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ROLE OF Karman VORTEX ON BLUFF BODY AERODYNAMICS-VORTEX-INDUCED VIBRATION

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ABSTRACT

In this paper, the role of Karman vortex(KV) on vortex-induced vibration(VIV) of bluff body is described , taking into account of aerodynamic interaction between KV and motion-induced vortex (MIV).

INSTRUCTION

Karman vortex(KV) has widely known as alternative and periodical vortex shedding in a wake of stationary bluff body at low Reynolds number(Re). In this paper KV is defined more widely as alternative vortex shedding in a wake of bluff body including at high Re. KV characteristics are remarkably sensitive not only to geometrical shape of bluff body, but also to Re, and fluid condition, that is smooth or turbulent state. Shedding frequency of KV is characterized by Strouhal number(St). However, the role of KV on bluff body aerodynamics has not been clarified at present even though KV has been widely known. The effect of KV, in particular, on aerodynamic response of bluff body has not been clarified yet including vortex induced vibration(VIV) of structures related to KV. Willamson and Roshko [1], Brika and Laneville[2], Nakamura and Nakashima[3] have contributed on the study of complex interference between KV and motion-induced vortex(MIV) of circular cylinder([1],[2]) and H-shaped section([3]), respectively.

KARMAN VORTEX (KV) AND IMPINGING SHEAR LAYER VORTEX (IMPV)

Karman vortex is generated in the wake as the stabilized vortex affected by the arrangement of other vortices basing on Kelivin-Helmholz (KH) instability. Fig. 1 shows the visualized stabilized KH vortices in one-side shear layer of 20 angular section by high speed camera. (by Central Research Institute of Electric Power Industry Japan). On the other hand, Nakamura studied on generation of impinging shear layer vortex(IMPV) of rectangular cylinder and H-shaped cylinders with flow reattachment on side. IMPV is visualized as shown in Fig.2(a)(Nakamura and Nakashima 1986[3]). It should be noted that IMPV changes similar vortex pattern of KV of circular cylinder(Fig.2(b). Thus IMPV might be a baby of KV. Basing on experiments and CFD analysis, Strouhal number(St(B)=fB/V: f:frequency of vortices, B:longitudinal length of body, V:velocity)) normalized by B of rectangular cylinder and H-shaped cylinder at the range of 2.8<B/D<6(D: cross flow length of body) and 2<B/D< 8 (as shown in Fig.3) , respectively, is expressed as follows(Nakamura and Nakashima 1986[3]):

$$St(B)=0.6 \quad (1)$$

IMPV formed on body-face is almost not affected by alternative vortex shedding (KV), which is confirmed by comparison of flow visualization with without splitter plate(SP) and with SP.(Nakamura and Nakashima1986[3]). Furthermore, number of IMPV existing on one body side of rectangular cylinder changes step-wisely with elongation of cylinder, single, double, triple four at the range of 2.8<B/D<6, 6<B/D<9, 9<B/D<12.5, 12.5<B/D, as shown in Fig.4(Tsuruta and et.al1988[4]).

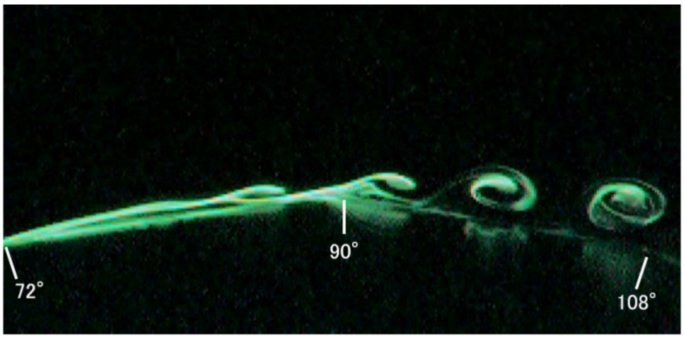
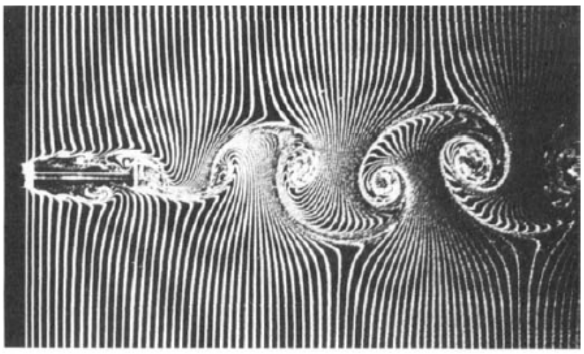


