BRIDGE DECK FLUTTER AND BUFFETING CONTROL BY WINGLETS

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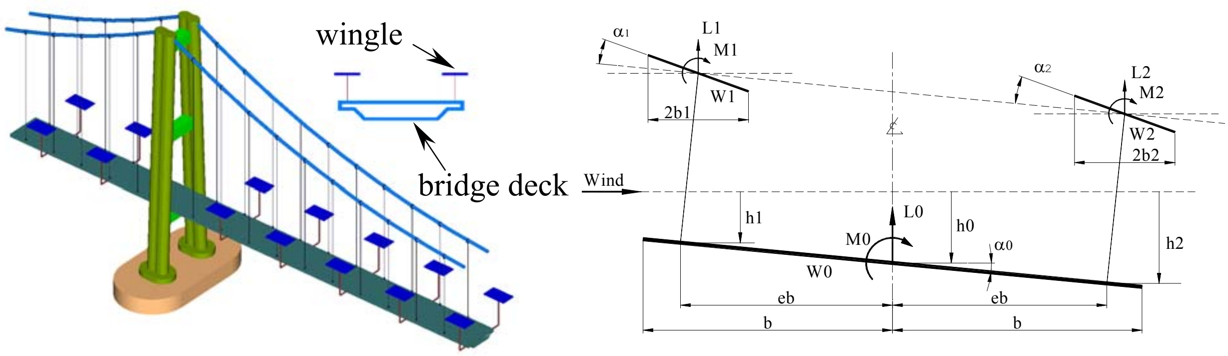
ABSTRACT

The alternative solution for flutter and buffeting stability of a long suspension bridge will be an active control using winglets. This method enables a light weight economic stiffening girder without an additional stiffness for aerodynamic stability. This paper deals with numerical and experimental studies on the flutter control by winglet which placed at the both side of a bridge deck section. The two dimensional numerical study shows the flutter can be suppressed by the adequate motion of winglets. The wind tunnel test with a spring mounted bridge model shows that the model is stabilized up to the divergence speed. The response in gusty wind is also controlled.

1. INTRODUCTION

The flutter and buffeting problem become more serious with increasing span length since critical speed decreases with decreasing stiffness and damping. A large number of proposals for avoiding such problems have already been given, e.g. viscoelastic damping elements, turned damping elements and eccentric masses as well as aerodynamic configuration of a deck. The other solution for a long span bridge will be active aerodynamic controls using winglets which are seen in aeronautical field. This method has been reported in the current literature [1,2].



(a) Bridge with winglet controls (b) Bridge deck system with winglets

Fig. 1 Active flutter control by winglets

As shown in Fig. 1(a), two winglets are attached on both edges of bridge deck of a suspension bridge. By providing the appropriate phase and amplitude for pitching motion of winglets, the positive aerodynamic damping forces produced by them overcome the aerodynamic excitation due to flutter or buffeting, thus the flutter or buffeting is suppressed and bridge deck is stabilized.

The bridge deck and winglets are assumed to be flat plates. The active flutter control system is composed of winglets and servo-driving devices installed in bridge deck. Two dimensional theoretical study and wind tunnel test are made herein for the smooth flow case. And the numerical study is also derived for the turbulent flow.

2. FLUTTER CONTROL IN SMOOTH FLOW

2.1 Control method

Two dimensional analysis of a bridge deck with no structural damping is carried out. Assuming that the mass of winglet is very small, so neglecting in numerical study.
Two control winglets are attached on struts as shown in Fig. 1(b). If system has pitching motion α_0 and heaving motion h_0, flutter equations are:

$$\begin{aligned} m\ddot{h}_0 + K_h h_0 &= -L_T \\ I\ddot{\alpha}_0 + K_\alpha \alpha_0 &= M_T \end{aligned} \tag{1}$$

where m = mass of system, I = moment of inertia of system, K_h = stiffness for heaving motion, K_α = stiffness for pitching motion, L_T and M_T are total aerodynamic forces:

$$\begin{aligned} L_T &= L_0 + L_1 + L_2 \\ M_T &= M_0 + M_1 + M_2 + L_1 e - L_2 e \end{aligned} \tag{2}$$

