

DRY GALLOPING CHARACTERISTICS AND ITS MECHANISM OF INCLINED/YAWED CABLES

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Mechanism of dry galloping (DG) of inclined cable of cable-stayed bridges is described in relation to Karman vortex (KV) mitigation. Furthermore, the role of Scruton number, Sc , on reduced critical velocity, V_{rcr} , of DG is investigated for practical use basing on wind tunnel tests and field observations of dry galloping or pseudo-galloping, which is classified as cable vibration with rain-state but response amplitude is abnormally large. It is verified that as far as divergent-type DG, the design criterion subject to Sc - V_{rcr} proposed by FHWA (Federal Highway Administration of U.S.) seems to be reasonable for practical use, on the other hand, as far as unsteady DG, Saito criterion for Sc - V_{rcr} diagram seems to be reasonable.

1. Introduction

The complicated inclined cable aerodynamics has been clarified through a lot of wind tunnel tests and researches. As a state of art of inclined cable aerodynamics, it can be described that rain vibration (RV) is caused by formation of upper water rivulet at particular position on cable-surface and axial flow, which flows along cable-axis, in near wake of cable. These two factors can mitigate Karman vortex (KV) shedding. KV mitigation interrupts the communication between upper and lower separated flows, which can generate galloping instability as self-excited oscillation. As far as dry galloping, the axial flow and critical Reynolds number, Re_{cr} , both of which can mitigate KV and then similarly with RV galloping instability is excited. Therefore, KV mitigation can be said to be substantial factor for RV and DG of inclined cable. In general, galloping is thought to be catastrophic divergent-type phenomenon, therefore this instability should be definitely suppressed for safe design of cable-stayed bridge. Recently in U.S. to achieve this matter, three different countermeasures are used. Those are cables lapped by PE with helical fin on cable surface, cross ties between stay-cables and damping devices. In particular, how to determine the damping capacity to sufficiently suppress DG is the most concerned. Then, FHWA in U.S.[1] proposed the diagram, so called as FHWA criterion as shown in Fig.1 to determine the required damping capacity. However, Saito[2] reported different wind tunnel test results associated to Sc - V_{rcr} diagram, so called Saito criterion. As shown, there is great difference between two criteria, in another expression, Basing on Saito criterion, it is really difficult to suppress DG by increasing structural damping. The clarification of definite discrepancy between two criteria is one of the most important issues in nowadays bridge aerodynamics. If using recent finding by one of author on galloping instability of bluff body aerodynamics in relation with KV role, the key to resolve this problem is found.

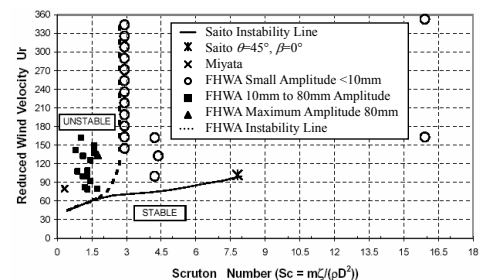


Fig.1 Comparison of wind velocity-damping relation of inclined dry cable

2. Galloping Generation Mechanism

Nakamura[3] pointed out that the galloping generation-mechanism 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. Taking into account that KV would be produced by communication of upper and lower separated flows, in another expression, KV shedding should promote the communication between two separated flows, therefore, the interruption of this communication between two separated flows should be identical to the interruption of KV shedding.

3. Divergent-type Galloping and Unsteady Galloping

Galloping can be classified into two different types, those are divergent-type galloping and unsteady galloping. Former one corresponds conventionally well known galloping, and its response characteristics can be explained by quasi-steady theory. If KV is sufficiently and in stationary suppressed, separated flow is released from the control of KV, then separated flow is so sensitive against external disturbance or stimulation, such as body motion, fluctuating coming-flow, applied sound and so on. Therefore, the mechanism of divergent-type galloping is appearance of motion induced-flow field which is released from KV influence. During downward motion of cable, down-side flow approaches to cable surface, on the contrary, upper flow leaves from cable surface. Thus down lift can be generated and self-excited vibration appears. The generation mechanism from the point of flow field, this galloping mechanism is substantially identical with the one of low-speed-galloping of bluff body with splitter plate studied by Nakamura.[4] On the other hand, as far as unsteady galloping, if KV mitigation is not sufficient nor stationary, cross flow response shows unsteady response with non-stationary amplitude. When KV is mitigated, response amplitude becomes large, on the contrary when KV sheds, amplitude becomes small. To confirm these characteristics a perforated splitter plate (PSP) is installed in wake center of non-yawed ($\beta=0^\circ$) circular cylinder, cross flow response varies with change of perforation ratio (PR) of splitter plate as shown in Fig.2. PSP can mitigate in stationary KV shedding, stationary galloping with steady amplitude is generated. As decreasing PR, galloping instability becomes more unstable. As

