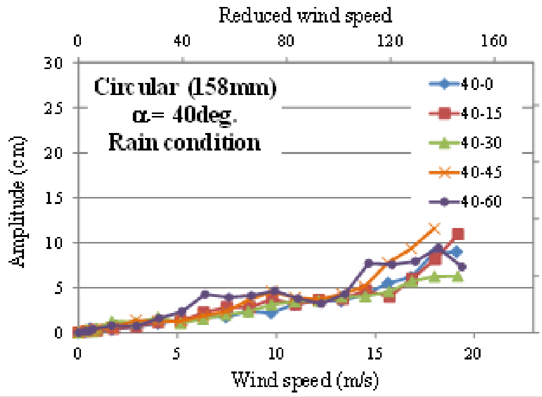
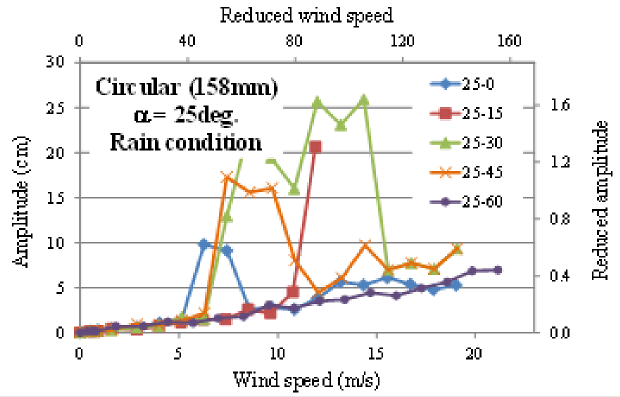
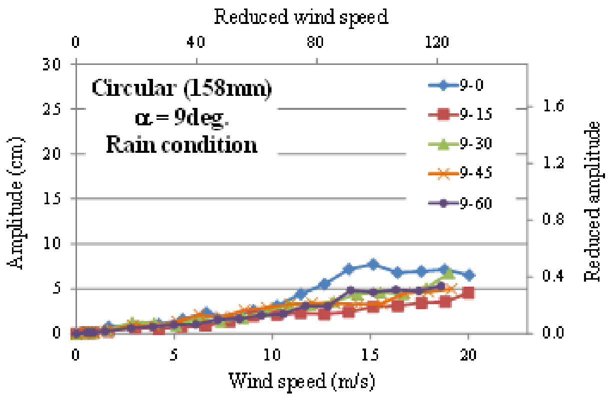


(1) α = 40 deg. (S_c = 7-9)



(2) α = 25 deg. (S_c = 6-9)

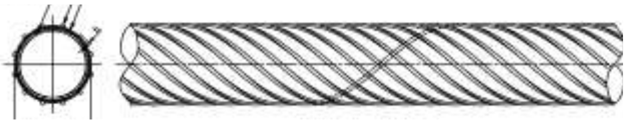


(3) α = 9 deg. (S_c = 3-4)

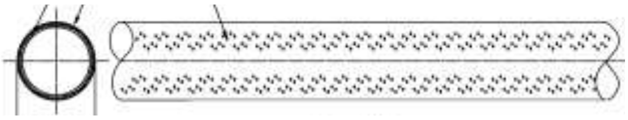
Fig. 5 Response amplitude of circular vs. wind speed in rain condition (D158mm)

4. RESPONSE OF SURFACE MODIFICATION CABLES UNDER RAIN CONDITION

As already described, some surface modification cables were developed for RWIV countermeasures. In this study, two types of surface modification cables; spiral protuberances (Yagi et. 2011) and indented (Miyata et al. 1994) were tested for RWIV. In addition, some parameter tests for the spiral protuberance were conducted. The models were supported in the same manner as in the circular model case. Scruton number condition is also nearly same as that of the circular model case which is shown in each case figure.



