DRY GALLOPING OF SURFACE MODIFICATION CABLE IN LOW SCRUTON NUMBER RANGE

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It is pointed out that normal cable can gallop divergently in both rain and dry condition which call rain-wind induced vibration and dry galloping (DG) respectively. For suppression rain wind induced vibration, indented surface and parallel protuberance cables have been applied in Japan and some Asia countries. Nevertheless, it is also figured that those methods are still defective in mitigating cable dry galloping. Moreover, DG characteristics of indented surface and parallel protuberances cable have not fully investigated yet. Therefore, the aim of this study is to figure out comprehensives the aerodynamic performances of indented surface and parallel protuberance in low Scruton number range. In addition, axial flow near the cable-wake will be measured and discussed. Wind tunnel test results elucidated that divergent galloping occurred in specific conditions in case of smooth surface. Similarly, large amplitude vibration still appeared in presence of indented surface and parallel protuberances. Finally, it also reconfirmed the existence of axial flow around cable wake which can excite galloping and this kind of axial flow still remains in for the other surface cables.

Keyword: dry galloping, indented surface, parallel protuberances, low Scruton number, axial flow

1. INTRODUCTION

After the rain-wind induced vibration (RWIV) was figured out as a dangerous vibration which can cause the harmfulness of cable attachment and bridge deck, so wind-resistant design of stay cables always requires a countermeasure versus RWIV. Indented surface and parallel protuberance cables have been developed for this aim. The main purpose of these countermeasures is rain rivulet destruction, leading to the suppression of RWIV. Indented surface was the first applied to Tatara stayed-cable Bridge and later to the Sutong and Stonecutters Bridges. This control method was initially proposed by Miyata et al.[1)]. In order to eliminate the rain rivulet, dimples were made on the cable surface with a specific scale and arrangement. It has been also found to improve the stabilization of cable under rain-wind interaction with low drag force. In the other scenario, parallel protuberances initially applied in Higashi Kobe Bridge. This countermeasure uses twelve of fillets along cable to control the forming of upper and lower rivulets, and then it can stop RWIVs. Recently, it is also pointed out that circular stay cable can gallop with large amplitude at high reduced wind speed in dry condition which called dry galloping. The characteristic of this phenomenon has attracted many researchers. Dry galloping was observed in wind tunnel tests (WTTs) by Saito et al[2)] Honda et al.[3)] and Vo et al.[4)] in the subcritical Reynolds number regime, and Miyata et al.[1)], Cheng et al.[4)], Jackobsen et al.[5)] in the transition and critical Reynolds number regime. Matsumoto et al.[6)] explained the differences between the Saito criterion and FHWA criterion by classifying galloping into divergent-type galloping and unsteady galloping. They also shed light on the role of axial flow for galloping instability by conducting wind tunnel test with and without artificial axial flow along the wake of cable. According to Cheng et al.[4)], both divergent type of motion and limited-amplitude vibration at high reduced wind speed were recorded. However, the characteristics and excitation conditions of these two phenomena are separately different. The former has

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similar response as galloping while the latter occurs only in certain narrow high reduced wind speed ranges and has different onset conditions. When compared the characteristics of dry-galloping between normal and indented cable surface, Katsuchi and Yamada[7)] found that the indented cable could not mitigate the dry-galloping effectively, in which divergent galloping still occurred. This conclusion agreed with the report of Hojo et al[8)]. However, the full aerodynamic responses in low Scruton number of these methods have not been clarified yet. Furthermore, due to the defectiveness of current mitigation methods, it is urgent to develop an effective aerodynamic countermeasure not only for RWIV but also for DG.

The aim of this study is to investigate the DG characteristics of indented surface and parallel protuberance in low Scruton number region. Firstly, the WTT will examine smooth surface in various wind attack for the base line. Then, aerodynamic responses of indented surface and parallel protuberances will be recorded with various conditions. Finally, the axial flow in the wake of cables will be measured and discussed.

