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Wind tunnel test on mitigation countermeasures for dry-state-galloping

*Duy Hung Vo1) , Hiroshi Katsuchi2), Hitoshi Yamada3) and Mayuko Nishio4)

1),2),3),4)Department of Civil Engineering, Yokohama National University, 79-5 Tokiwadai,
Hodogaya-ku, Yokohama, 240-8501, Japan
vo-hung-sc@ynu.jp

ABSTRACT

The complex cable aerodynamics has being studied. The traditional vibration of cable caused by rain-wind combination has been known as most typical type and many kind of countermeasures has been proposed for suppressing this kind of vibration. Recently, stayed-cables were proved that they could be vibrated not only in rain-wind condition but also in dry state. Some of authors have pointed out the significant role of an axial flow in a wake of inclined/yawed cable for galloping instability. In this study, dry-state galloping was investigated by a wind tunnel test with various kinds of relative wind angles and three types of countermeasures have been proposed to suppress dry-state galloping of stay cable.

Keywords: dry-state galloping, single spiral wire, double spiral wire, circular rings

1. INTRODUCTION

Dry state galloping is classified as one of the wind-induced large amplitude vibration phenomena in dry weather, onset at relatively higher reduced wind speed compare to vortex-induced vibration. Nevertheless, it also showed characteristics of limited amplitude vibration. Some reports showed the existence of dry-state galloping, not only wind tunnel test but also the field of observation. However, the guideline for design and installing of the countermeasures for dry-state galloping are under developing and has not understood well. The divergent type of motion induced by wind for a dry-state inclined cable was observed in wind tunnel tests by Saito et al (1994) and Honda et al (1995) in the subcritical Reynolds number regime, and Miyata et al (1994) and Cheng et al (2008) in the transition and critical Reynolds number regime. Matsumoto et al.(2008) and Katsuchi et al(2009) also showed some of results about mechanism of this phenomenon. Recently, some of researchers pointed out that dry-state galloping appeared in relation to the formation of an axial flow in the wake of cable. Matsumoto at el (2008) proved the role of axial flow for galloping instability by

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[1)] PhD scholar
[2) 3)] Professors
[4)] Associate Professor

conducting wind tunnel test with and without artificial axial flow along the wake of cable. The test results of Matsumoto also indicated clearly that the axial flow near the wake could interrupt Karman vortex (KV) shedding and it can excite galloping instability. In addition, Matsumoto at el (1990) also had pointed out that the axial flow also was visualized in the field by using the light strings for the proto-type stayed cable with relative angle around 40º-50º.

Currently, the range of onset wind angles wherein dry-state galloping can occur and the mitigated countermeasures for this phenomenon are under researching. In this paper, dry-state galloping of a round-shape cable was investigated in different attitudes with smooth cable surface and smooth wind flow. Besides that, single spiral wire, double spiral wire and circular rings were proposed and developed for suppressing the dry-state galloping.

2. EXPERIMENTAL CONDITIONS

The wind tunnel test was carried out in a wind tunnel circuit of the Yokohama National University, the size of the working section of which is 1.3m wide and 1.8m high. The maximum wind speed is about 18m/s. Cable model was supporting by 1-DOF spring system in the vertical direction, as shown in Fig 1. Cable model was tested to observe the characteristics of the cylinder oscillation as well as to determine the critical relative angle for dry-state galloping.

In order to arrange the wide range of wind directions, the experiments was carried out by changing yawed/inclined angles and only yawed angles as shown in Figs. 2. Table 1 shows the test conditions in which the cable model diameter was 75mm in considering the blockage ratio of less than 5%. The experiments were carried out with normal surface and smooth flow.

Table 1 Conditions of WTT

Parameters	Values
Diameter: *D*	75 mm
Length	1800 mm
Cable surface	Smooth
Natural frequency (Hz)	1.15
Scruton number ($2m\delta/\rho D^2$)	14.67
Reynolds number	0 - 7×10^4

In the Table 1, Scruton number is a non-dimensional parameter that characterizes the mass and damping properties of a flexible body. In this study, Scruton number was defined as $2m\delta/\rho D^2$ where m and δ are unit-length mass and logarithmic decrement of the cable model.

