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INVESTIGATION ON WIND-INDUCED STABILITY OF INCLINED CABLE WITH SPIRAL PROTUBERANCES

Kyoto University Student Member ○ Tung Quang Do
Kyoto University Member Tomomi Yagi
Central Japan Railway Company Takuya Shimoda
Kyoto University Student Member Haruki Fukushima
Kyoto University Thu Minh Dao
Kyoto University Member Kyohei Noguchi

1. INTRODUCTION

Recently cable with 12 spiral protuberances and 27° winding angle is applied to control the rain-wind induced vibration and reduce drag force[1]. However, several aerodynamic properties of this cable remain unknown. One of such properties is the buffetting problem coming from the lift force generated by inclined helical wires which share the same properties with cable with spiral protuberances[2]. Also, dry galloping is likely to occur because of drag crisis. In this research, by conducting wind tunnel static force measurement tests, the aerodynamic performance of cable with spiral protuberances was investigated to examine the dry galloping and buffeting problem of the inclined cable.

2. STATIC FORCE MEASUREMENT OF CABLE WITH SPIRAL PROTUBERANCES

The definitions of inclined angle α [°], yawed angle β [°] and wind relative angle β^* [°] are presented in Fig. 1. In the uniform flows, aerodynamic characteristics of inclined cable can be determined by wind relative angle β^*. The relationship between β^*, β and α is shown by Eq. (1). Because wind forces defined by wind axis is independent of α. α was kept at 0° while $\beta = \beta^*$ varied from 0° to 45° with an increment of 5°. Static force measurement was conducted for both circular cable and cable with spiral protuberances. The drag and lift coefficients (C_D and C_L) were obtained from Eq. (2). Where ρ: air density [kg/m^3], U: wind velocity [m/s], D: diameter of cable [m], F_x and F_y: drag and lift force acting on the cable [N], L: length of cable [m]. Fig. 2 shows C_D of cable with spiral protuberances with respect to Reynolds number (Re). Drag crisis region is observed where Re < 2.5 × 10^4. C_D of cable with spiral protuberances at $\beta^* = 0°$ was smaller than 1.2 which is the common value for circular cables in the subcritical region. Results for the super-critical-Re region agree well with the previous research[1]. Dry galloping characteristics should be examined in terms of drag crisis. Fig. 3 shows that C_L increases when β^* increases which corresponds to past research[2]. Because of surface configuration of inclined cable, the time average flow field is asymmetric. When the inclined angle of cable increased, the direction of spiral protuberances on upward surface of model becomes closer to parallel to the cable axis, while that of downward surface is closer to perpendicular to the cable axis. Hence, non-zero lift force was observed. To eliminate the lift force on the whole cable span, the winding direction of spiral protuberances is reserved alternatingly among segments of the cable.

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

$$C_D = \frac{F_x}{\frac{1}{2}\rho U^2 DL}, \quad C_L = \frac{F_y}{\frac{1}{2}\rho U^2 DL} \qquad (2)$$