2. MATERIAL AND METHOD

(1) Wind tunnel

The wind tunnel tetst were performed at the 1.3mx1.3m^2 cross-section open-circuit wind tunnel in Yokohama National University, Japan (Figure 1). Cable model was supported by a 1-DOF spring system in vertical plane and small wire system was used in horizontal plane in order to keep cable model unmoved laterally. The flow conditions were measured at cable model position by hot wire anemometer and turbulence intensities of 0.48–0.62% were recorded for 25%/50%/100% of maximum wind speed.

Figure 1: Wind tunnel in Yokohama National University

(2) Models fabrication

Three models were examined, included a plain HDPE smooth cylinder for reference, a HDPE cylinder with parallel protuberances and a HDPE cylinder with indented surface. The model samples were fabricated with same scale to real bridge cables. Cable diameters are 110mm and 158mm with an effective model length of 1.5 m, the aspect ratio is 13.6 and 9.5, respectively. The indented surface was fabricated same pattern of stayed-cables of Tatara stayed cable Bridge while a parallel protuberances cable was fabricated similarly to Higashi Kobe Ohashi Bridge cables by adding the twelve rubber fillets. The detail of surface modification can be seen as Figure 2 and 3.

Figure 2: Indented surface cable

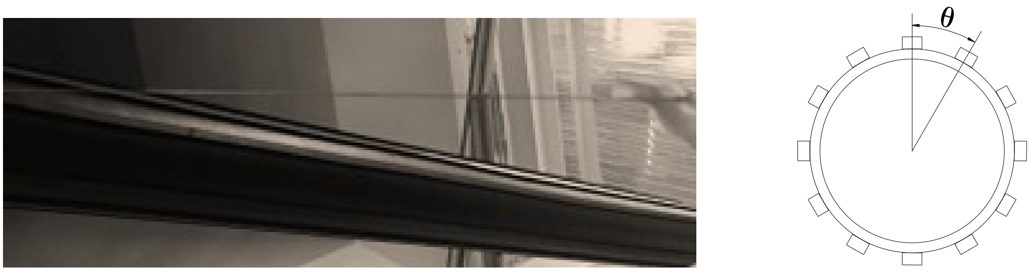


Figure 3: Parallel protuberances cable

(3) Inclined angle and flow angle

Wind attack angle can be created by moving the cable suspended frame by two angles: inclined angle α and flow angle β. Then, wind relative angle β*, which defines the angle between wind direction and cable axis as shown in Figure 4, can be calculated by below formula:

$$\beta^* = \sin^{-1}(\cos\alpha \cdot \sin\beta) \quad (1)$$

In this WTT, the inclined angle was fixed at 40° and 25° combined with the flow angle of 0°, 15°, 30°, 45° and 60°. These inclinations were selected to take into account an inclined angle of stay cables in middle and top section of a normal cable-stayed bridge, respectively.

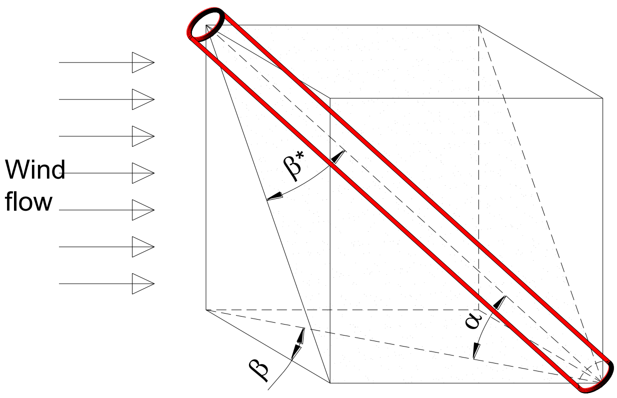


Figure 4: Inclined angle and flow angle

(4) WTT parameters

Table 1 shows the detail of experiment parameters in which cable diameters are 110mm and 158mm. Damping ratio ranges from approximately 0.08% to 0.25% and natural frequency is around 0.77 - 1.02 Hz in considering typical stay cables values. Due to the limitation of wind tunnel capacity, maximum wind speed is up to 20m/s equivalent to Reynolds number around 2.1×10^5. Nevertheless, according to previous studies DG of inclined cable could be observed in the subcritical Reynolds number regime as well as in the transition and critical Reynolds number regime. Therefore, above range of Reynolds number enable to reproduce the DG.