Fig.1 visualized stabilized vortex of 20 angular section in terms of Kelvin-Helmholz Instability (Re=2.1x104)(presented by and Courtesy: Central Research Institute of Electric Power Industry, Japan)



(a)

Fig2(a) visualized MIV on side face and KV in a wake of stationary H-shaped cylinder with B/D=5 (Nakamura and Nakashima1986[3])

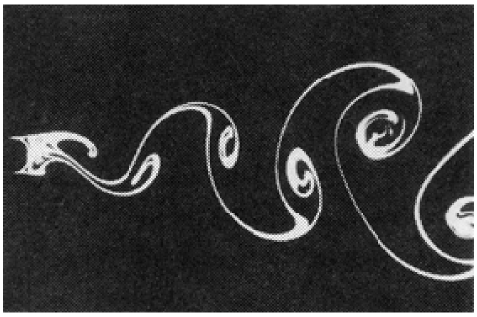


Fig.2(b) visualized KV of circular cylinder

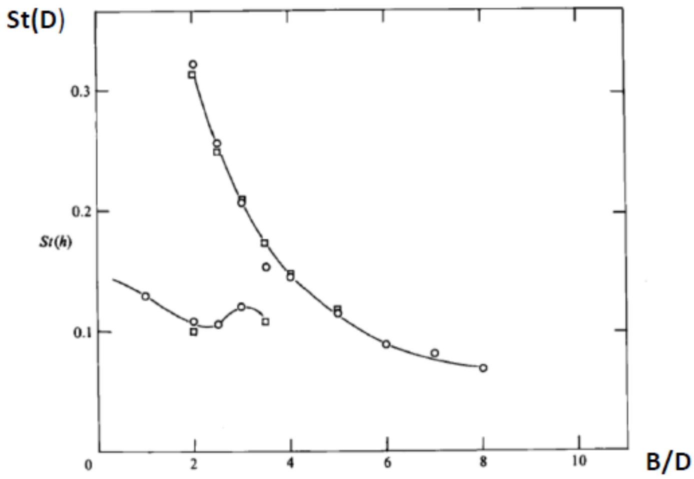


Fig.3 Strouhal number St(D) of H-shaped cylinder(Nakamura and Nakashima[3])

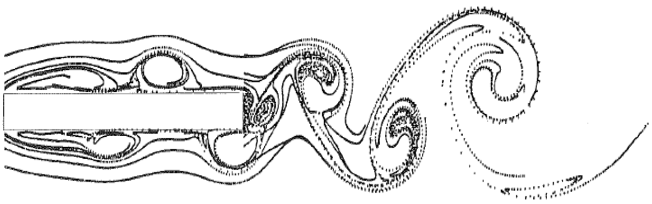


Fig.4(a) MIV of stationary rectangular cylinder B/D=8 analyzed by CFD(Tsuruta, and et.al 1988[4])

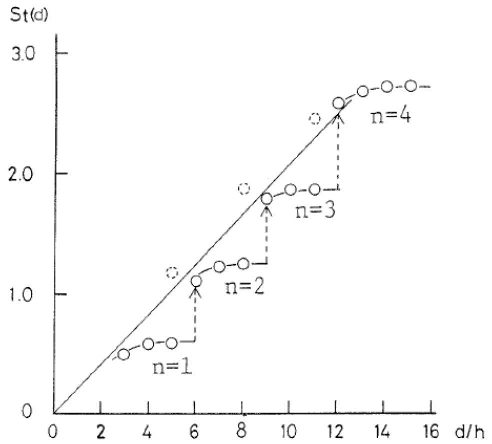


Fig.4(b) Step-wise change of MIV of rectangular cylinder (Tsuruta and et.al1988[4])

MOTION-INDUCED VORTEX(MIV)

