

Fig.3 shows the PSD diagrams of fluctuating lift force measured at the condition of V=8m/s, D=0.05m non-yawed circular cylinder /without with a protuberance at the range of θ =0° and 90° are shown in Fig.4.   The multiple-peaks are particularly found, in the one at θ=50°, which id critical stalling angle. The low frequency slight peak arises at of θ=55°and θ=60° , corresponding on the
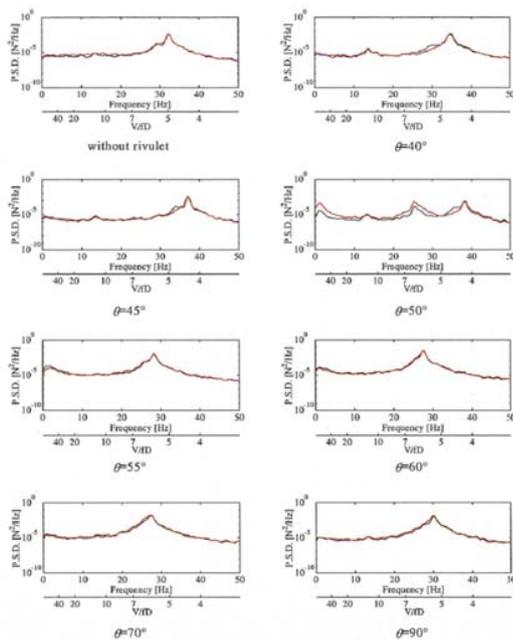

Fig.3 PSD of fluctuating lift force of non-yawed circular cylinder with a protuberance. (V=8m/s)

Fig.4 shows the PSD of lift force of a non-yawed circular cylinder with symmetrical double and same size protuberances,   measured at the conditions of V=6m/s, D=0.05 in smooth flow and at θ=50°. The low frequency fluctuation of flow/lift force can be observed similarly with the case of a single protuberance. The aerostatic properties of a non-yawed circular cylinders with symmetrical double protuberances are precisely studied by Hori[34]. Their drag and fluctuating lift and Strouhal number associated to protuberance position are interestingly similar with the ones with the case of a single protuberance explained above, exceptionally the results of lift force. Because of symmetrical shape, lift force shows zero exceptionally θ=50°. Which means the separation bubble is formed at

the critical stalling angle, $\theta=50°$, on one side face of cylinder, then the asymmetrical flow appears and the sequential aerostatic properties, including the appearance of bi-stable flow and the low frequency flow/vortex, caused by the "bubble-burst". The flow thought to be "bubble-burst" calculated by CFD is shown in Fig.6.(Hori[34]) The significant asymmetrical flow and the intensive vortex shedding in a near wake can be observed. The cross-flow vibration of the non-yawed cylinder with symmetrical protuberances and a single protuberance at $\theta=50°$ and $\theta=54°$, respectively. In summary, the stall galloping can be excited in relation to the "bubble-burst" of the "stall", the bubble burst can produce the low frequency flow/ vortex similarly with the case of airfoil.
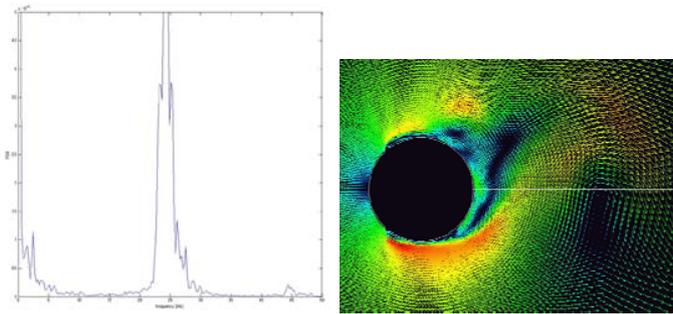

Fig.4 the PSD of lift force of a non-yawed circular cylinder with symmetrical double and same size protuberances,　measured at the conditions of V=6m/s, D=0.05 in smooth flow and at $\theta=50°$（top left）and　the Unsteady and instant flow visualized at $\theta=50°$.(top left) (Hori[34])

(2)　Yawed　smooth circular cylinder with yawed angle of 45° and non-yawed cylinder with a perforated splitter plate