Moreover, Scruton number ($2m\delta/\rho D^2$) is a non-dimensional parameter that characterizes the mass and damping properties of a flexible body. In this study, Scruton number range from 5.1 to 15.6.

Table 1: Conditions of WTT

Diameter: D (mm)	110 and 158
Effective length (mm)	1,500
m (kg/m)	11.98 - 13.02 (D110 mm) 14.55 - 16.13 (D158 mm)
Natural frequency (Hz)	0.82 – 1.02
Damping ratio	0.08% - 0.25%
Scruton number ($2m\delta/\rho D^2$)	5.1 – 15.6
Reynolds number	0- 2.1×10^5

3. RESULTS AND DISCUSSIONS

(1) Dry galloping of smooth surface cable

In order to reproduce dry galloping for smooth surface cable, 158mm and 110mm diameters were examined in these tests. WTTs were carried out in a dry condition and results are summarized in Figure 5 and 6. Generally, dry galloping took place in many cases. For 110 mm cable, divergent vibration took place at several attitudes such as the inclined angle (α) 40° with the flow angles (β) 15°, 30° and 45°, and (α) 25° with (β) 30° in the subcritical Reynolds number region (6×10^4 - 1.2×10^5). In the case of cable diameter of 158 mm, similar divergent vibration also recorded in most cases. This experimental result is consistent with previous studies that DG can occur at some specific wind attack angles and wind speed range[10, 11, 12, 13].