With aerodynamic lift L_i and moment M_i are defined by [3]:

$$\begin{aligned} L_i &= \pi\rho b_i^2\left(\ddot{h}_i + U\dot{\alpha}_i\right) + 2\pi\rho U b_i C(k_i)\left(\dot{h}_i + U\alpha_i + b_i\dot{\alpha}_i/2\right) \\ M_i &= \pi\rho b_i^3\left(-U\dot{\alpha}_i/2 - b_i\ddot{\alpha}_i/8\right) + \pi\rho U b_i^2 C(k_i)\left(\dot{h}_i + U\alpha_i + b_i\dot{\alpha}_i/2\right) \end{aligned} \tag{3}$$

where ρ = air density, U = wind velocity, $k_i = \omega b_i/U$ = reduced frequency, ω = flutter frequency, b_i = half width of the deck or winglets, $C(k_i)$ = Theodorsen's function, h_1, h_2 = displacements at the struts and i = 0; bridge deck ($b_0 = b$), i = 1; leading edge winglet and i = 2; trailing edge winglet.
When flutter happens, the following harmonic flutter motion appears:

$$\alpha_0 = \tilde{\alpha} e^{i\omega t} \qquad h_0 = \tilde{h} e^{i(\omega t + \phi)} \tag{4}$$

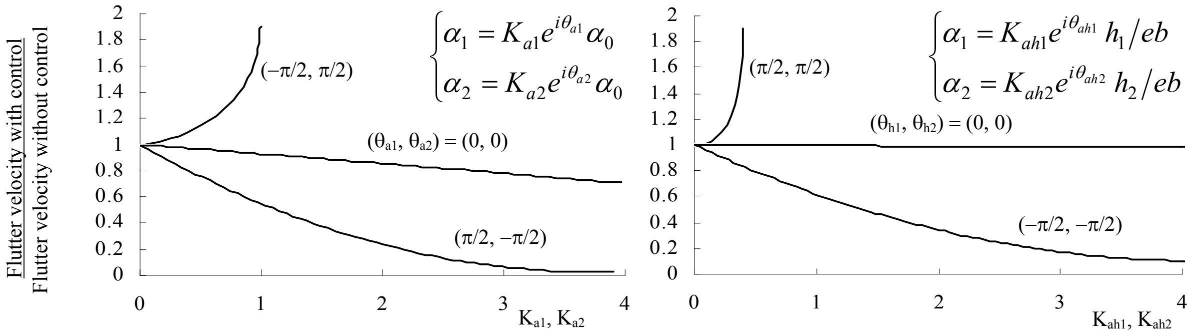
To reduce the motion of the bridge deck, winglets are driven with adequate amplitude and phase:

$$\begin{aligned} \alpha_1 &= K_{a_1} e^{i\theta_{a1}} \alpha_0 + K_{h_1} e^{i\theta_{h1}} h_0/b = K_{ah_{11}} e^{i\theta_{ah11}} h_1/eb + K_{ah_{12}} e^{i\theta_{ah12}} h_2/eb \\ \alpha_2 &= K_{a_2} e^{i\theta_{a2}} \alpha_0 + K_{h_2} e^{i\theta_{h2}} h_0/b = K_{ah_{21}} e^{i\theta_{ah21}} h_1/eb + K_{ah_{22}} e^{i\theta_{ah22}} h_2/eb \end{aligned} \tag{5}$$

where $i = \sqrt{-1}$, K = amplitude factors, θ = phase angles measured from target motion of bridge deck. With adequate amplitude and phase of winglets, the positive damping forces have sufficient magnitude to suppress the bridge flutter. In this case, the bridge deck is stable even if the wind velocity is in the flutter region. To obtain this stability, amplitude factors K and phase angles θ are adequately selected.

2.2 Numerical study

The numerical study is conducted using a two dimensional bridge deck model with winglets of 10% of the bridge deck width.



$$\begin{cases}\alpha_1 = K_{a1}e^{i\theta_{a1}}\alpha_0 \\ \alpha_2 = K_{a2}e^{i\theta_{a2}}\alpha_0\end{cases} \qquad \begin{cases}\alpha_1 = K_{ah1}e^{i\theta_{ah1}}\, h_1/eb \\ \alpha_2 = K_{ah2}e^{i\theta_{ah2}}\, h_2/eb\end{cases}$$

(a) control after pitching motion (b) control after h_1 and h_2

Fig.2 Flutter velocities by various winglet control modes

Fig. 2(a) shows the flutter speed when the winglets are driven with the feedback signal of the pitching motion of the bridge deck α_0. When the winglets are driven with the amplitude factors $K_{a1} = K_{a2} > 1$ and phase angles $\theta_{a1} = -\pi/2$, $\theta_{a2} = \pi/2$ flutter can be suppressed completely. The phase angles $\theta_{a1} = \theta_{a2} = 0$ or $\theta_{a1} = \pi/2$, $\theta_{a2} = -\pi/2$ give the decreasing flutter speed. Fig. 2(b) is the result when the winglets are controlled after h_1 and h_2. the effect appears with smaller amplitude factor when $\theta_{h1} = \theta_{h2} = \pi/2$.