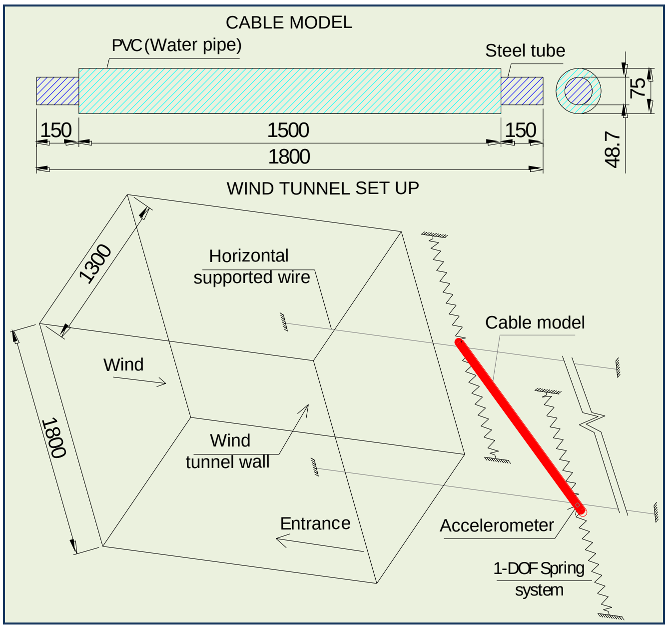


Fig.1 Cable model and set-up of the model in wind tunnel

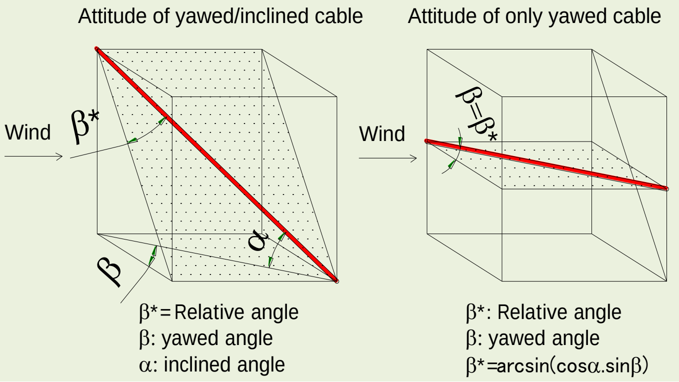


Fig. 2 Schematic diagram of different attitudes of cable model

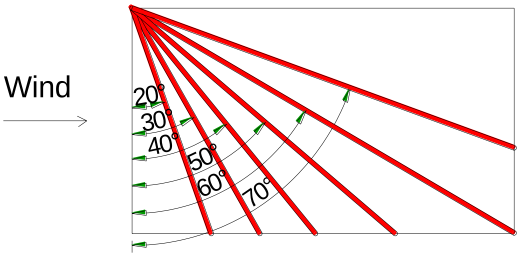


Fig.3 Definition of yawed angle

Experimental results are illustrated in Fig. 4. It can be seen that large amplitude occurred from 30^o to 60^o of the relative wind angle (in these cases $\alpha=0$, $\beta=\beta^*$). Moreover, the divergent vibration took place at reduced wind speed of 110 to 130 in this test series. In the case of 50^o of the yawed angle, the vibration is the most extreme, in which, it started divergent vibration from the reduced wind speed at *U/fD* = 90 (*D* is diameter), reach the amplitude 0.7*D* at *U/fD*=120 and its gradient is the sharpest. These outcomes agreed with the test of Katsuchi and Yamada (2009). On the contrary, there is no considerable large amplitude in the cases with 20^o and 70^o of the yawed angles, the largest amplitude is under 0.2*D*. As a result, the critical yawed angle range shown as Fig. 5.

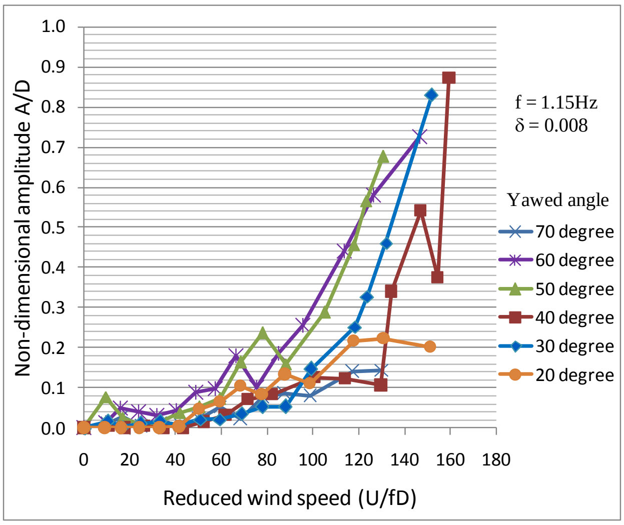


Fig.4 Vibration amplitude of cable in different yawed angles

According to the WTT experimental results of Matsumoto at el (2008), K. Kleissl, and C.T. Georgakis (2012), there was an existence of axial flow in near wake of cable, which can excite galloping of cable, and its velocity increased with yawed angle. For this reason, it seems to be that changing of relative onset wind angles may affect to axial flow near the wake of cable. Hence, divergent galloping can occur in a range of relative wind angle.