(1) Spiral protuberance cable



(2) Indented cable

Fig. 6 Surface modification cables

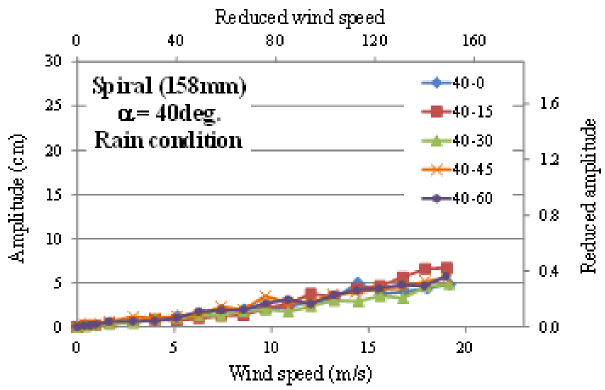
(1) Spiral protuberance

(2) Indented

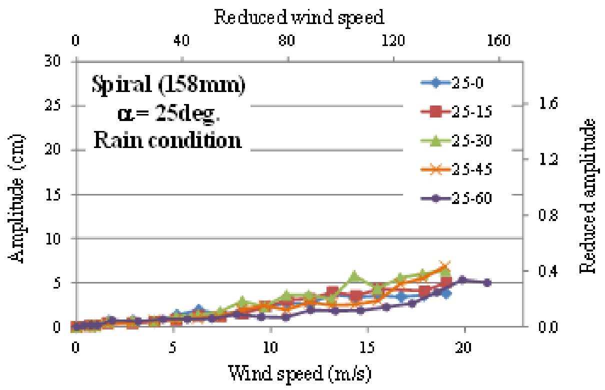
Fig. 7 Set up of surface modification cable models

4.1 Response Characteristics of Spiral Protuberance and Indented Cables

Figs. 8 and 9 show response amplitude of the spiral protuberance and indented cables with the diameter of 158mm in a rain condition, respectively. RWIV took place in the case of the indented cable at some angles. It was observed that water rivulet passed over indentations during RWIV. However it is understood that RWIV observed in this study was due to a small Scruton number condition. On the other hand, the spiral protuberance cable did not exhibit RWIV for all cases but only small amplitude buffeting like random vibration.

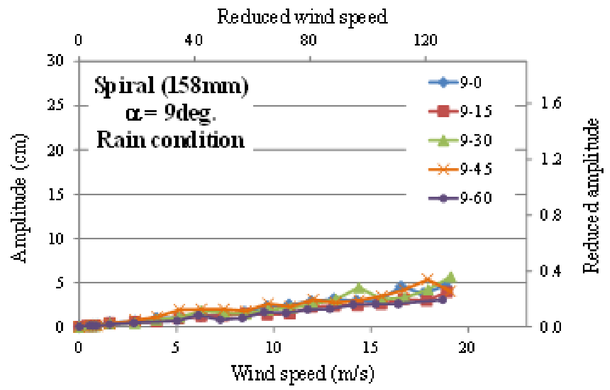


(1) α = 40 deg. (S_c = 9)



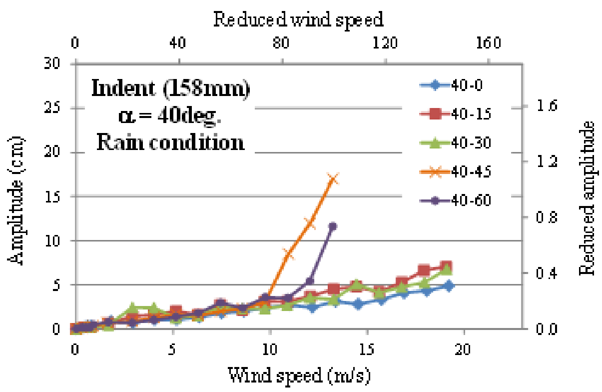
(2) α = 25 deg. (S_c = 5-12)