2.3 Wind tunnel test

Two dimensional wind tunnel test was carried out. The cross sections of the model are shown in Fig. 3. The pitching motion of the control winglets was given by the pitching motion of the driving motor which is installed inside the bridge deck.
Time histories of the response of the model with and without control are shown in Fig. 4. The effect of the control winglets is seen in this figure. One of the results of winglet control test are shown in Fig. 5. Where ω_h, ω_α = frequencies, δ_h, δ_α = logarithmic decrements, $\tilde{h}, \tilde{\alpha}$ = amplitudes of heaving and pitching motion respectively. The bridge deck without control ($K = 0$) meets flutter at reduced velocity $U/\omega_\alpha b \cong 2.2$. The wind speed at which instability occurs is increased about $U/\omega_\alpha b \cong 5.0$. In this wind speed large static displacement took place. Other amplitude factor was checked. The result is shown in

3. FLUTTER AND BUFFETING CONTROL IN TURBULENT FLOW

3.1 Control method

In this study, wind gust is caused by vertical component of wind speed, the buffeting forces and motion induced forces are treated by quasi – static force method. As shown in Fig. 1(b), To reduce the bridge deck motion effected by gusty wind, winglets are driven after motions of the deck as follows.

$$\begin{aligned}\alpha_1 &= X_1\dot{h}_0 + X_2\dot{\alpha}_0 + X_3\alpha_0 + X_4 h_0 \\ \alpha_2 &= Y_1\dot{h}_0 + Y_2\dot{\alpha}_0 + Y_3\alpha_0 + Y_4 h_0\end{aligned} \tag{6}$$

The equations of motion of bridge deck system with winglets are:

$$\begin{aligned}\ddot{h}_0 + 2\eta_h\omega_h\dot{h}_0 + \omega_h^2 h_0 &= F_w(t)/m + H_1\dot{h}_0 + H_2\dot{\alpha}_0 + H_3\alpha_0 + H_4 h_0 \\ \ddot{\alpha}_0 + 2\eta_\alpha\omega_\alpha\dot{\alpha}_0 + \omega_\alpha^2\alpha_0 &= M_w(t)/I_\alpha + K_1\dot{h}_0 + K_2\dot{\alpha}_0 + K_3\alpha_0 + K_4 h_0\end{aligned} \tag{7}$$

where $F_w(t)$ and $M_w(t)$ are buffeting forces.
H_i and K_i are related to the control motion X_i and Y_i as follows:

$$
\begin{array}{ll}
H_1 = -L_0/m\left[A_1/U + k(X_1+Y_1)\right] & H_2 = -L_0/m\left[k(X_2+Y_2)\right] \\
H_3 = -L_0/m\left[A_1 + k(X_3+Y_3)\right] & H_4 = -L_0/m\left[k(X_4+Y_4)\right] \\
K_1 = M_0/I_\alpha\left[A_2/U + (A_3X_1 + A_4Y_1)\right] & K_2 = M_0/I_\alpha\left[B + (A_3X_2 + A_4Y_2)\right] \\
K_3 = M_0/I_\alpha\left[A_2 + (A_3X_3 + A_4Y_3)\right] & K_4 = M_0/I_\alpha\left[A_3X_4 + A_4Y_4\right]
\end{array}
\tag{8}
$$

where $L_0 = 2\pi\rho bU^2$, $M_0 = \pi\rho b^2U^2$, $k = b_1/b = b_2/b$, $B = -4ke^2b/U$, $A_1 = 1 + 2k$, $A_2 = 1 + 2k^2$, $A_3 = k^2 + 2ke$ and $A_4 = k^2 - 2ke$.