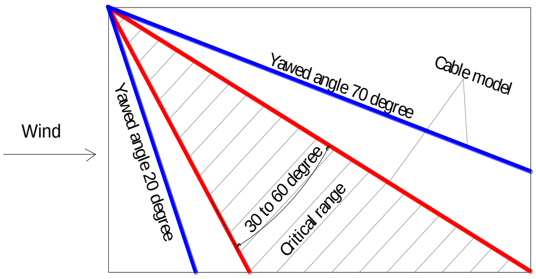


Fig.5 The critical zone of yawed angle

3.2 Vibration under yawed/Inclined angle cases

These WTTs conducted with inclined angles changing gradually from 25^o to 70^o in considering the effect of attitudes to the vibration of cable whereas yawed angle was unchanged at 45^o, which is one of the critical cases according to the tests with only yawed angles (Fig 5). Additionally, the other conditions of the WTT were same as the above tests. The detail of yawed angle, the inclined angle and relative angles can be seen in Table 2. In this study, relative angle (β*) is defined as the combination of inclined and yawed angle, which can be seen in Fig.1 and it can be simply calculated by the following formulation:

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

Generally, divergent galloping occurred in a relative angle range as shown in Fig. 6. The cases 30^o relative angles tend to exhibit the most critical responses. As the reduced wind speed (*U/fD*) increases from zero to 120. At first, vibration of cable was quite inconsiderable but then cable galloped dramatically with significant amplitudes and reached 0.6*D* at around 140 of reduced wind speed. What is more, in the range of wind relative angle (β*) from 24^o to 40^o, the divergent vibration was taken place at higher reduced wind speed of around 120 to 140 compared to 110 to 130 of only yawed angle cases. This can be caused by the cable model end attitudes, which are different between yawed angle cases and yawed/inclined angle cases.

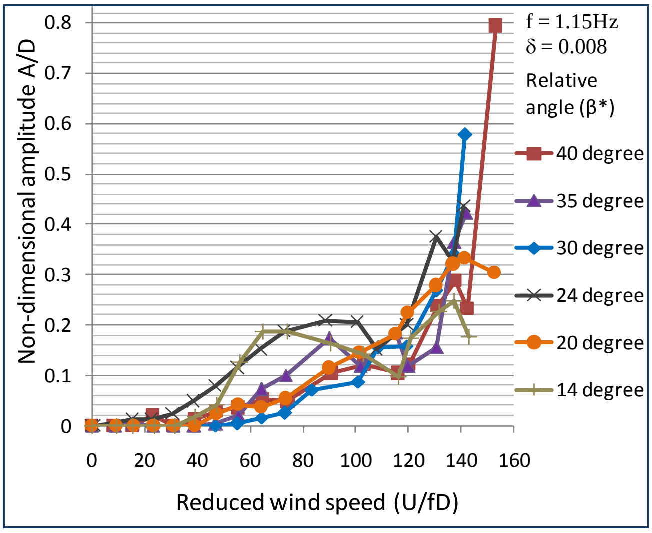


Fig.6 Responses of cable in different inclined angles

Table 2. Yawed and inclined angle cases

Inclined angle (α)	Yawed angle (β)	Relative angle (β*)
25^o	45^o	40^o
35^o	45^o	35^o
45^o	45^o	30^o
55^o	45^o	24^o
60^o	45^o	20^o
70^o	45^o	14^o

3.3 Effect of Cable Attitude on Vibration Response

In order to investigate impact of cable attitudes to vibration and to compare the responses of yawed angle and yawed/inclined angles cases, which have same wind relative angles, three wind relative angle cases (40^o, 30^o and 20^o) were clarified as shown in Table 3.

Table.3 Comparison cases for same relative angle

Yawed angle only (β)	Yawed (β) and inclined angle (α)	Relative angle (β^*)
40^o	45^o and 25^o	40^o
30^o	45^o and 45^o	30^o
20^o	45^o and 60^o	20^o