　　　An intensive axial flow with the velocity of around 20% to 50% of the one of approaching flow is generated at a near wake of a stationary yawed ($\beta=45°$) circular cylinder. The intensity of axial flow velocity varies in the axial direction, X/L (X is distance from the upstream end of the yawed cylinder, L: cylinder length) as shown in Fig.5 (top right). In the PSD of the lift measured at V=4m/s, the low frequency peak is observed additionally the peak at the Strouhal number of the yawed cylinder with $\beta=45°$, St≈0.14. Both cases, yawed ($\beta=45°$) state and with a perforated splitter plate, the galloping instabilities are observed, moreover as in Fig.5(bottom right and left), Their PSD diagrams of lift force show significantly similar, including the low frequency peak. In consequence, both of their galloping are thought to be the "stall-type galloping".
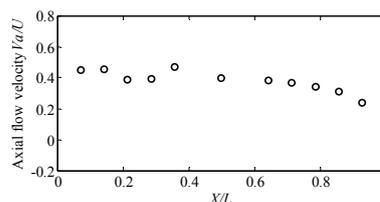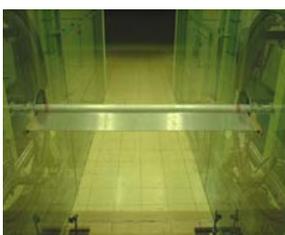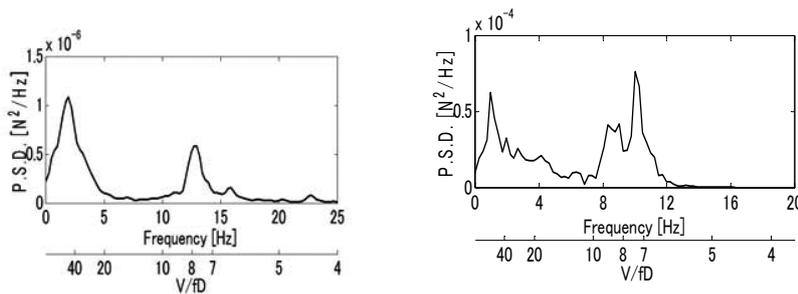
Fig.5 non-yawed cylinder with a separately installed splitter plate with 30% perforation and the length of 4D(top left), the axial flow intensity along yawed(β=45°) cylinder maesured in a wake positioned at vertically clinder center and 1D in along wind (top right), PSD of lift of nonywed cylinder with a 30%perforated splitter plate, and the one of yawed(β=45°) cylinder, (bottom left and bottum right , respectively)

(3)   A circular cylinder at the critical Reynolds number

As described before, Schewe[11] reported the detail information on the aerostatic properties of non-yawed circular cylinder at the critical Reynolds number, in particular on the appearance of non-zero stationary lift and low frequency lift during the drag-crisis. The non-zero stationary lift was measured at the range of the critical Reynolds number by Larose[14], Liu[31], Matsumoto[16] and Flamand[32]. Furthermore, Liu[31] reported the appearance of the velocity-restricted cross-flow response of non-yawed circular cylinder corresponding to the specified velocity where the stationary lift appears and disappears. It has been known that the laminar separation bubble is formed on the one-side of cylinder face at the critical Reynolds number(Sato[35], Basu[36], Jakobsen[14]). The aerostatic characteristics affected by the cylinder surface roughness have been studied by (Georgakis[30]). The cross-flow response characteristics have been studied by Kimura[29] and Katsuchi[28].   It can be said that almost recent these studies are to understand more clearly the complex generation mechanism of the "Dry Galloping (DG)" of inclined stay cables. Furthermore, Saito[37] and Kimura[29] have experimentally reported significantly important cross-flow response property of the yawed cylinder with β=45° , those are first divergent-type response starts at the reduced velocity (Vr=V/fD) of around 40 till up to the critical Reynolds number. At this critical Reynolds number, the responsive amplitude becomes small, but the second divergent-type response continuously starts. Taking into account of the existence of the axial flow in a near wake formation at the sub-critical Reynolds range and formation of the laminar separation bubble at the critical Reynolds number, these cross-flow vibration should be excited in relation to the "stall", in another expression, both of their first and second responses must be the "stall-type galloping". On the DG of cable related the critical Reynolds number, Macdonald[15] and Kimura[29] pointed the less/non effect of the Scruton number, Sc, on their galloping. The authors evaluate their view-points as follows: 1. The separation bubble is formed at around 130°(230°) from the front stagnation point evaluated from the pressure distribution on cylinder surface (Flamand[32]), therefore the stationary lift appears at this point. Based on the quasi-steady theory, when a cylinder moves downward, the quasi-steady lift can be expressed as follows;

LFDy=Lsin(θ+αre)=Lsinθ+Lcosθsin(dy/dt)cosθ≈Lsinθ+Lcosθ(dy/dt)

Where L:stationary lift at the critical Reynolds number (upward positive), y:displacement of a cylinder (down ward positive) and θ is central position of the laminar separation bubble measured from the front stagnation point.   Based on this hypothesis, the term of Lcosθ(dy/dt) is the quasi-steady damping term, then it can excite a cylinder because of θ≈130° or θ=230°. Therefore if the effect of this term would mainly play, Sc must make significant effect on the cross-flow vibration of a cylinder at the critical Reynolds number, which is contradictory to the view-points by

Macdonald[15] and Kimura[29].

On the other hand, taking account of separated flow caused the cross-flow vibration, when a cylinder moves downwards, it can be easily evaluated that the separated flow tends to move far away from the cylinder face, and contrary the one of from down side of cylinder tends to approach. In, consequence, if a laminar separated bubble would be formed on upper-side of cylinder, it would be easily destructed or significantly weakened. On the contrary, when a cylinder moves upwards, the separation bubble should be amplified because of promotion of reattaching of the separated flow .Which means the lift force must be always produced in the same direction of the cylinder movement. In the case of formation of separated bubble is formed on the down-side of cable surface, the same role of the cylinder motion on the intensity of the separation bubble is easily confirmed. These cases are thought to be excited by the displacement, y, plays definitely play an important role, instead of displacement velocity, (dy/dt). Based on the discussions explained, the later effect might be more effectively on the excitation of the "stall-type galloping".