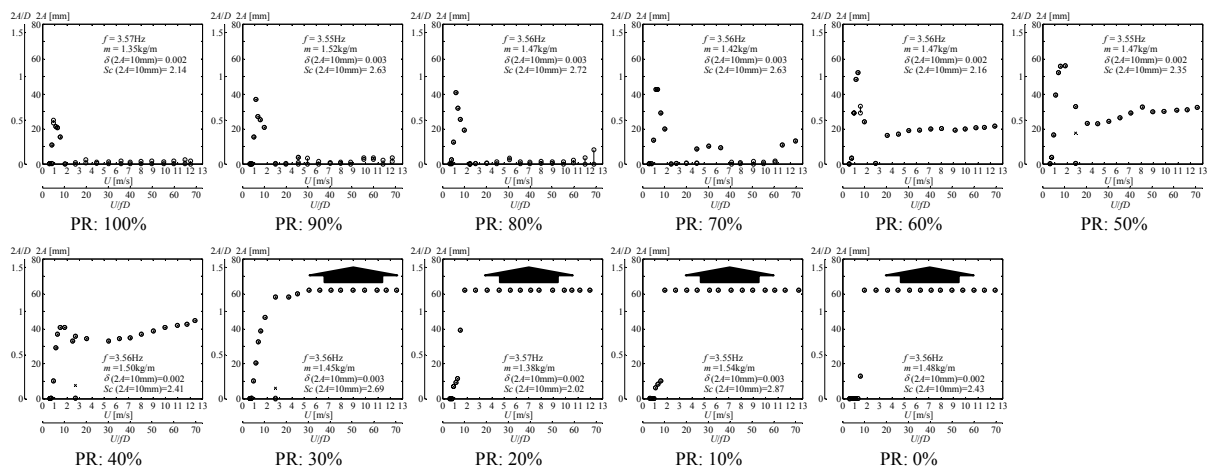


Fig.2 Velocity – Amplitude diagrams with various perforated splitter plate ($\beta=0^\circ$, $D=50\text{mm}$, in smooth flow)

show, it should be noted that the maximum amplitude of vortex-induced vibration near resonant reduced velocity, $V_{cr}=1/St$, becomes large as decrease of PR because of more mitigation of KV shedding. On the contrary, as far as unsteady galloping of yawed cable with smooth surface can be observed by wind tunnel test as shown in Fig.3. As shown, KV shedding is unsteadily mitigated by axial flow and response amplitude varies according to the intensity of KV shedding.

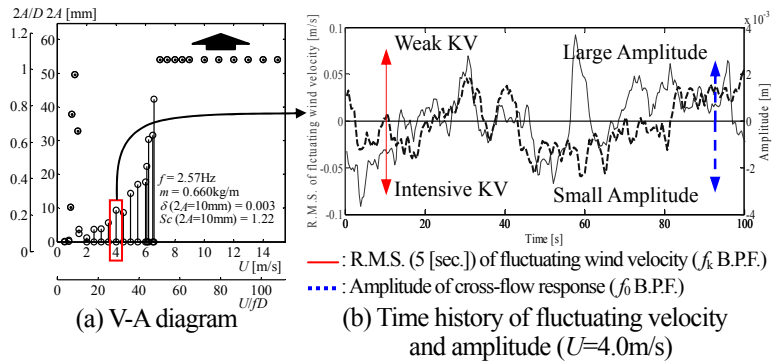


Fig.3 Free vibration test results used cable model with smooth surface ($\beta=45^\circ$, $D=54\text{mm}$, $Sc=1.22$, in smooth flow, 200mm window)

4. Wind tunnel tests in terms of Scruton number Sc vs. reduced critical velocity V_{cr} of galloping characteristics of yawed cable with $\beta=45^\circ$

Under three different cable-surface conditions, those are smooth surface, with axial protuberances, helical fins and with rings, free vibration tests were carried out in smooth flow. Suitable size windows are holed on both wind tunnel walls were installed to promote axial flow in near wake. The measured cross-flow response shows unsteady galloping with unsteady amplitude. Corresponding variation of KV shedding, amplitude varies with fairly good correlation as shown in Fig.3. If typical divergent-type galloping is not observed, the reduced critical velocity is determined as the lowest reduced velocity where double amplitude is reaches to 40 % of diameter, D , it means $0.4D$. If Scruton number is enough small such as 1.22, divergent-type galloping was observed, but majority results indicate unsteady galloping under larger Sc than about 20. Some test results, associated with Sc - V_{cr} are indicated in Fig.4. Furthermore, by use of test result in terms of Scanlan derivative H_1^* obtained by forced vibration, Sc - V_{cr} characteristics are obtained as shown in Fig.4. As shown, test results obtained from free-vibration tests and forced vibration tests shows fairly well good agreement with Saito criterion. As a matter of fact, wind tunnel data obtained by Saito using proto-type cables with 150mm diameter and approximately 10m length in large-scale wind tunnel, is also associated to not divergent-type galloping but unsteady galloping. Saito describes to author's inquiry that the determination of V_{cr} is also threshold velocity crossing 40% p-p amplitude. Thus it can be concluded that Saito criterion in Sc - V_{cr} should correspond unsteady galloping.