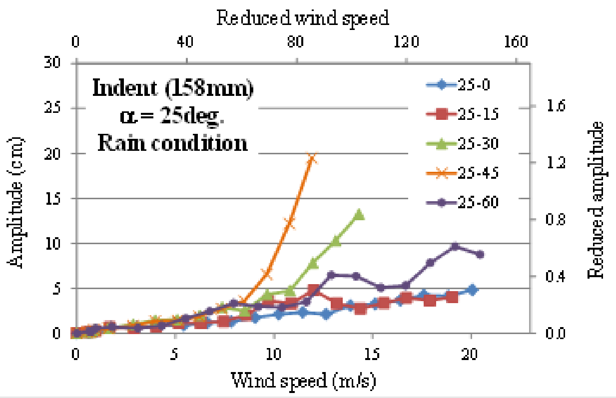
Fig. 8 Response amplitude of spiral protuberance vs. wind speed in rain condition (D158mm)



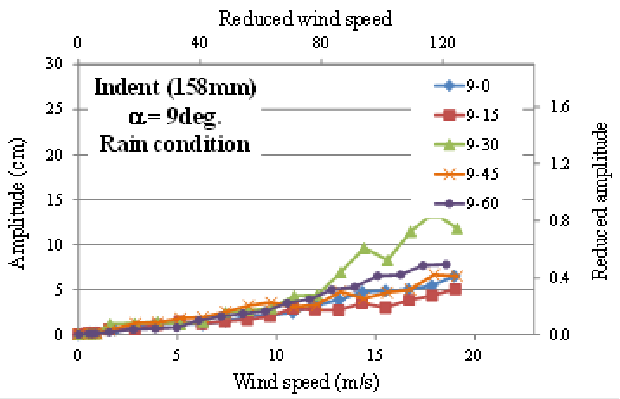
(3) α = 9 deg. (S_c = 4)

Fig. 8 Response amplitude of spiral protuberance vs. wind speed in rain condition (D158mm) (cont.)





(1) α = 40 deg. (S_c = 8-9) (2) α = 25 deg. (S_c = 5-8)



(3) α = 9 deg. (S_c = 3-4)

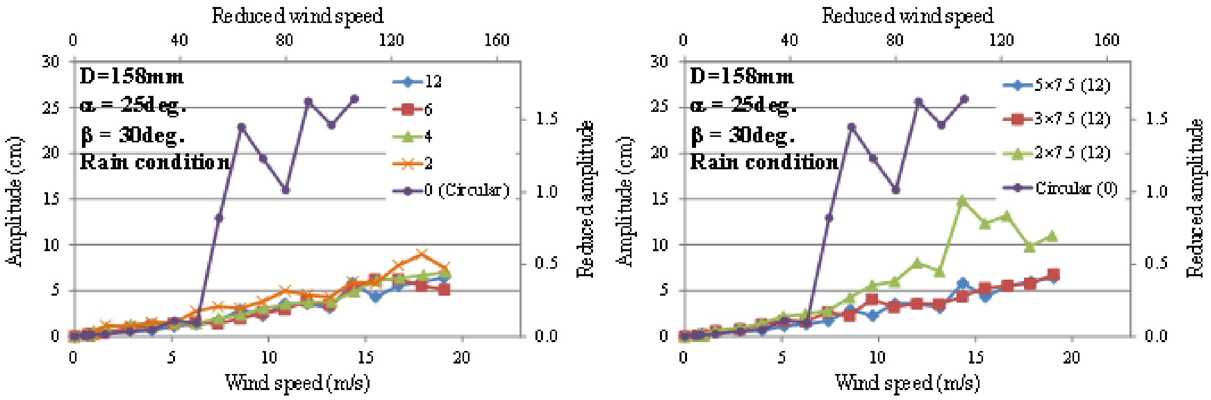
Fig. 9 Response amplitude of indented model vs. wind speed in rain condition (D158mm)

4.2 Effects of Protuberance Dimensions on Response

Dimensions of the spiral protuberance were decided based on the past study (Yagi et al. 2011). It considered that the drag force coefficient is kept low and rivulet formation is prevented. Basic dimensions are circumferential 12 protuberances of 5mm height and 7.5mm width with the spiral angle of 27 degrees. However those effects were only confirmed in a wind tunnel in a no rain condition (DG). Therefore, it is desired that effects of protuberance dimensions should be confirmed in a rain condition.