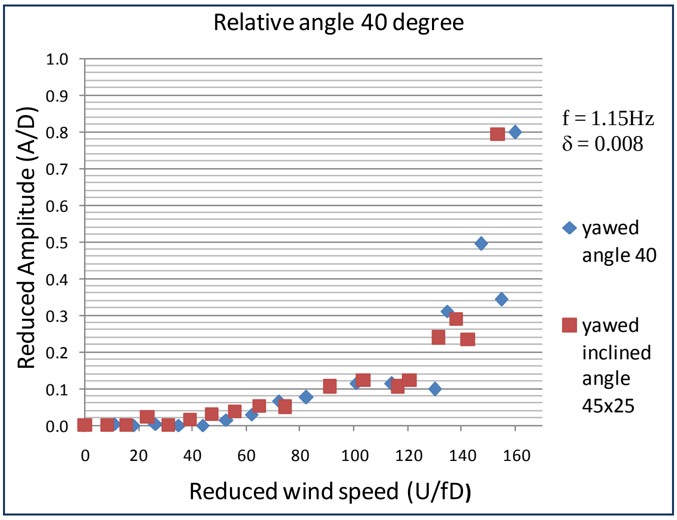


Fig.7 Comparison of yawed angles and yawed/inclined angles

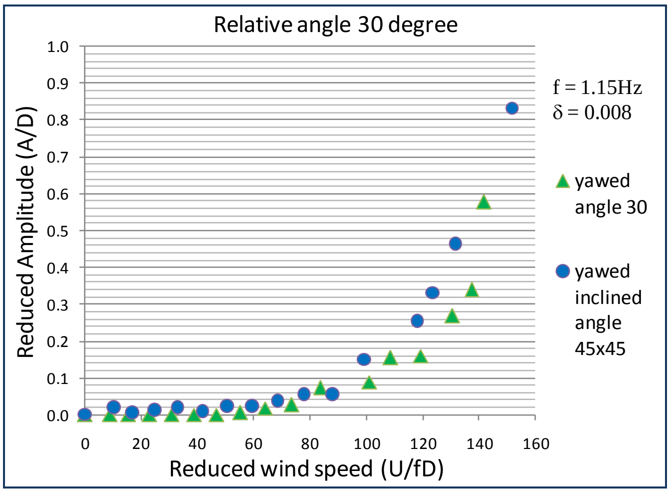


Fig.8 Comparison of yawed angles and yawed/inclined angles

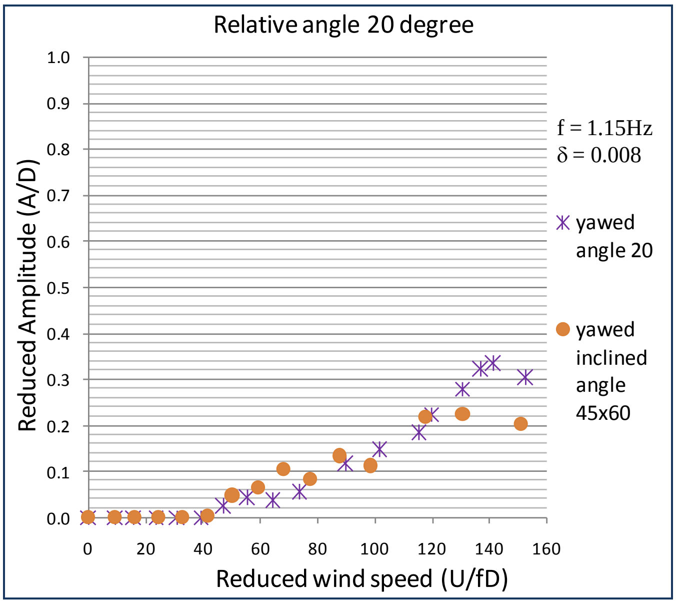


Fig.9 Comparison of yawed angles and yawed/inclined angles

According to the comparision in Figs. 7- 9, it can be seen that the same relative angle (β^*) illustrates the same vibration trends in all three cases though the cable model were fixed in different attitudes. Consequently, it can be seen that the attitude of cable plays minor role in exciting the vibration of cable. This conclusion can plays a significant role for later WTT. On the similar expression, instead of setting up cable model in different attitudes, we can set up the cable model simply at only horizontal plane, which has the same relative angle. However, it should investigate the other cases as well as study on flow field for further conclusions.

3.4 Mitigation Countermeasures

It was pointed out that the level of instability of a cable is sensitive to the cable surface. Therefore, some types of cable surface modification were proposed to suppress rain-wind induced vibration. Flamand used helical fillets of 1.5 mm on the cable surface of the Normandie Bridge and this method was proven effectively (1994). Since then, this kind of cable surface modification has come to be used for cable-stayed bridges. Moreover, Ming Gu and Xiaoqin Du (2005) concluded that only proper spacing of the spiral wires could destroy the upper rivulet and further suppress rain–wind-induced vibration of cables. What is more, Phelan et al.(2006) showed some test cases about this kind of countermeasure to suppress rain-wind-induced vibration. Recently, K. Kleissl and C.T. Georgakis (2012) presented the smoke visualizations of the near-wake flow structures of the cable for 45^{o} relative wind angle. The first WTT with plain cable (normal surface) showed that a strong channel of axial flow was observed clearly along the leeward side of cable. Nevertheless, this type of flow is found to be almost suppressed in the WTT with the helical fillets. These test results affirmed that the helical wire could eliminate the axial flow but we should be clear that their WTTs were conducted under static condition. In this paper, single spiral wire, double spiral wires and circular rings are proposed mitigate dry-state galloping of cable and also investigate the level of efficiency. The details of three types of countermeasure are as Fig. 10.