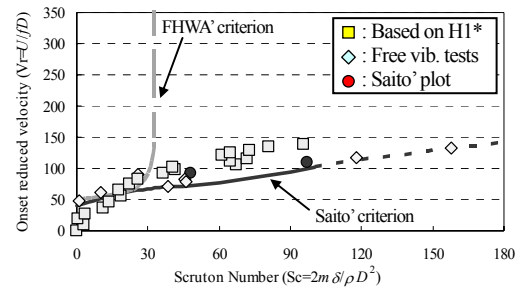


Fig.4 Comparison of galloping onset velocity ($\beta=45^\circ$, Smooth cable, in smooth flow)

5. Sc - V_{cr} characteristics for observed for proto-type inclined stay-cables in the field

Recently, some DG phenomena, including violent cable vibration under precipitation, have been observed in Japan. Typical DG occurred recently in Japan under without rain state. This cable-stayed bridge has curved bridge girder, therefore the longest stay cables are stayed directly on the ground. One longest cable showed violent vibration as shown in Fig.5, whose p-p amplitude is over than 1.5m, then hit the girder. Bridge girder, handrail and stay cable are seriously damaged. Four cases, in which one case of four is large scale cable elastic model with 30m length in the field, structural dynamics and climate conditions were comparatively

verified. These four cases, their cable vibration look divergent-type galloping because of their significantly large amplitude. These data are plotted on the $Sc-V_{rcr}$ diagram by use of measure structural-dynamic data. As shown in Fig.6, these data look to fit to Saito criteria. However there are some unsolved issues on structural damping. For Bridge, inspection after violent cable vibration found totally damage of the installed oil damper as shown in Fig.7. But same oil dampers installed to another stay cables which did not vibrate showed oil leakage. Therefore, before DG the installed oil damper already had not done work well as damper. If so, cable structural damping should be much smaller than indicated in Fig.8. The other two cases cable structural damping are unexpectedly large, because cable structural damping of another stay cable showed much smaller such as $\delta=0.003$ or 0.005 from test carried out on same day. Therefore If as cable structural damping of these three cases, $\delta=0.005$, which is mostly reasonable value for general stay-cables, would be used, their Scruton numbers are revised, then their plots on $Sc-V_{rcr}$ shows fairly good agreement with FHWA criterion. Therefore, FHWA criterion on $Sc-V_{rcr}$ diagram should correspond divergent galloping.



Fig.5 Violent cable vibration (courtesy of Mr. H. Yoshikawa)

Fig.7 Damaged oil damper

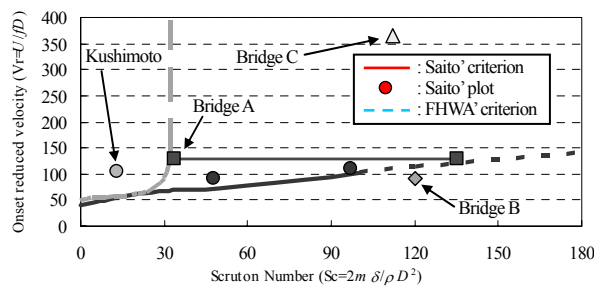


Fig.6 Field observation data at proto-type stay cable of cable-stayed bridges

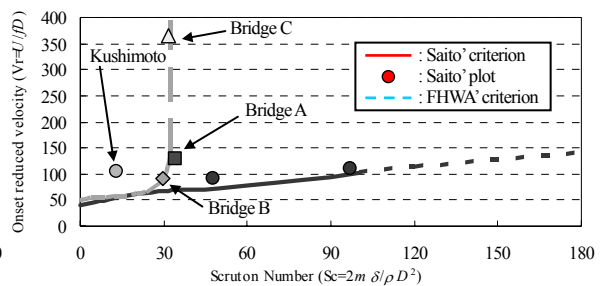


Fig.8 Field observation data at proto-type stay cable of cable-stayed bridges

6. Conclusion

In conclusion, it is verified that the dry galloping is caused by mitigation of Karman vortex (KV) shedding, which is fundamentally identical mechanism of galloping by interruption of communication between two separated flows by motion-induced self-excited vibration associated to low speed galloping of rectangular cylinder or circular cylinder with splitter plate in near wake pointed out by Nakamura. Furthermore, Galloping can be classified into steady galloping, including divergent-type galloping, with steady amplitude and unsteady galloping with unstable amplitude corresponding KV mitigation level. In $Sc-V_{rcr}$ diagram, FHWA criterion and Saito criterion correspond steady galloping and unsteady galloping, respectively.

Reference

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