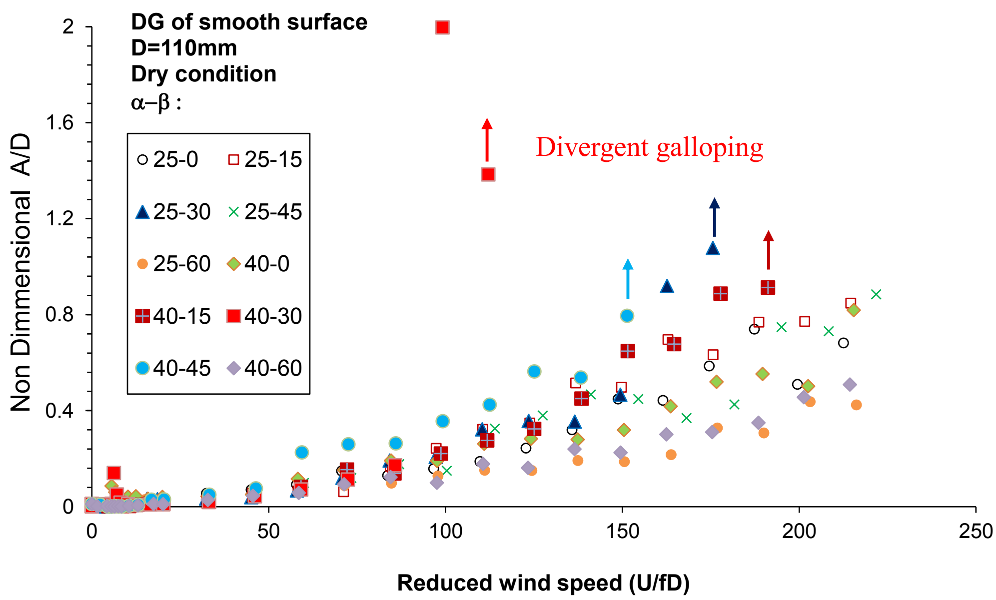


Figure 5: Dry galloping of smooth surface cylinder, D110mm

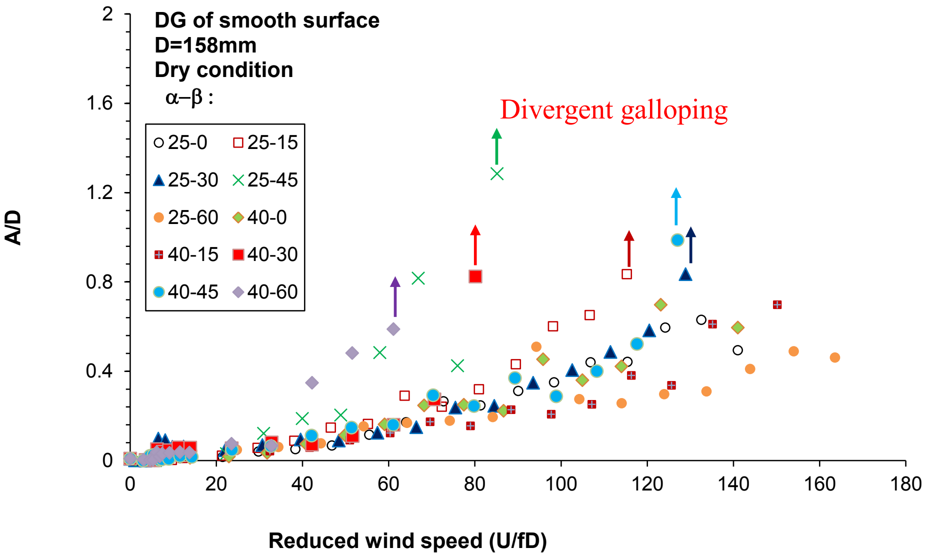


Figure 6: Dry galloping of smooth surface cylinder, D158mm

(2) Effectiveness of indented surface

Indented surface has been applied for some cable-stayed bridges in Japan and East Asia. Tatara Bridge was the first case applying the indented surface cable. Nevertheless, it is pointed out that this modification type could not suppress well DG particularly in a low Scruton number condition[3]. Hence, the main purpose of the present test is to examine mitigation efficiency for dry galloping. WTT parameters were unchanged to the circular cylinder cases.

Figure 7 illustrate the aerodynamic responses of indented surface in dry condition. Generally, mostly divergent vibration was mitigated, except unexpected cases of the inclined angle (α) 25° with the flow angle (β) 45°. Nevertheless, limited vibration still appeared for many cases. This may be due to the inherent unstable characteristic of stayed cables in small Scruton number range. It is also observed that D158 mm cable tended to be more unstable rather than 110 mm cable. Large vibration mostly started at the reduced wind speed (*U*/*fD*) of approximately 70 with amplitude of around 1.2D in case of α 25°and β 45°. In range of Scruton number around 5.1 – 15.6, indented surface is still defective in eliminating DG.