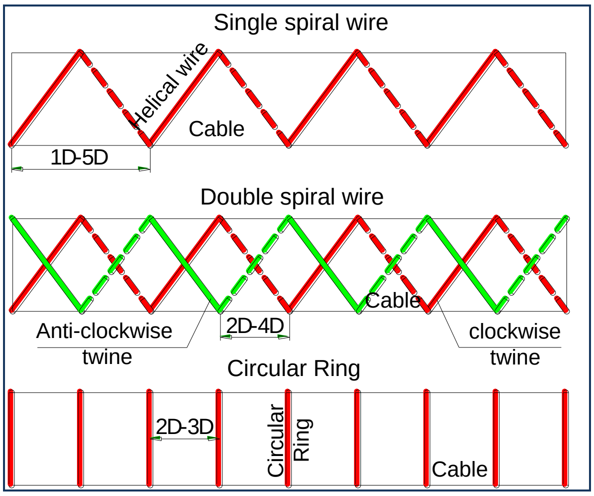


Fig.10 Details of countermeasures

(1) Single spiral wire countermeasure

The main key for selecting spiral wire diameter is that wire should be large enough to suppress the formation of an axial flow in the wake of cable. In these series of the test, a single spiral wire of diameter $D/25$ (3mm), $D/15$ (5mm), $2D/15$ (10mm) and $D/5$ (15mm) were twisted along the cable with the different spacing of one time of cable diameter to five times of cable diameter ($1D$-$5D$). In order to verify the mitigation efficiency clearly, the cable model was set up in the horizontal plane with 45 degree of yawed angle. The WTT installing is as Fig. 11.

The Fig. 12 to Fig. 15 illustrated the effectiveness of spiral wire on the mitigating vibration of cable. In these WTTs, different wire diameter and twine spacing were tested. The single spiral wire cases of $D/15$ and $2D/15$ in spacing of $2D$ to $3D$ along the cable showed the dominant cases. In the $2D/15$ spiral test, the twine at spacing $2D$ to $4D$ showed the highest mitigation level. The amplitude less than $0.2D$ occurred at 120-130 of reduced wind speed, compared to $0.65D$ of none-countermeasure case. However, as increasing the pitch to $5D$ or decreasing to $1D$, the effectiveness of the spiral wire decreased moderately as shown in Fig. 12. In addition, the nearly same effectiveness was found for the case of wire $D/15$ as shown in Fig. 13. On the other hand, the cases with the spiral wire of $D/25$ and $D/5$ did not perform well in reducing the vibration as shown in Figs. 14 and 15. In the $D/25$ case, the non-dimensional amplitude around $0.2D$ and $0.4D$ found at reduced wind speed around 120 with the spacing of $2D$ and $4D$, respectively. Nevertheless, the case of wire $D/5$ was quite ineffective, as shown in Fig. 15. The diameter of a helical wire in combining with the twined pitches must play the vital role in mitigating dry galloping in a complicated manner. The changing of each factor will lead to different level efficiency.

Fig.11 Single spiral wire set-up

What is more, the single spiral wire also showed high efficiency in case of yawed angle 30 degree when the wire were twisted with the spacing of 2*D* and 3*D* as shown in Fig. 16. It can be seen that diameter of helical wire accompany with twined pitches must play the vital role in mitigating dry galloping. The change of each factor will lead to different efficiency. Currently, the cases with diameters from D/15 to 2D/15 at a pitch of 2D-3D are the most eligible for suppressing dry-state galloping.