Vortex-induced vibration(VIV) of bluff body is, in general, excited by motion-induced vortex(MIV). It has been understood that VIV should be excited by particular MIV, which has been thought to be "locked-in" KV to frequency of body-motion near at critical reduced velocity, Vr=1/St. However, it has been verified that MIV, that is vortex mode, near at Vr=1/St is extremely complicate and sensitively affected by slight change of amplitude and Vr.. Vortex mode around circular cylinder has been firstly studied by Williamson & Roshko[1], as shown in Fig.5 . Complex characteristics of vortex pattern around circular cylinder and H-shaped cylinder with B/D=5 has been visualized by Dallaire and et.al [5] and Nakamura and Nakashima[3], respectively. It should be noted that vortex patterns, that is mushroom–pattern, in a wake are similarly generated in a wake even though different vortex generation-mechanism of circular cylinder and H-shaped cylinder, those are complete flow-separation type, in which initial rolling flow in early wake grows up KV, and flow impinging type, in which IMPV generates KV in a wake, as shown in Fig. 6(a) and Fig.6(b). Furthermore, MIV can be generated at the lower reduced velocity than Vr=1/St. At higher reduced velocity. Fig.7 shows the flow pattern around rectangular cylinder with B/D=2 under heaving forced oscillation with y0/D=0.1, obtained by CFD analysis by Shimada[6]. At higher reduced velocity than Vr=1/St (St=0.08), flow pattern shows similar the one of stationary cylinder. The vortex structures during VIV are completely characterized MIV affected more or less by KV, in particular, in VIV of circular cylinder KV exists at the particular condition with restricted amplitude and reduced velocity, as shown in Fig.8(Matsumoto and et.al[7]). In another expression, it can be said that "lock-in phenomenon", which is defined as deformed KV with frequency of body motion, apart from St-frequency, does not exist, but MIV and KV exist during VIV. VIV generation mechanism should be caused by that MIV can be significantly enhanced near at particular reduced velocity, Vr=1/St. MIV associated to IMPV is sensitively affected by the motion of leading edge of body and trailing edge of rectangular and H-shaped cylinders. Initial MIV are simultaneously or with 90 degree phase lag generated at leading and trailing edge of cylinder in heaving motion or torsional motion around mid-chord point, respectively. To generate stable vortex(KV) in near wake, these two vortices, those are major IMPV-vortex from leading edge and secondary vortex and trailing edge vortex should coalescence at early wake closing trailing edge.(see Fig.9(Shiraishi and Matsumoto[8])) Basing on a lot of flow visualizations around bluff bodies with various kinds of geometrical shape, leading edge vortex-MIV moves to the trailing edge with average velocity of 60%. From these characteristics of MIV during heaving and torsional motion, the following conditions should be satisfied to stabilization of MIV and excitation VIB (Shiraishi and Matsumotoi[8]):

Vr=(1/n)0.6(B/D) (2) for heaving motion
Vr=(1/n)(2/3)0.6(B/D) (3) for torsional motion

where, Vr=V/f0D, n; number of vortices on one side face of cylinder

Different MIV characteristics for heaving and torsional motions are confirmed by different onset reduced velocity of heaving and torsional VIV as shown in Fig.10(Shiraishi and Matsumoto[8]). Moreover, torsional VIV of rectangular cylinder with B/D=4 with torsional axis at leading edge or trailing edge appears at Vr defined by equation (2), because of simultaneous generation of leading edge vortex and trailing edge vortex as heaving VIV. Maximum amplitude of torsional VIV is observed in the case of rotational axis at trailing edge, since generation of intensive leading edge vortex caused by largest cross-flow amplitude at leading edge, as shown in Fig.11.(Matsumoto and et.al[9]). It is known from Equation(2) that heaving VIV of flow impinging type is identical to heaving VIV of circular cylinder as a completely flow separated type at subcritical Re, because of Vr*= V/(foB)=1/St(B)=1/0.6.