There is not significant effect of the number of protuberances (Fig. 10(1)) as long as the 5mm height is kept. However slight increase in the amplitude is found for the two protuberance case. In order to investigate the minimum height of protuberance, 2mm and 3mm height keeping twelve protuberances and 7.5mm width were tested. It is found that the 2mm height case increased the vibration amplitude significantly (Fig. 10(2)).

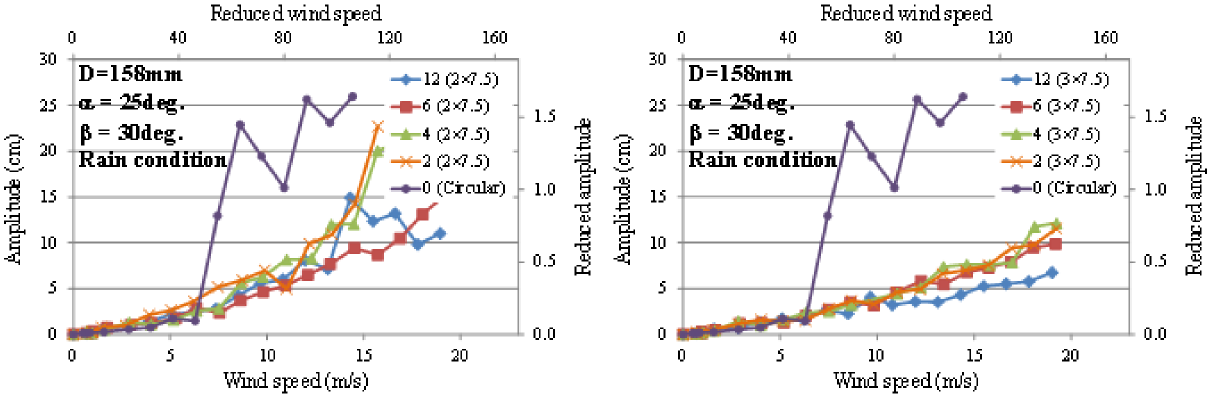
Further investigation on effects of the height and the number was conducted. The 2mm height increased RWIV amplitude even with twelve protuberances more than the basic 5mm height case as shown in Fig. 10(3). In the case of 3mm height, the decrease of protuberance number affects the vibration amplitude as shown in Fig. 10(4). Even the six protuberance case increased the amplitude. Based on those results, it is understood that the protuberance height needs at least 5mm to prevent rivulet and RWIV.



(1) Number of protuberance
(5mm height)

(2) Size of protuberance
(height x width)

Fig. 10 Response amplitude of spiral protuberances vs. wind speed for different protuberance dimensions (D158mm, α = 25 degrees, β = 30 degrees)



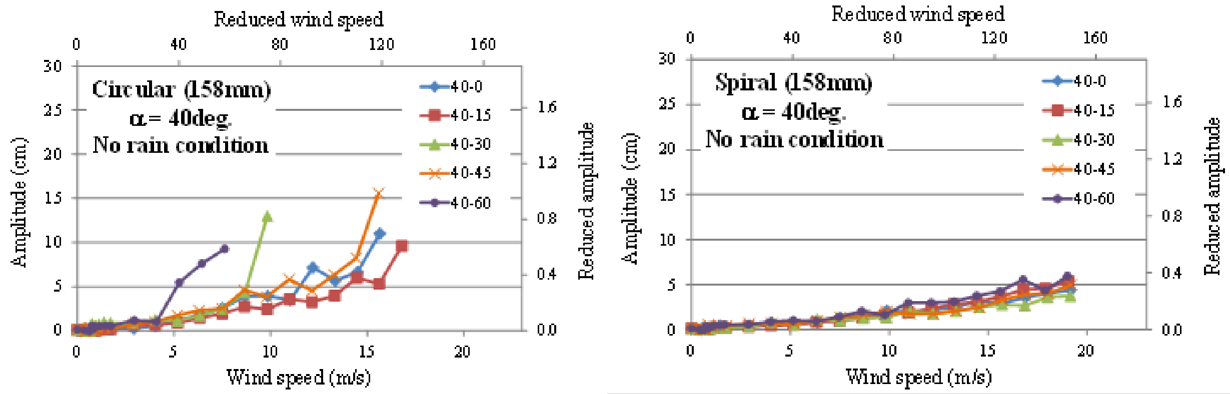
(3) Number of protuberance (2mm height)　(4) Number of protuberance (3mm height)