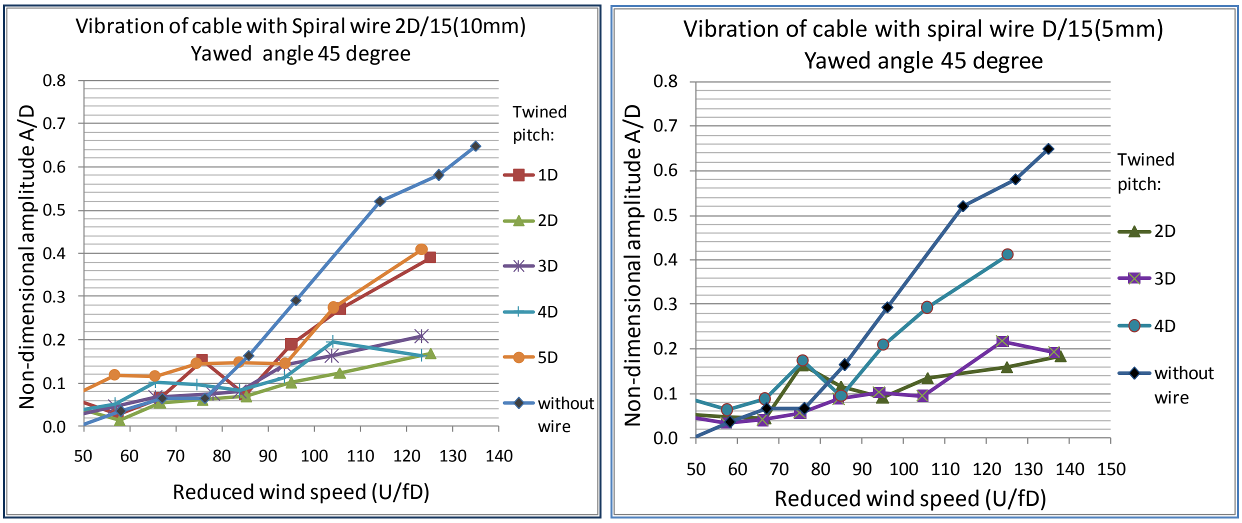


Fig. 12 and Fig. 13 Effect of twined spacing on mitigation efficiency

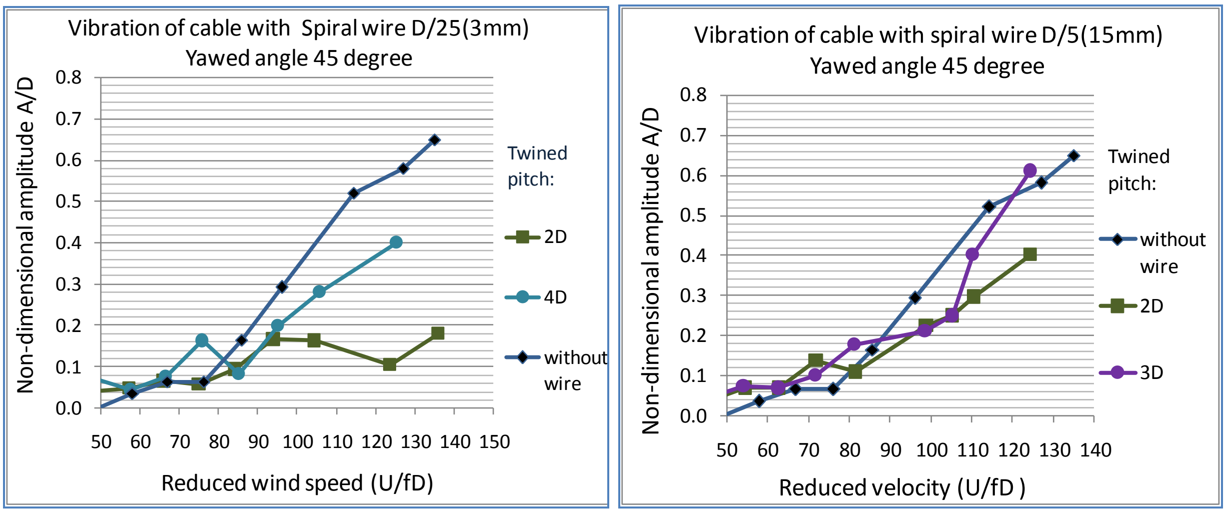


Fig. 14 and Fig. 15 Effect of twined spacing on mitigation efficiency

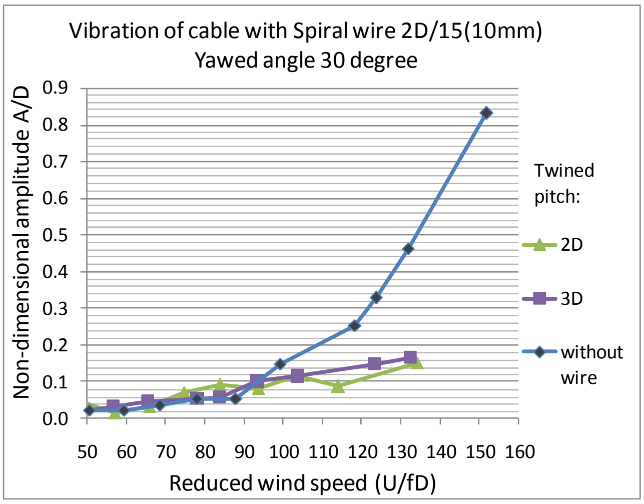


Fig. 16 Confirm the mitigation efficiency with yawed angle 30^o

(2) Double spiral wire countermeasure

According to the test result of the single wire case, the double spiral wire of the diameters D/15 (5mm) and D/25 (3mm) were chosen. The wires were twined clockwise and anti-clockwise along the cable model with spacing of 2*D*–4*D* to confirm the effectiveness and compare to single spiral wire cases. The setting up of double spiral wire countermeasure illustrates as Fig. 17. The vibration amplitude with double spiral wires at spacing of 2*D* to 4*D* is quite small, according to test results as Figs. 18 and 19. Dry-state galloping at high- reduced wind speed was reduced efficiently. For the *D*/25 (3mm) double spiral wire case, the vibration was almost suppressed at the spacing 2*D* and 3*D*, the non-dimensional amplitude under 0.2*D* can be found at reduced wind speed 140 while none-wire case reached amplitude 0.65*D* at same wind speed. When the twined spacing was increased to 4*D*, the level of mitigation was declined moderately, in which non-dimensional amplitude 0.3*D* occurred at the reduced wind speed of around 125. Consequently, it is obvious that the spacing has great effect on the mitigation of vibration. Besides that, the cases with D/15 (5mm) double spiral wire exhibited more effective than the D/25 case. However, the most important finding is that both cases showed the good performance in eliminating the large amplitude vibration of cable. On the other hand, this kind of countermeasure worked well when experiment conducted with yawed angle of 30 degrees as Fig. 20. Therefore, the double spiral wire countermeasure seems to mitigate the dry state galloping significantly. However, it need to conduct with the other onset wind angles.