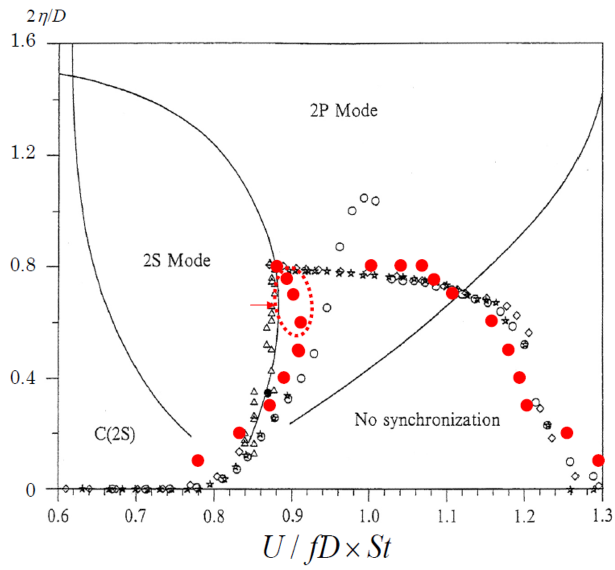
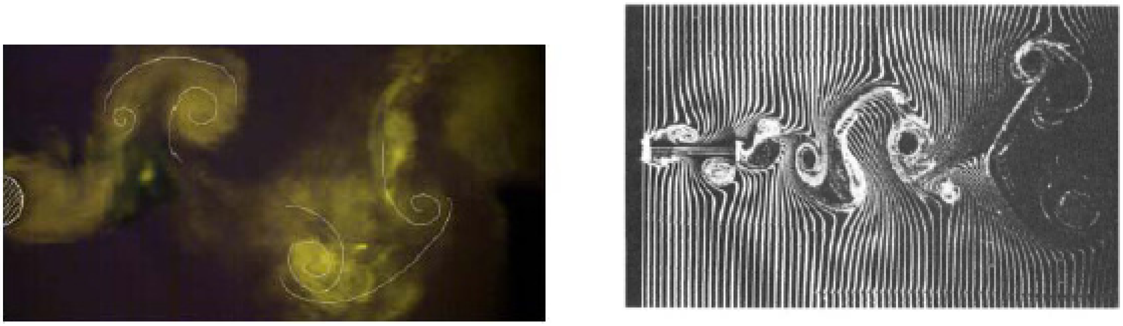


Fig.5 vortex modes during VIV of circular cylinder (vortex mode by Roshko&Williamson[1], Amplitude property indicated by white and black circle, star symbol by Brika&Laneville[6], red circle (Matsumoto and et.al[8])



(a) (b)

Fig.6 vortex structures in a wake associated to VIV of (a) 2P mode of circular cylinder (V/Vcr=0.981, y0/D=0.4) (Dallaire and et.al [5]) and (b) H-shaped cylinder with B.D=5 (Vr=1/St, y0/D=0.19)(Nakamura and Nakashima[3])

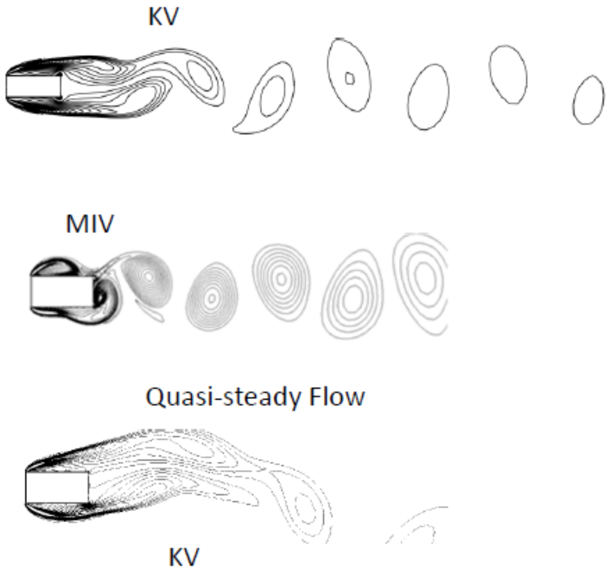


Fig.7 Vortex pattern of stationary/cross flow oscillating(y0/D=0.1) rectangular cylinder with B/D=2 at stationary state(top figure), at Vr=6 (<1/St=12.5) (middle figure)and at Vr=16 (bottom figure) (CFD results by Shimada[6])