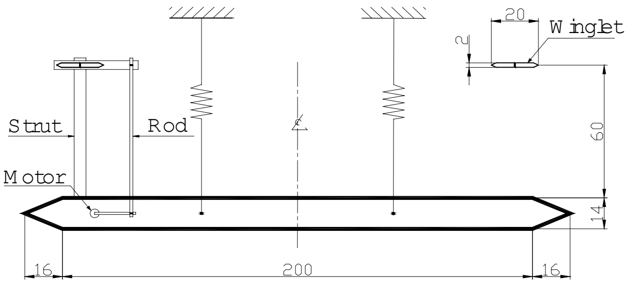


Fig.3 Cross sections of models

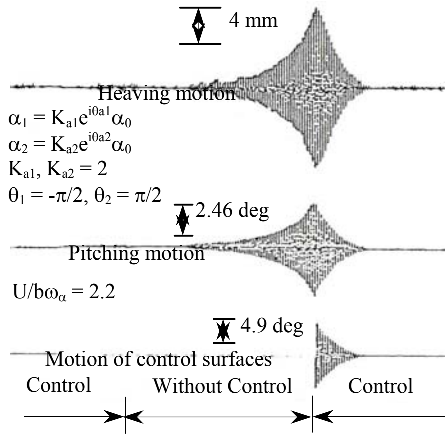
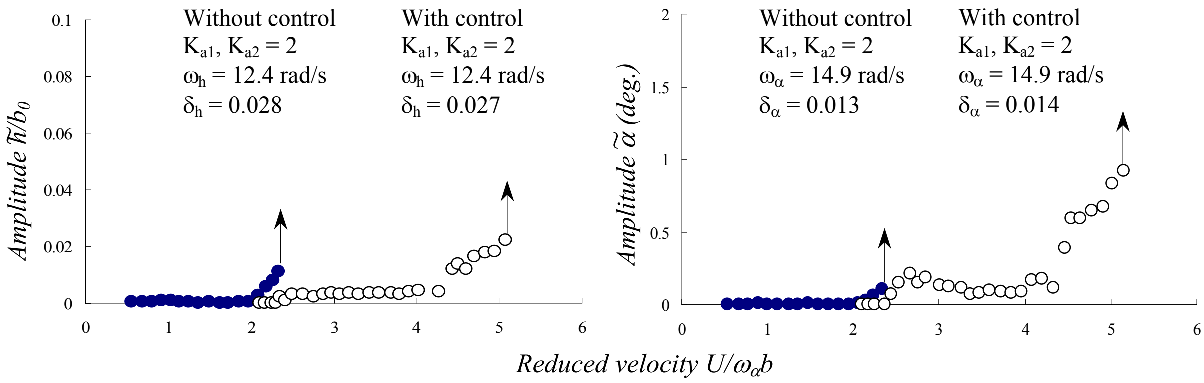


Fig.4 Effect of control winglets

Table 1. Critical velocity $U/\omega_\alpha b$ by amplitude factor K

K	0	0.5	1	2	3	4
$U/\omega_\alpha b$	2.2	2.5	5.2	5	3.2	2.8



(a) Heaving (b) Pitching

Fig. 5 Response of bridge deck with and without winglet control

3.2 Numerical study

The winglets of 15% of bridge deck width are used in this numerical study. The vertical wind *w(t)* is derived from the Von – Karman spectrum. RMS of *w(t)* is 10% of U, horizontal wind speed. The employed values of the system are $m = 35 \times 10^3$ Kg/m, $I_\alpha = 2.9867 \times 10^6$ Kgm^2/m, $K_h = 3679$ Kg/m/s^2, $K_\alpha = 2.7206 \times 10^6$ Kg/m/s^2, $C_h = 227$ Kg/m/s, $C_\alpha = 57010$ Kg/m/s, $b = 16m$.

First, the "*trial and error*" study being performed with the coefficients H_1, K_2 and K_3 are defined by $H_1 = K_{h1}\left(-L_0 A_1/mU\right)$, $K_2 = K_{k2}\left(M_0 B_2/I_\alpha\right)$ and $K_3 = K_{k3}\left(M_0 A_2/I_\alpha\right)$, where H_1 and K_2 relate to the damping and K_3 relates to flutter speed. Other coefficients are set to zero. The desirable values K_{h1}, K_{k2}, K_{k3} were selected in the viewpoint of small gust responses and large flutter speed. Those were $K_{h1} = (1\sim4)$, $K_{k2} = (100\sim170)$ and $K_{k3} = (-40\sim-10)$.

In the calculation, winglet motion was limited within $\pm\ 10^0$ to avoid stalling. The results are shown in Fig. 6. The critical velocity of flutter motion without control is about 36.5 m/s. RMS is suppressed and the critical velocity becomes very high after controlling. With adding of appropriate values K_4, heaving motion was reduced and pitching motion was increased as shown with □ and ■. The time traces of winglet control at velocity U = 44m/s is shown in Fig. 7. The harmonic flutter motion happens for the no control case, but the flutter is suppressed and buffeting reduced after controlling.