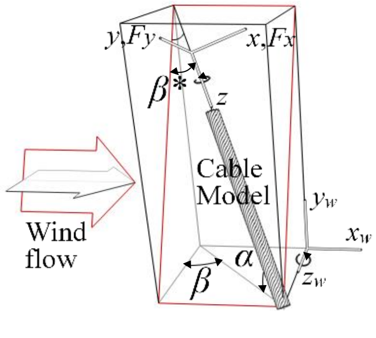

Fig. 1. Definition of β^*

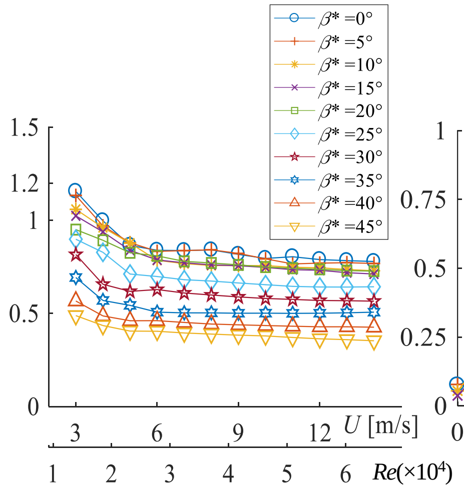

Fig. 2. Drag coefficient C_D

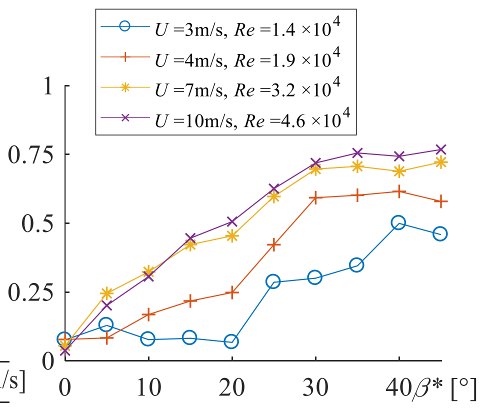

Fig. 3. Lift coefficient C_L

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連絡先: 〒615-8540 京都市 西京区 京都大学桂 京都大学大学院工学研究科社会基盤工学専攻 Tel: 075-383-3170

3. DRY GALLOPING CHARACTERISTIC OF CABLE WITH SPIRAL PROTUBEANCES

Eq. (3) is to calculate the aerodynamic damping ratio ξ_a using the quasi-steady theory to judge the galloping instabilities[3]. $\xi_a > 0$ suggests that cable is stable against galloping.

$$\xi_a=\frac{\mu \mathrm{Re}}{4m\omega_\mathrm{n}}\cos\theta_v\left\{\cos\theta_v\left[C_D\left(2\cos\beta^*+\frac{\tan^2\theta_v}{\cos\beta^*}\right)+\frac{\partial C_D}{\partial \mathrm{Re}}\mathrm{Re}\cos\beta^*+\frac{\partial C_D}{\partial \beta^*}\mathrm{Re}\sin\beta^*\right]-\sin\theta_v\left[C_L\left(2\cos\beta^*-\frac{1}{\cos\beta^*}\right)+\frac{\partial C_L}{\partial \mathrm{Re}}\mathrm{Re}\cos\beta^*+\frac{\partial C_L}{\partial \beta^*}\mathrm{Re}\sin\beta^*\right]\right\} \quad (3)$$

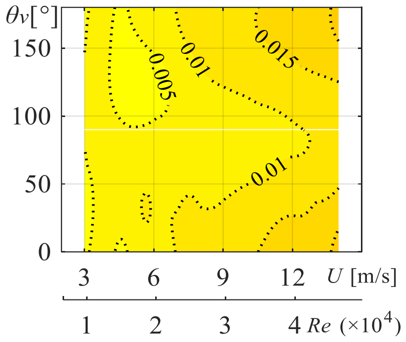


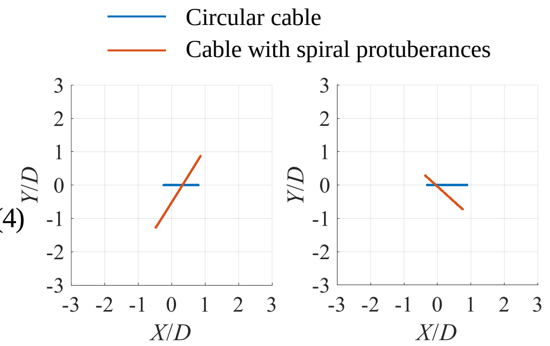
Fig. 4. ξ_a at β^*=45°

where μ: dynamic viscosity of air, θ_v [°] : angle between cable-wind plane and the moving cable velocity direction, ω_n [rad/s]: angular frequency of the structure. Fig. 4 shows ξ_a at β^* = 45° for cable with spiral protuberances. Lift force caused the asymmetric contour of ξ_a at θ_v = 90° and the decrease of ξ_a below the drag-crisis region. Since ξ_a remains positive for the Re including drag crisis region, dry galloping will not occur for cable. Thus, cable with spiral protuberances is stable against galloping.