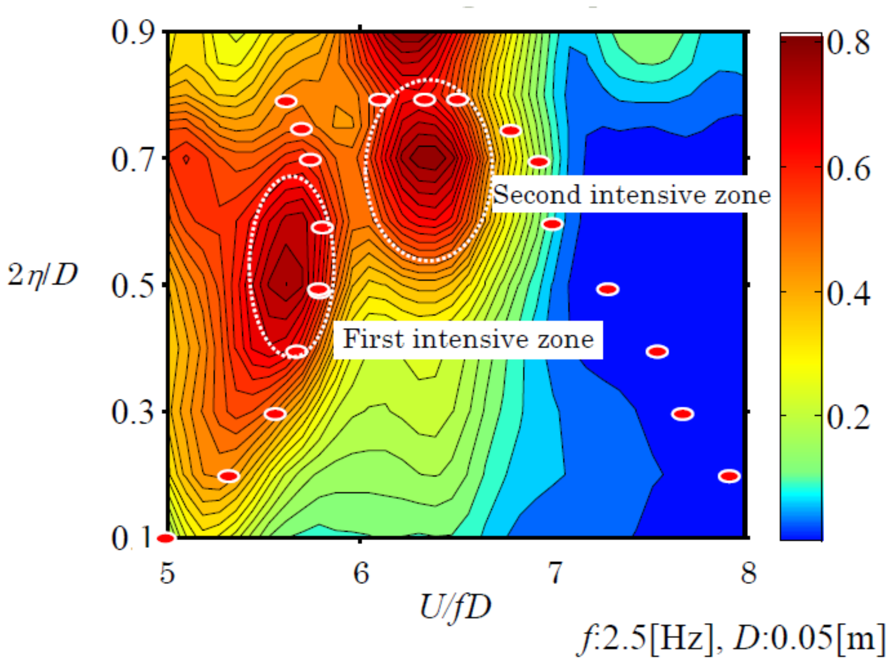


Fig.8 KV existence in VIV of circular cylinder in which red zone indicates KV component in vortex structures, obtained by BPS filtered by KV frequency in fluctuating lift force (Matsumoto[7])

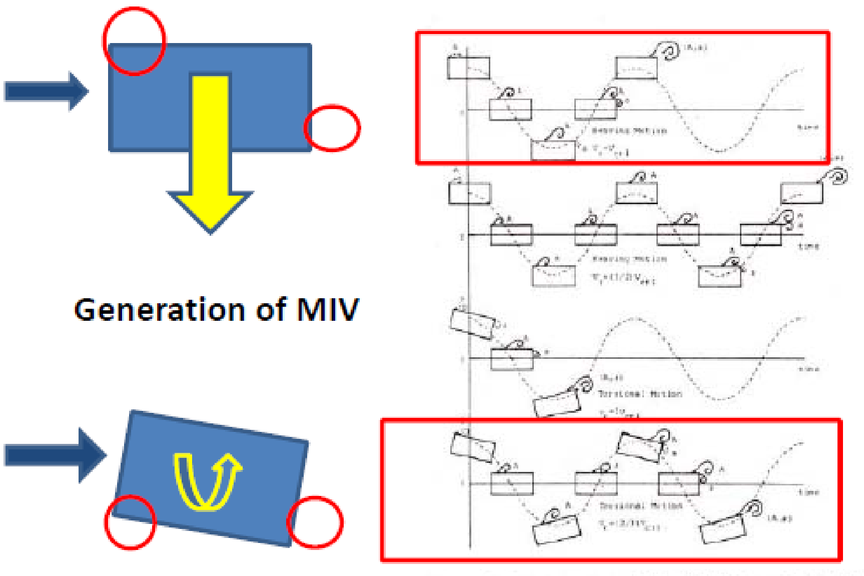


Fig.9 Generation of leading edge MIV and trailing edge MIV and their coalescence at trailing edge during heaving and torsional motion of rectangular cylinder with B/D=2 (Matsumoto[8])