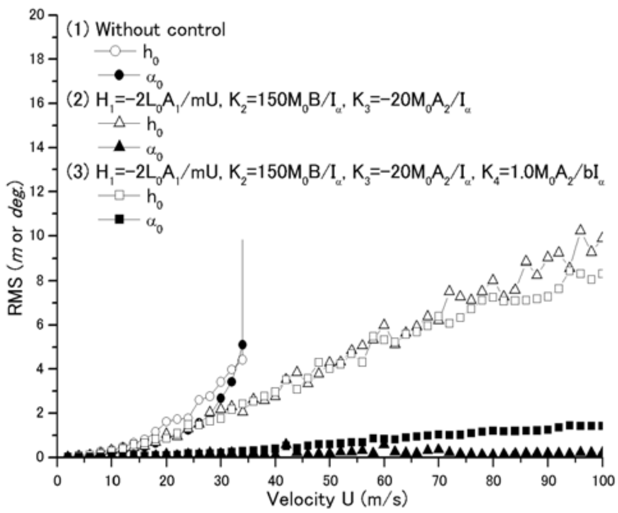
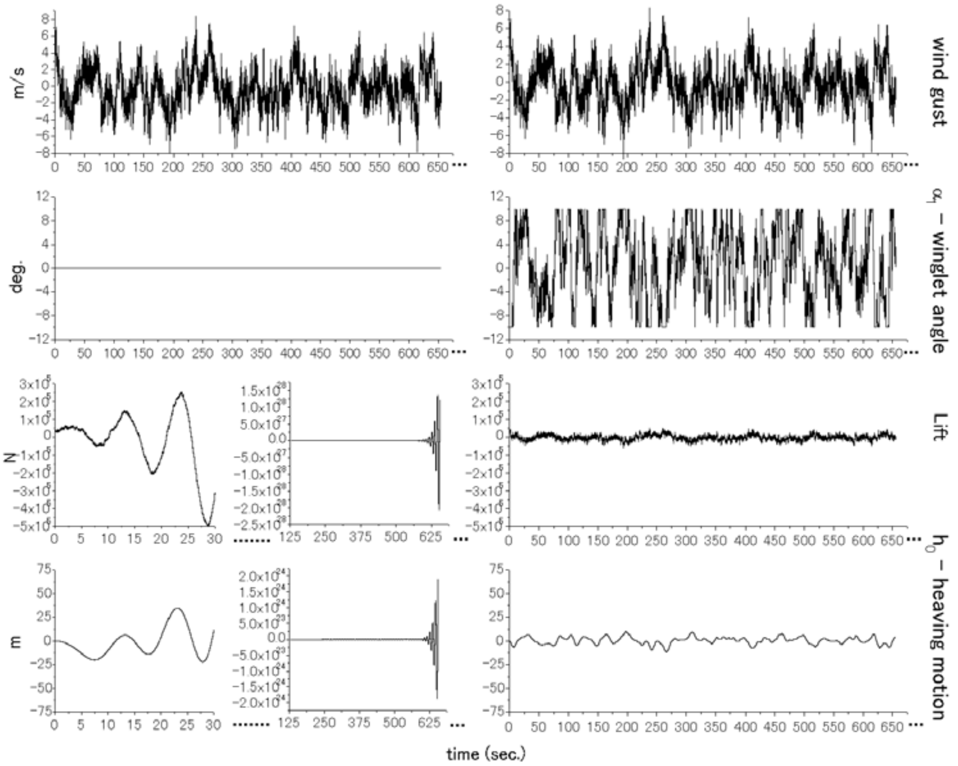


Fig. 6 Effect of winglet control



(a) without control (b) with control

($H_1 = -2L_0A_1/mU$, $K_2 = 150M_0B/I_\alpha$, $K_3 = -20M_0A_2/I_\alpha$)

Fig. 7 Time simulated result (U = 44m/s)

4. CONCLUSIONS

The flutter of a bridge deck being controlled by winglets using the feedback signal of bridge deck motion could suppress the flutter in smooth flow. The model tests confirmed the results of the numerical simulation.

The bridge deck response in gusty wind was analyzed. Winglets could reduce the buffeting and increase the critical flutter speed.

REFERENCES

1. Kobayashi, H. and H.Nagaoka (1992), "Active Control of Flutter of a Suspension Bridge", *Jour. Wind Eng. and Ind. Aerodyn.*, 41 – 44 (1992) 143 – 151.
2. Kobayashi, H., R.Ogawa and S.Taniguchi (1998), "Active Flutter Control of a Bridge Deck by Ailerons", *Proc, 2nd World Conf. on Structural Control*, Kyoto, 1998.
3. Scanlan, R.H. and Rosenbaum, R. (1951), "Introduction to the Study of Aircraft Vibration and Flutter", *The Macmillan Company*, N.Y., 1951, pp.192 – 204.