Fig. 10 Response amplitude of spiral protuberances vs. wind speed for different protuberance dimensions (D158mm, α = 25 degrees, β = 30 degrees) (cont.)

5. DG OF SURFACE MODIFICATION CABLES

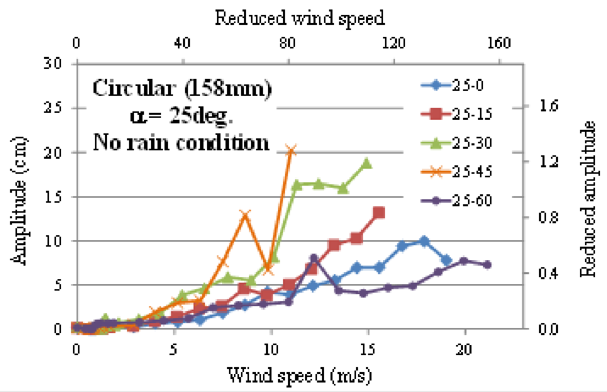
In addition to RWIV, DG was also tested for the surface modification cable model. Fig. 11 shows response amplitude of the spiral protuberance model in a dry (no rain) condition compared with the circular model.

The circular model exhibited large amplitude DG particularly with the flow angle β = 30 and 45 degrees. However these vibrations occurred with a low Scruton number of around 10. It was confirmed that large amplitude DG was suppressed below 0.5D reduced amplitude with the increase of Scruton number to around 60. On the other hand, the spiral protuberance model was completely stable and exhibited only small amplitude buffeting like random vibration.

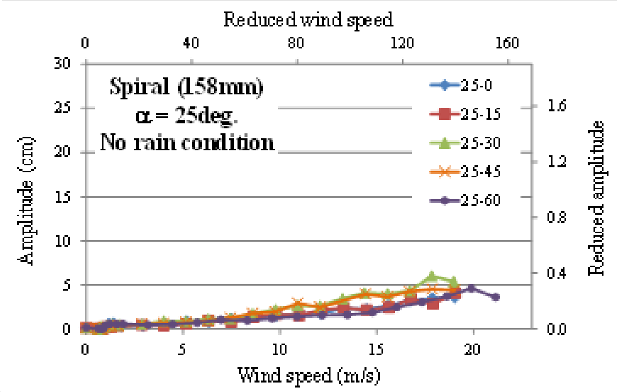


(1) Circular, α = 40 deg. (S_c = 7-9)　(2) Spiral, α = 40 deg. (S_c = 9)

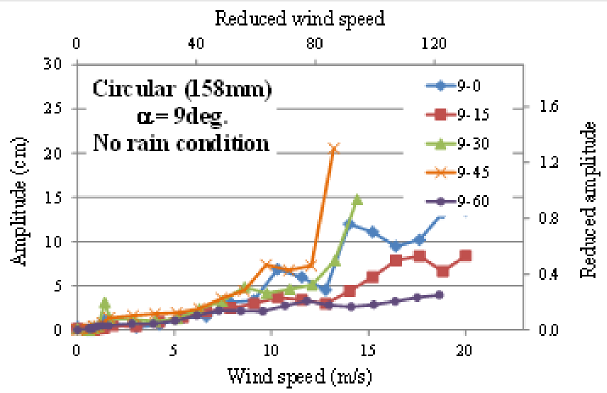
Fig. 11 Response amplitude vs. wind speed in dry condition (D158mm)