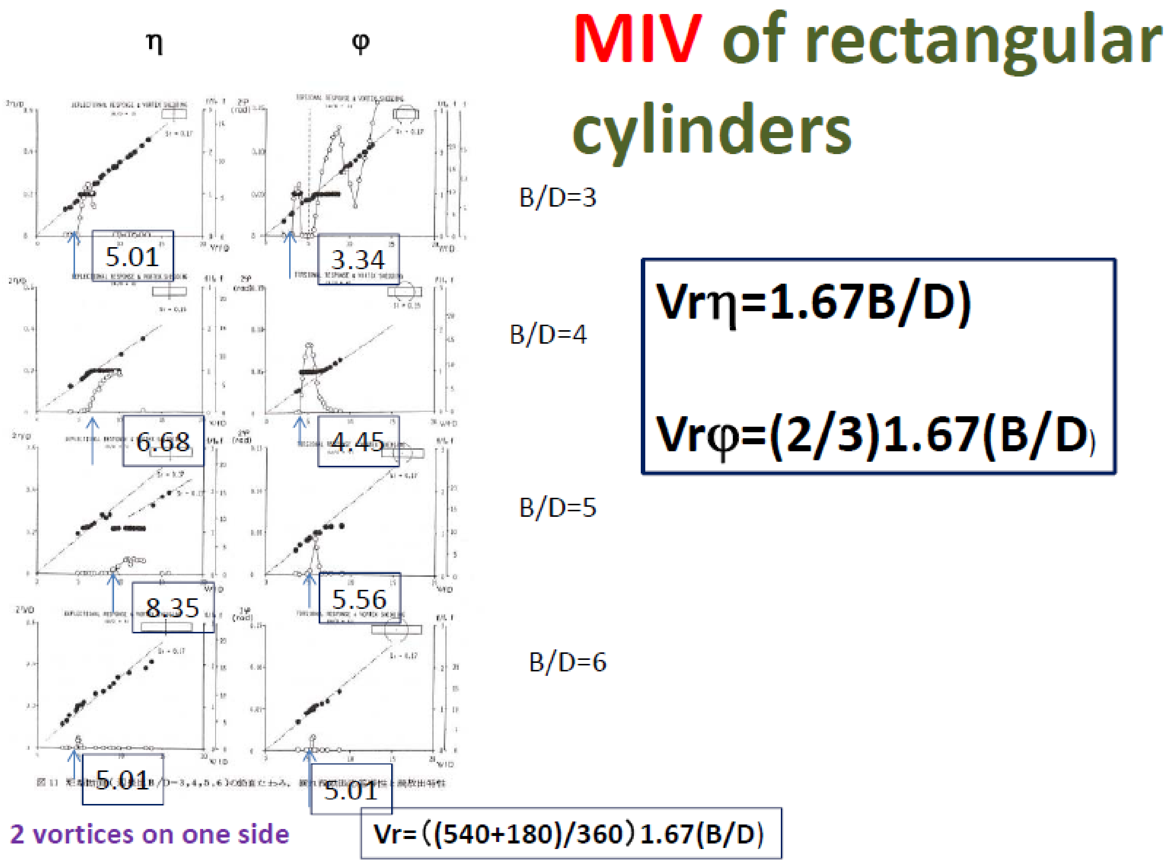
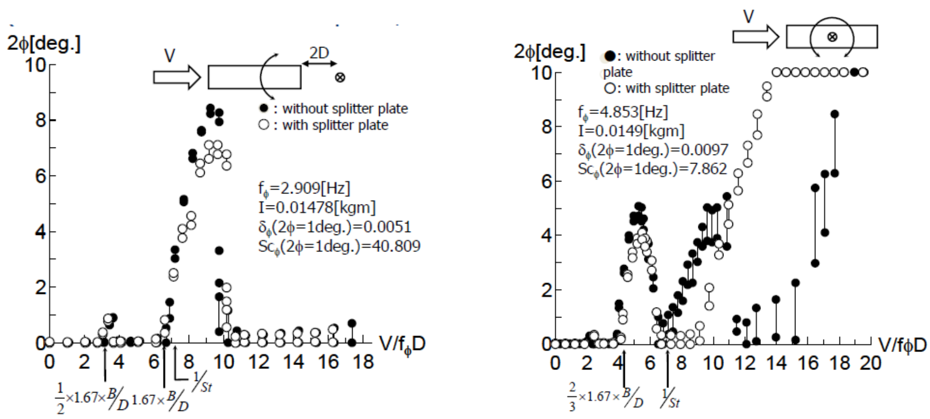
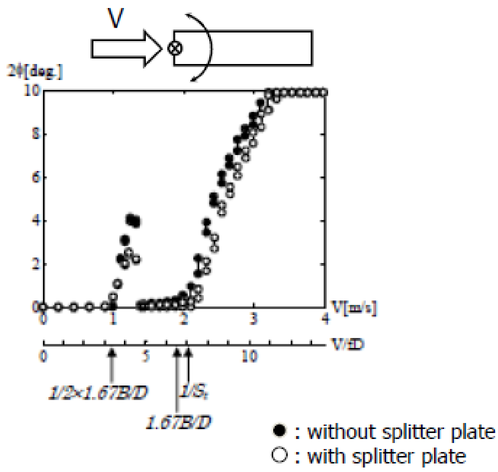