Fig. 17 Double spiral wire set up

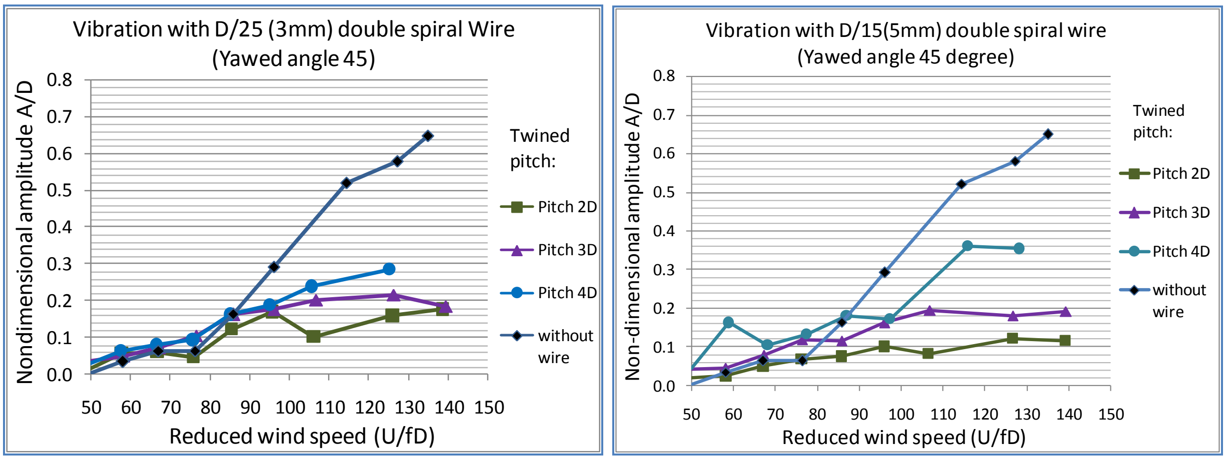
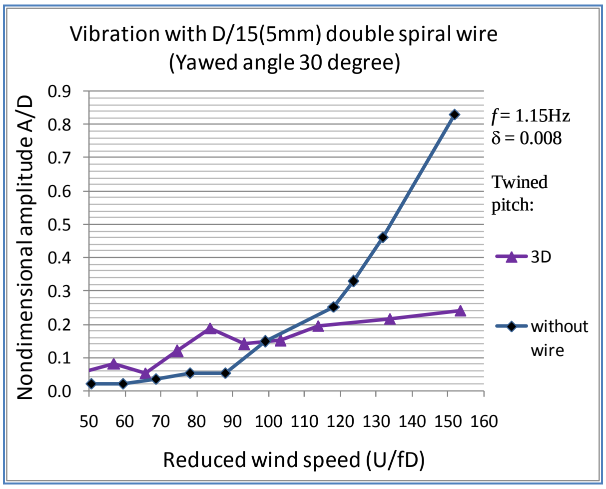


Fig. 18 and Fig. 19 Effect of double spiral wire



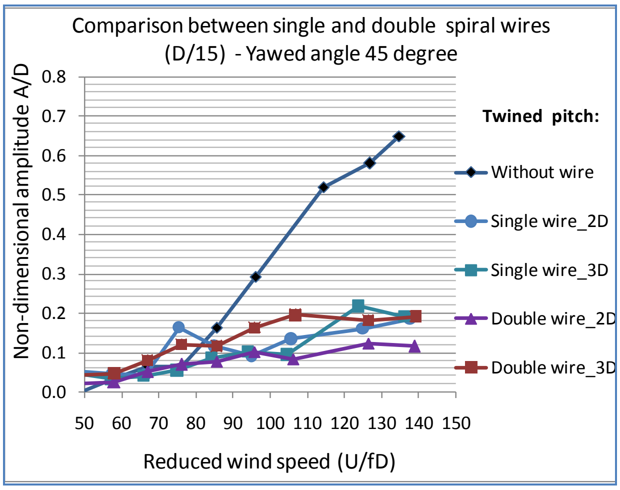


Fig. 20 Confirmation at yawed angle 30^{o}; Fig. 21 Single and double spiral wires

Fig. 21 exhibits the comparison in mitigating dry-state galloping of single and double spiral wires countermeasures. Overall, almost divergent vibration was suppressed totally, typical amplitude under 0.25D. Among of these, double spiral wire D/15 at the pitch of 2D shows more dominant than the other. In detail, vibration amplitude tends to level off approximately at 0.1D even though reduced wind speed increases up to 140.