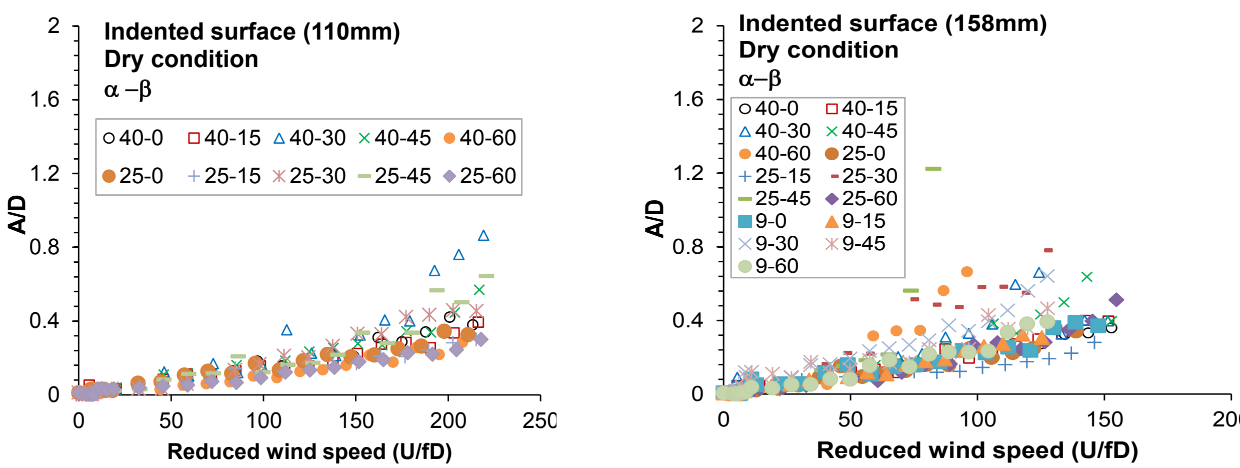


Figure 7: DG of indented surface cable

(3) Effectiveness of parallel protuberance

For comparison with the indented surface cable, same extensive WTTs were carried out for verifying the effectiveness of the parallel-protuberance countermeasure to DG. In dry condition, parallel protuberance can mitigate cable vibration to some extent as shown in Figure 8. Nevertheless, divergent type vibration still appeared. The largest amplitude is approximately 1.4*D* in the case of the inclined angle 25° with the flow angle 15° for 110 mm cable. Large vibration started occurring at reduced wind speed around 100-170 in cases of wind angles 40°-30°, 25°-45° and 25°-15°. In case of D158, divergent galloping appeared at wind angles 25°-45° and 25°-45 whereas the remained cases still exhibited the large amplitude vibration.

In addition, when cable model was rotated around its axis to check the effect of protuberances location, vibration response was almost similar. This result totally agreed with the WTT result of Higashi Kobe Ohashi Bridge[10)]. Above discussions suggest that one should be careful when applying the indented surface and parallel protuberance for suppressing RWIV and DG, especially for the cables with low Scruton number. It is also urgent to propose an innovative cable surface which can mitigate both RWIV and DG more efficiently.