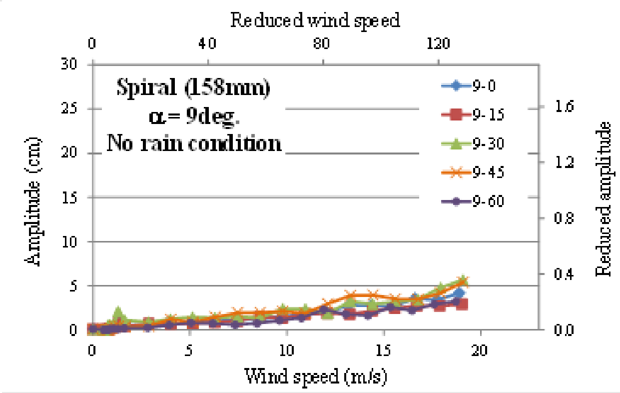
(3) Circular, α = 25 deg. (S_c = 6-9)



(4) Spiral, α = 25 deg. (S_c = 5-12)



(5) Circular, α = 9 deg. (S_c = 3-4)



(6) Spiral, α = 9 deg. (S_c = 4)

Fig. 11 Response amplitude vs. wind speed in dry condition (D158mm) (cont.)

6. CONCLUSIONS

In this study, using a renovated wind-tunnel with a rain simulator system, performance of a couple of surface modification cables was investigated. Results obtained as follows:

RWIV was successfully reproduced in the wind tunnel. It was also observed that rivulet on the cable surface vibrated in the circumferential direction synchronously with the cable vibration. Those characteristics were well coincide with past reports.

Surface modification cable of indented showed good performance for both RWIV and DG, except for some particular conditions. However the increase in Scruton number can suppress vibrations. Spiral protuberance cable showed completely good performance for both RWIV and DG.

Finally effects of protuberance dimensions were clarified. There is a certain limit of dimensions such as the height and number to suppress RWIV.

REFERENCES

Flamand, O. (1995), "Rain-wind induced vibration of cables", *J. of Wind Engineering and Industrial Aerodynamics*, **57**, pp.353-362.

Gu, M and Du, X. (2005), "Experimental investigation of rain–wind-induced vibration of cables in cable-stayed bridges and its mitigation", *J. of Wind Engineering and Industrial Aerodynamics*, **93**, pp.79-95.

Hikami, Y. and Shiraishi, N. (1988), "Rain-wind Induced Vibrations of Cables in Cable Stayed Bridges, *J. of Wind Engineering and Industrial Aerodynamics*, **29**, pp.409-418.

Matsumoto, M. (2011), "On generation mechanism of "rain vibration" and "dry galloping" of inclined stayed cables of cable-stayed bridges, basing on their flow fields", *Proc. of 9th International Symposium on Cable Dynamics*, Shanghai, China, pp.207-214.

Miyata, T., Yamada, H. and Hojo, T. (1994), "Aerodynamic response of PE stay cables with pattern-indented surface", *Proc. of International Conference on Cable-stayed and Suspension Bridges*, Vol.2, Deauville, France, pp.515-532.

Saito, T., Matsumoto, M. and Kitazawa, M. (1994), "Rain-wind excitation of cables on cable-stayed Higashi-kobe Bridge and cable vibration control", *Proc. of International Conference on Cable-stayed and Suspension Bridges*, Vol.2, Deauville, France, pp.515-532.

Yagi, T., Okamoto, K., Sakaki, I., Koroyasu, H., Liang, Z., Narita, S. and Shirato, H. (2011), "Modification of surface configurations of stay cables for drag force reduction and aerodynamic stabilization", *Proc. of 12th International Conference on Wind Engineering*, Amsterdam, Netherland.

Zuo, D. and Jones, N.P. (2010), "Interpretation of field observations of wind- and rain-wind-induced stay cable vibrations", *J. of Wind Engineering and Industrial Aerodynamics*, **98**, pp.73-87.