4. BUFFETTING CHARACTERISTIC OF CABLE WITH SPIRAL PROTUBEANCES

Kikuchi showed that lift force may induce buffeting on inclined helical wire[2]. Therefore, the equations of motion containing buffeting terms were derived as presented in Eq. (4).

$$\begin{cases} m\ddot{x}+c\dot{x}+kx=\dfrac{1}{2}\rho\left(C_D(\hat{\beta}_\mathrm{r},U_\mathrm{r})\cos\theta+C_L(\hat{\beta}_\mathrm{r},U_\mathrm{r})\sin\theta\right)DU^2(1-\dfrac{2}{U}\dot{x}\cos\hat{\beta}) \\ m\ddot{y}+c\dot{y}+ky=\dfrac{1}{2}\rho\left(-C_D(\hat{\beta}_\mathrm{r},U_\mathrm{r})\sin\theta+C_L(\hat{\beta}_\mathrm{r},U_\mathrm{r})\cos\theta\right)DU^2(1-\dfrac{2}{U}\dot{x}\cos\hat{\beta}) \end{cases} \quad (4)$$



a. U = 7m/s, $\hat{\beta}(t)$ = 30°+10°sin(2πft)

b. $U(t)$ = 7+ 0.5sin(2πft) m/s, $\hat{\beta}$ = 30°

Fig. 5. Trajectory of cable's motion

where m: mass of cable per unit length [kg/m], $\hat{\beta}_\mathrm{r}$ and U_r : relative wind flow angle and relative wind velocity due to the self-motion of cable, θ : relative angle of attack (angle between relative wind and structure axis). To validate of the proposed equations, two examples of time-varying components $\hat{\beta}(t)$ and $U(t)$ were given. The buffeting responses of inclined cable was observed by solving Eq. (4). Fig. 5 shows the steady buffeting response when $\hat{\beta}(t)$ or $U(t)$ oscillates at the same frequency as the natural frequency of cable. Vertical vibration occurred for the cable with spiral protuberances. Fig. 5.a and. 5.b show that amplitude of cable with spiral protuberances is larger than that of circular cable. The vibrations in two examples hardly occur in reality since out-of-plane displacement of cable does not exist in an actual cable-stayed bridge. For that reason, buffeting is not significant in the stability of stay cables with spiral protuberances. In the case where out-of-plane displacement exists, the results show vertical amplitude occurs which is caused by lift force coefficients. The lift force on the whole cable span can be eliminated by using the countermeasure as mentioned in section 2.

5. CONCLUSION

1) When spiral protuberances were attached on circular cable, cable is stable against dry galloping in the drag crisis region where Re is smaller than 2.5 × 10^4. 2) Lift force appeared for cable with spiral protuberances in inclined condition. 3) Alternatingly changing the winding direction of spiral protuberances among segments is suggested to eliminate lift force on the whole cable span. 4) Buffeting forces cause vertical and horizontal vibration for cable with spiral protuberances, however it is not significant for actual cables in cable-stayed bridges.

REFERENCES 1) Yagi et al.: Modification of surface configurations of stay cables for drag force reduction and aerodynamic stabilization, Proc., 13th Int.Conference on Wind Engineering, 2011. 2) 菊池：ヘリカルロッド巻き電線に生じた振動の観測結果と揚力抗力の影響，第 25 回風工学シンポジウム論文集，2018. 3) Macdonald et al: A unified approach to aerodynamic damping and drag/lift instabilities, and its application to dry inclined cable galloping, Journal of Fluids and Structures, 229-252, 2006.