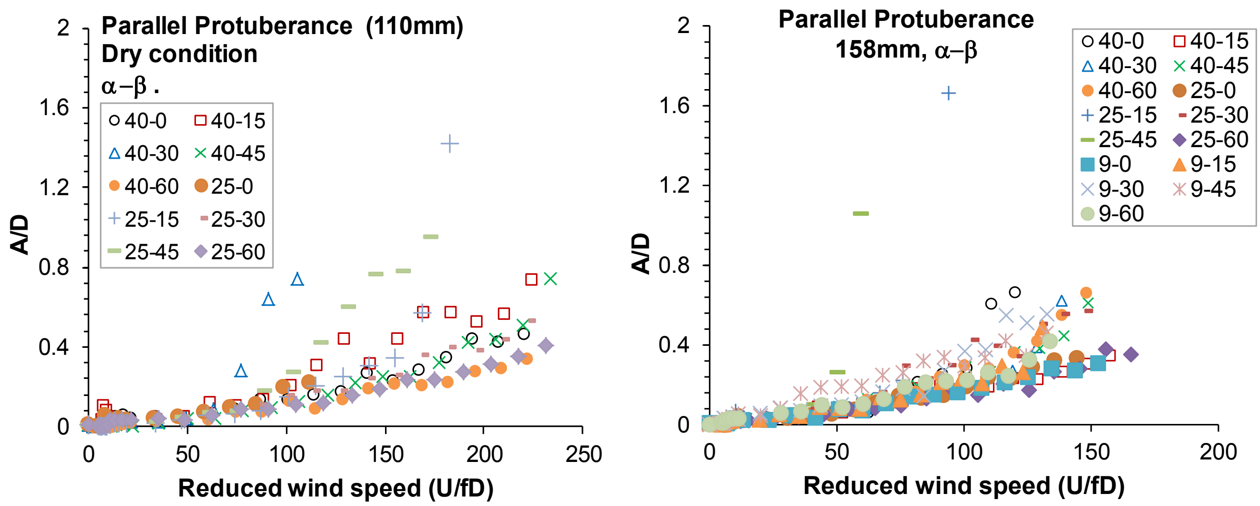


Figure 8: Dry galloping of Parallel protuberance cable

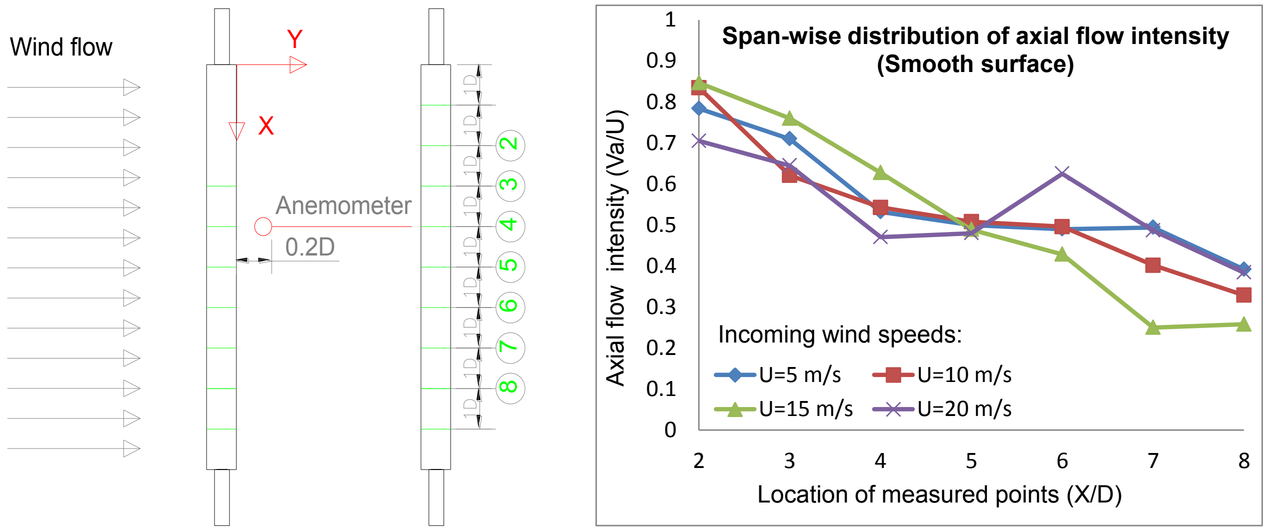
(4) Axial flow near the wake of cable

It is pointed out that axial flow in a wake of cable plays significant role for galloping instability in dry condition[6)]. To confirm this characteristic, the axial flow was measured by anemometer with smooth surface, indented surface and parallel protuberances. The static model was installed at inclined angle 25° and flow angle 30°. Diameter of 158mm was used in this experiment. The detail of measured results can be seen in below sections.

a) Smooth surface

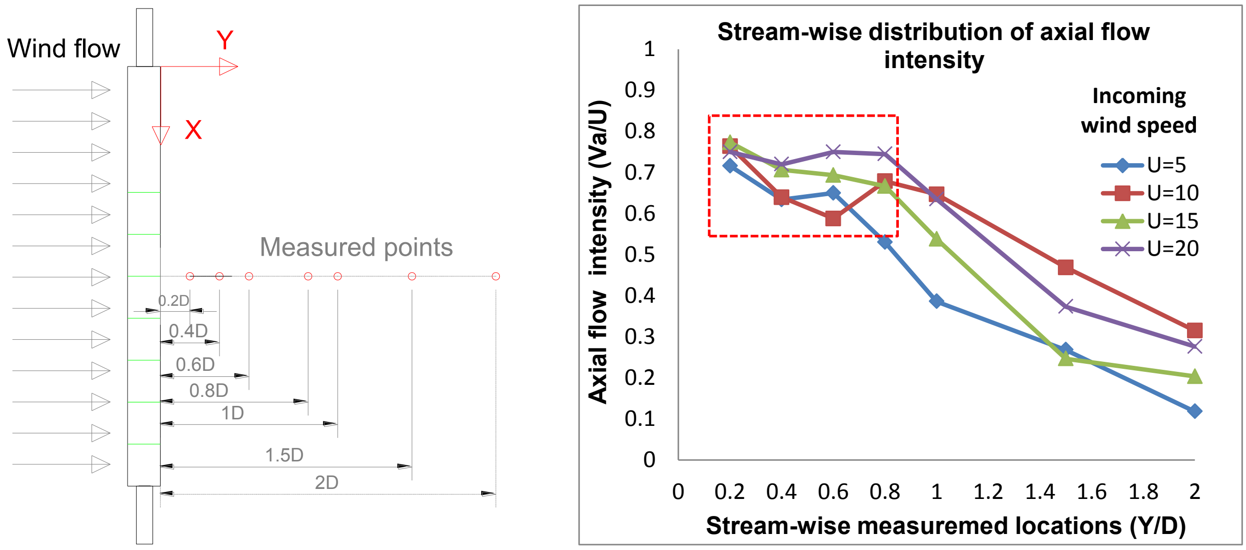
The axial flow velocity was measured in span-wise direction and stream-wise direction. The measurement plan is illustrated in Figure 9a and 10a. For measuring the span-wise axial flow velocity, anemometer was located 0.2D from the wake of cable. Figure 9b elucidates that axial flow velocity distributes non-uniformly and decrease gradually from the upstream cable end to the downstream one. In the upstream cable end, axial flow velocity was around 70-85% of incoming velocity whereas it was 30-40% in the downstream cable end. The distribution of axial flow intensity seems to be similar to every incoming velocity as Figure 9b.