(3) Circular ring countermeasure

In order to investigate the effectiveness of this countermeasure, the *D*/10 (7.5mm) circular rings were attached at pitches from two times to four times of cable diameter. The attachment of circular ring countermeasure is as Fig. 22.

Fig. 22 Setup of circular rings

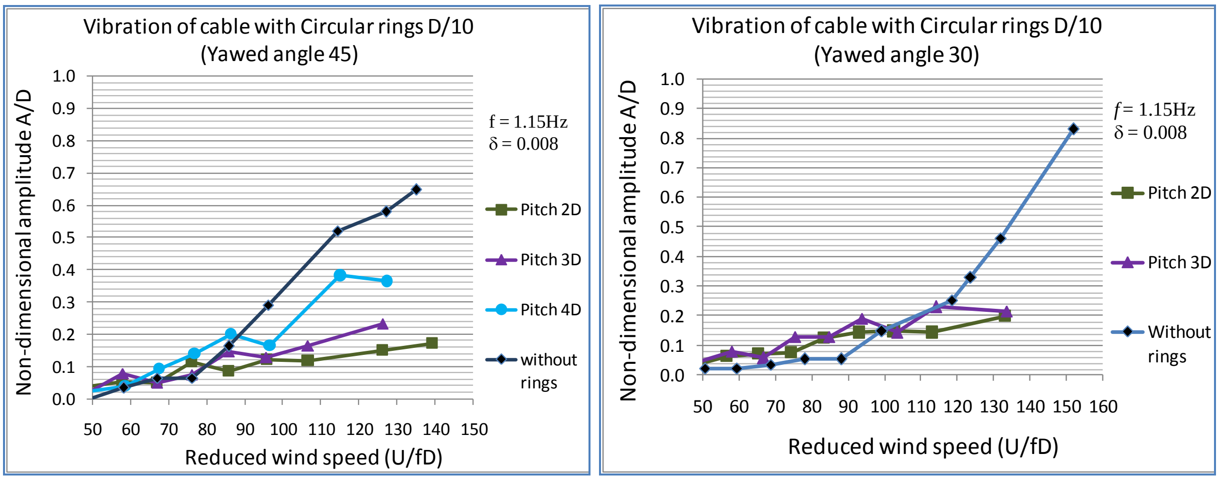


Fig. 23 and Fig. 24 Effect of circular rings in difference wind angles

From the Fig. 23, it is clear that the rings were much effective when placed at two to three times of diameter (2*D*-3*D*). No divergent galloping was observed. Among three cases of the test, it is obviously seen that the case with 2*D* spacing exhibited the most effectiveness. The non-dimensional amplitude did not exceed 0.2*D* even at high reduce wind speed 140. Similarly, the spacing of 3*D* almost suppressed large amplitude vibration; however, the efficiency is a little less than the case with pitch of 2*D*. On the other hand, the pitch at 4*D* only mitigated the vibration moderately, approximate 0.4*D* amplitude occurred at 115 – 130 of reduced wind speed. This result absolutely agreed with the outcomes of Phelan at el10) in which the ring countermeasure exhibited effectiveness in suppressing the vibration of cable. Additionally, the effectiveness of the circular ring countermeasure was also confirmed by the yawed angle of 30^o as shown in Fig. 24.

To summarize, spiral wire and the circular ring are adequate countermeasures for mitigating the vibration of cables; nevertheless, the selection of twined pitches as well as the diameter of wires should be considered carefully. The spacing of 2*D* to 3*D* showed the most effectiveness in almost all cases.

4. CONCLUSIONS

Dry-state galloping of cable were investigated by wind-tunnel test in using a smooth cable surface and smooth wind flow. Some types of countermeasures were suggested for reducing dry-state galloping. Responses of the cable at the high-reduced wind speed and the effectiveness of its countermeasures were recorded. Important results obtained from this study are as follows:

1) Divergent galloping occurred in some range of yawed angles at high reduced wind speed. For the cases of yawed/inclined angle combination, the divergent galloping is almost identical to the only yawed angle case.

3) Cable galloping are governed by the wind relative angle even for different cable attitudes to wind flow. In other expression, as the experiments are conducted with same relative wind angles (β^*), the same responses will be exhibited.

4) Single spiral wire, double spiral wire and circular ring countermeasures are much effective to suppress dry-state galloping when those are installed at proper twined spacing and by selecting suitable wire sizes.

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