5. THE LOW FREQUENCY FLOW/VORTEX IN RELATION TO THE "STALL"

The reason of the appearance of the low frequency flow/vortex has been mainly reported to be in relation of H-S Instability and T-S Wave Instability in the field of the aeronautical engineering field. However its detail remains not clear. The authors investigate that the generation of the low frequency flow/vortex during the "stall" of bluff body as follows: The flow changes from the separated-type to the reattached-type at the "stall". The Karman vortex, in consequence, must be drastically suppressed/ mitigated. The Karman vortex in a wake of bluff body is also stabilized vortex of separated shear layer instability in relation to K-H instability. In another words, the stabilized Karman vortex might interrupt the stabilization of another vortices from the shear layer with various frequencies. In the case of the "stall" of the bluff bodies, including the circular cylinders under the various conditions described above, because of mitigation of the Karman-vortex, the low frequency flow/vortex might be produced in original and latent Strouhal numbers-property, like the" DNA", of the bluff body. The fluctuating flow in relation to the latent Strouhal numbers might be amplified by certain stimulation to the shear layer, when the Karman Vortex is sufficiently mitigated. In order to verify this scenario of appearance of the low frequency flow/vortex by mitigation of Karman vortex , regarding to the "stall" of a circular cylinder, the Karman vortex is mitigated by the splitter plate installed separately from a cylinder with the gap length between cylinder and the splitter plate of 0.1D, the length of 18D and 70% and 10% perforated plate. The fluctuating lift by the Karman vortex is mitigated into be almost 10% and almost 0% by these splitter plates respectively. The longitudinal and sinusoidal fluctuating-flow, with the extremely slight amplitude, that is u/U, of 0.67% can be generated by the sinusoidal generator, which is composed by two rotators installed on a perforated plate at the wind tunnel-outlet, by changing the air-volume at the wind tunnel outlet. The wake velocity was measured at 1.5D along-wind and 1D cross-wind from cylinder center in a wake. Fig.6 shows the diagrams of the PSD of wake velocity-frequency-fluctuating flow frequency measured at 6m/s. The enhanced flows/vortices at the peculiar frequencies are observed in these diagrams corresponding to the characteristic Strouhal numbers, in particular, significantly low frequency, in another expression significantly lower Strouhal number than St=0.2, such as St=0.05, 0.025,0.0125, •••. Thus, the hypothesis of the role of mitigation of Karman vortex caused by "the stall" explained above might be thought to be supported.
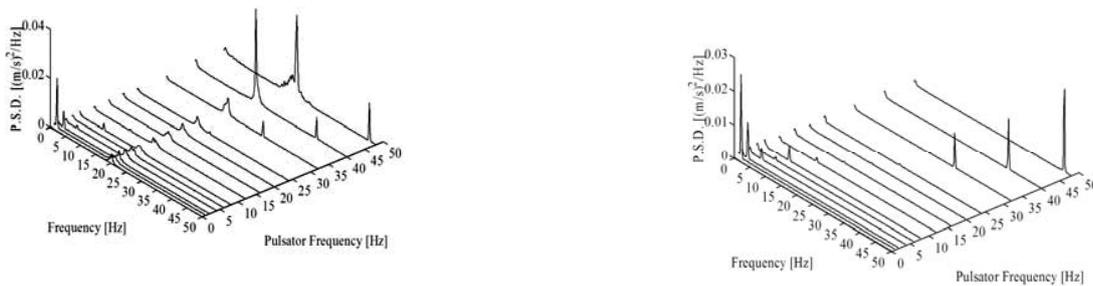
Fig.6 the PSD diagrams of wake velocity of non-yawed circular cylinder with perforated splitter plate in a wake, affected by the longitudinal fluctuating flow measured at 6m/s. (70% perforated splitter plate(left) and 10% perforated splitter plate(right))

6.CONCLUSIONS

The conclusions of this study are as follows:

1. The galloping of bluff body can be excited by the stall. This kind of galloping is called as the "stall-type galloping".
2. The "stall" should be related to the "bubble-burst/ destruction" similarly with an airfoil stall.
3. Significantly low frequency flow/vortex can be generated by the "stall" of bluff bodies, similarly with the case of airfoil.
4. The "stall" of bluff bodies can be characterized by following factors :1. Negative slope of lift slope associated to pitching angle, 2.mitigation of Karman vortex, 3. Unsteady appearance of bi-stable flows, those are separated f-type and reattached-type flows, 4. Appearance of low frequency flow/vortex and 5. Appearance of cross-flow vibration.
5. RWIV (rain wind induced vibration) and DG(dry galloping), induced by the water-rivulet formation, the axial flow in a near wake and the critical Reynolds number, of stay cables of the cable stay bridges must be kinds of the "stall-type galloping".
6. The low frequency flow/vortex caused by the "stall" of bluff bodies might be related to the mitigation of Karman vortex caused by the "stall"

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