In addition, the stream-wise axial flow distribution was also recorded. In this measurement, the anemometer was located at center-line from 0.2D to 2D with steps as Figure 10. Interestingly, the velocity intensity of axial flow in the range from 0.2D to 0.8D seems to be unchanged with high intensity around 60-80%. This strong channel can play the role as “splitter plate” which can stop the communication between upper and lower flows. From that, this can excite galloping. This finding agreed with the conclusion of Matsumoto et al[6].



a. Measurement arrangement b. axial flow distribution

Figure 9: Span-wise velocity distribution of axial flow



a. Measurement arrangement b. axial flow distribution

Figure 10: Stream-wise distribution of axial flow velocity

b) Indented surface and parallel protuberances

The distribution of axial flow velocity near wake of indented surface and parallel protuberances cables can be seen in Figure 10 and Figure 11. Obviously, strong channel of axial flow still existed with intensity above 50% of coming flow. Upper cable end still exhibited higher velocity intensity compare to lower side. Axial flow patterns are quite similar for both cable types. However, the difference between upper end and lower ends of cable is smaller compare to smooth surface case. This fact elucidates that why DG appeared with these cables.

In addition, the comparison between smooth surface, indented surface and parallel protuberances can be seen in Figure 11. In this Figure, incoming wind speed is 15m/s in order to take in to account the occurrence range where DG. Generally, the axial flow distributions of three cables were quite similar for all cases. In the other expression, it seems to be that the axial flow is one of inherent characteristic of inclined cable again wind incoming wind and it does not depends on the cable surface much. Further investigation should be carried out.