Fig.10 Heaving and torsional VIV and their onset reduced velocities of rectangular cylinders with B/D=3,4,5 and 6 (Shiraishi and Matsumoto[8])



(a) Trailing edge rotational axis (b) Mid-chord rotational axis



(c)Trailing edge rotational axis
Fig.11 change of onset reduced velocity and peak amplitude of torsional VIV of rectangular cylinder with B/D=4 (Matsumoto and et.al[9])

INTERACTION BETWEEN KV AND MIV

It is meaning to verify the effect of KV in wake on MIV for understanding of generation-mechanism of VIV. As shown in Fig.8, cross-flow response of circular cylinder seems to be excited as if avoiding the KV intensive zone. Thus KV might mitigate MIV more or less MIV which excites VIV classified into flow separation type. Intensity of KV in a wake was controlled by a perforated splitter plate(PSP) fixed at a wake center, as shown in Fig.12. Opening ratio(OR) was changed from 100%(without splitter plate) to 0%(solid splitter plate) with every 10 %. Less than 80% of PR, KV is drastically mitigated as shown in fluctuating lift coefficient, CL'. v.s. OR. Peak amplitude of VIV of circular cylinder changes with mitigation ratio of KV in a wake as shown in Fig.13 (Matsumoto[10]). Decreasing intensity of KV, significant increasing of peak amplitude of VIV is observed, though VIV is not classified because of sequential appearance of galloping less than 30%of OR. On the other hand, for heaving/ torsional VIV of flow impinging type, KV in a wake does not affect on VIV response caused by IMPV, as shown in Fig.14(heaving VIV) and Fig.11(torsional VIV). These differences of effect of KV in a wake on MIV/VIV are caused by that VIVs of flow non-reattachment type and flow impinging type are excited MIV generated in early wake and MIV generated on side body-face, respectively. Furthermore, heaving VIV of rectangular cylinder with B/D=4 appears at Vr=(1/2)(1/0.6)(B/D) and Vr=(1/0.6)(B/D) as shown in Fig.14. In particular it should be noted that VIV at lower Vre indicates that intensive MIV can be generated not only at near Vr=1/St, but also at its half reduced velocity.

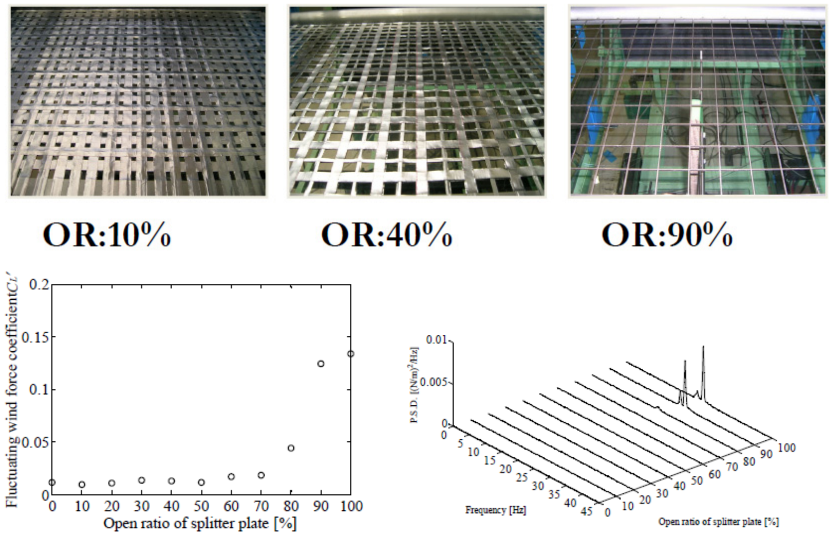


Fig.12 PSPphotos(top figure) and CL’ mitigation property by PSP and PSD of fluctuating lift force of circular cylinder(bottom figures) (Matsumoto[10])

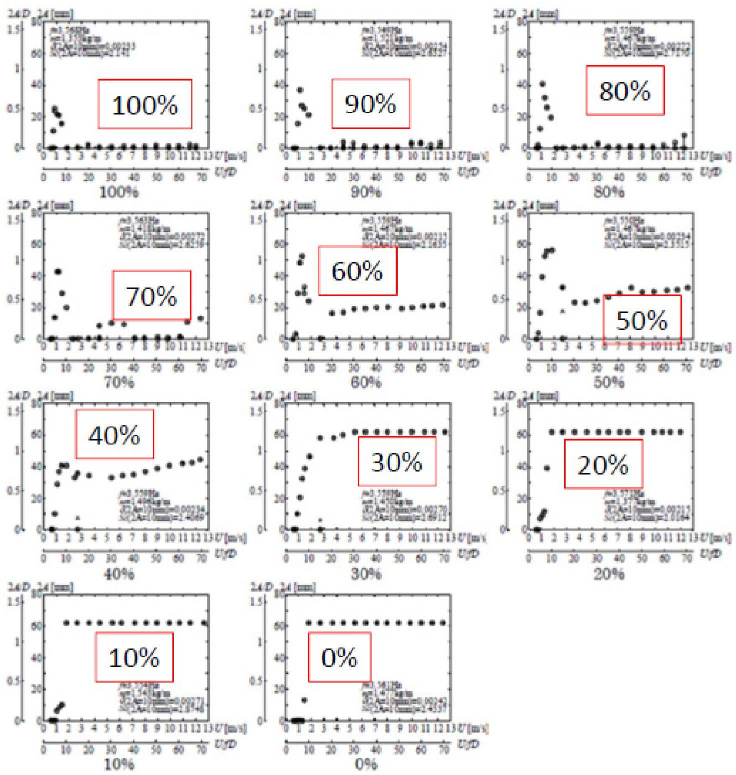


Fig.13 Change of cross flow response of circular cylinder by installation of PSP with various Opening Ratio(OR) in a wake (Matsumoto[10])

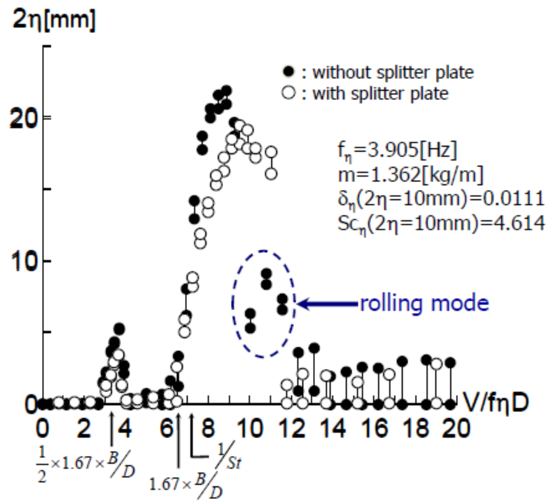


Fig.14 Heaving VIV of rectangular cylinder with B/D=4 without and with SP in a wake (Matsumoto and et.al[9])

ANOTHER ROLE OF KV ON BLUFF BODY AERODYNAMICS

In this study, role of KV is explained, but further significant roles of KV on bluff body aerodynamics, such as “bias flow” of symmetrical section, “bi-stable flows” around bluff body, “bifurcation of vortex”, “burrier effect” on external stimulation and unsteady galloping will be shown in another chance.

CONCLUSION

1. Impinging shear layer vortex(IMPV) observed on side face is baby or children of KV, because of vortex formation in a wake to identical to KV.
2. Motion-induced vortex(MIV) are generated at lower reduced velocity than Vr<1/St, and near at Vr=1/St, MIV is significantly amplified.
3. During Vortex-induced vibration(VIV) of circular cylinder, at particular zone in Velocity and Amplitude(V-A) diagram characterized by Vr and amplitude(y0/D), KV still exists. Which means lock-in phenomenon, defined as involving of KV to MIV, does not exist.
4. On effect of KV on VIV, for separated flow type VIV, intensive KV mitigates VIV, on the other hand, for imping flow type IV, KV-mitigation in a wake slightly decreases VIV peak amplitude.

Finally Authors would like to acknowledge to many former graduated students at Bridge Engineering Laboratory of Kyoto University for their contribution to wind tunnels tests and CFD analysis.

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