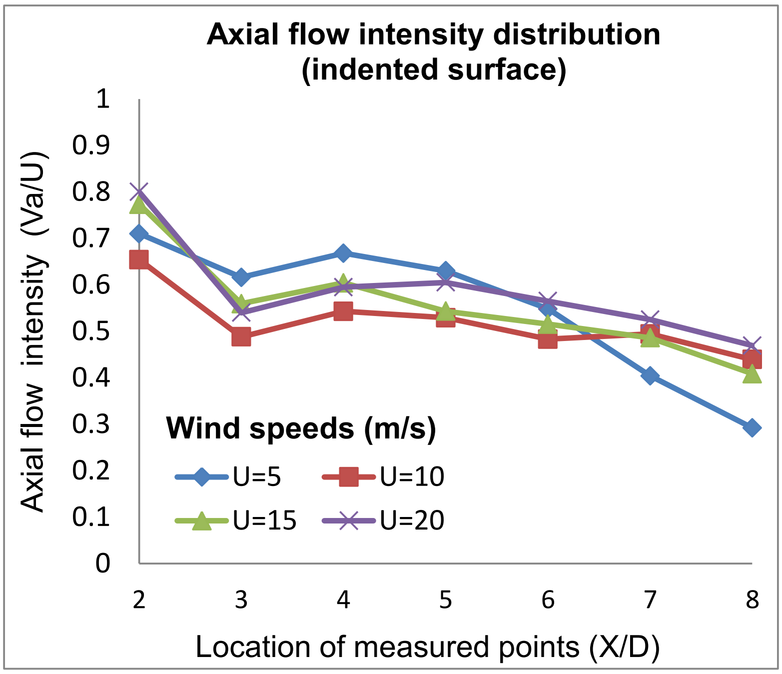


Figure 9: Span-wise distribution of axial flow of indented cable

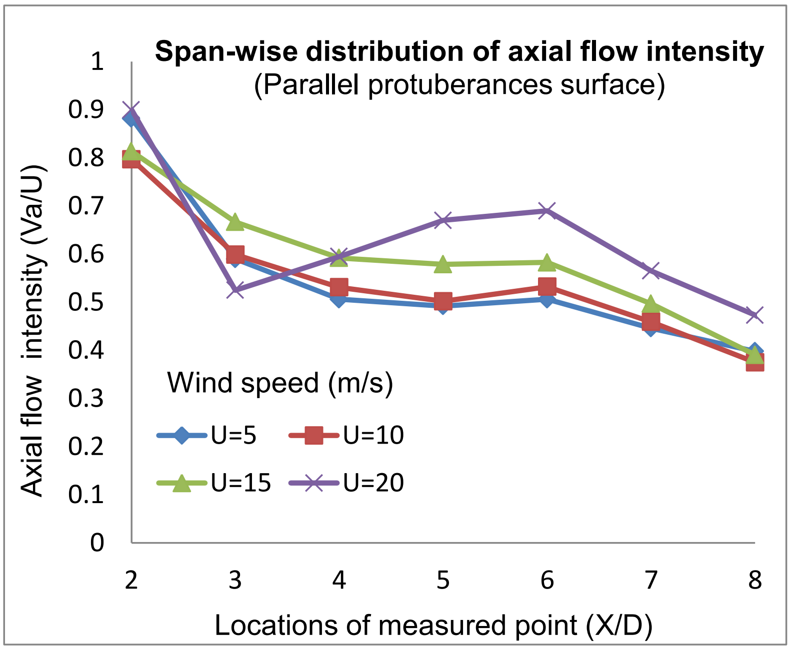


Figure 10: Span-wise distribution of axial flow of parallel protuberances cable

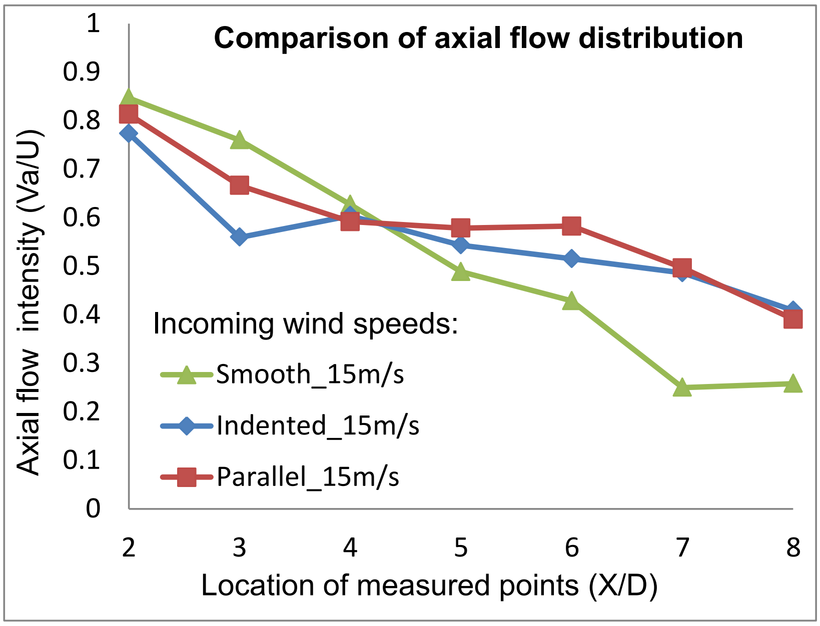


Figure 11: Comparison between smooth surface, indented surface and parallel protuberances cables.

3. CONCLUSIONS AND RECOMMENDATION

The main objectives of this paper are to give the general understanding about the dry-galloping of indented surface and parallel protuberances. Under each case, responses of cable were different and it depended on wind attack angle, surface modification. In addition, the axial flow near the wake of cable was investigated. The present study allows the following conclusions to be drawn:

1) Dry galloping is one of large amplitude vibration which can damage the cable attachment.
2) Indented surface and parallel protuberances used to apply for RWIV; however, it could not eliminate dry galloping well. Large amplitude vibration still occurred for many cases in low Scruton number range.
3) There is existence of axial flow with high intensity around 60-80% located from 0.2D to 0.8D near wake of smooth cable which can excite galloping. These flow channels still remain in case of indented surface and parallel protuberances cable. Therefore, axial flow is one of inherent characteristic of inclined cable again wind incoming wind and it does not depends on the cable surface much.

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