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An experimental study of flutter and buffeting control of suspension bridge by mechanically driven flaps

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Abstract. The alternative solution for flutter and buffeting stability of a long suspension bridge will be a passive control using flaps. This method not only enables a lightweight economic stiffening girder without an additional stiffness for aerodynamic stability but also avoid the problems from the malfunctions of control systems and energy supply system of an active control by winglets and flaps. A mechanically control using flaps for increasing flutter speed and decreasing buffeting response of a suspension bridge is experimentally studied through a two dimensional bridge deck model. The result shows that the flutter speed is increased and the buffeting response is decreased through the mechanical drive of the flaps.

Keywords: flutter; buffeting; suspension bridge; passive control; flaps.

1. Introduction

There is a growing need for extremely long suspension bridges. Such bridges have already been designed for the future, but are not yet constructed. The longest suspension bridge today is the Akashi Kaikyo Bridge in Japan (main span 1990 m). It is believed that in the future designs with improved girder forms, lightweight cables, and control devices may be up to 5000 m long. For such extremely long bridges, besides problems of strength of material (cable); economic design (lightweight deck); seismic safety (earthquake); girder stability in the wind may be a serious problem – flutter and buffeting, especially when the girder depth-to-width ratio is small compared with existing long bridges.

After the disaster of Tacoma Narrows Bridge, the aerodynamic stability of a suspension bridge was approached with a high torsion rigidity truss-stiffening girder. Although the Severn Bridge showed that a box-girder with nearly streamlined section could also achieve the wind stability of a long span bridge, the adequate stability cannot be assured beyond certain spans (Brancaleoni 1992, Ostenfeld and Larsen 1992). The Akashi Kaikyo Bridge has a vertical stabilizer in the center span located along the centerline of the truss-type stiffening girder to improve aerodynamic stability. However, truss sections usually exhibit quite high wind forces (drag loading) which must be resisted by the bridge structure. This will have relative effect on costs. The truss girder still remains an

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alternative for future long span bridges – particularly from the point of view of aerodynamic stability.

One of the promising solutions is the change of the cross section, for instance, a multi-box cross section. The aerodynamic advantages of this solution have been exploited in the multi-box cross section design of the proposed 3,300 m span suspension bridge for the crossing of the Messina Strait (Brown 1996, 1999). Another proposal for Japanese project is 2-box with slot girder (Sato *et al.* 2000, 2002).

The box girder and truss girder possess qualities which today make them structurally and economically, but aerodynamically they may encounter stability problems if applied to the extreme spans of the future, beside the maintenance and fabrication costs dramatically.

For suspension bridges with a main span of several kilometers, active methods to achieve the aerodynamic stability can provide a new design alternative. The application of the active mass driver was studied (Dung *et al.* 1996, Miyata 1994). The flutter prevention by an active eccentric mass method was also proposed (Wilde *et al.* 1996, Songpol 1998). Körlin and Starossek (2007) also proposed the active mass damper to enhance the flutter stability. With linear control, the measured critical wind speed of the sectional model rises by about 16.5%.

The passive aerodynamic control is more attractive from a practical point of view. If a proper mechanism for a passive system is invented, it can easily be applied to the actual bridge because of its simplicity and reliability. One kind of the passive system is the tuned mass damper TMD was examined (Okada *et al.* 1998, Lin *et al.* 2000, Kwon *et al.* 2000, 2004, Gua *et al.* 1998, 2001, 2002), and its performance was proven to be effective against flutter and buffeting.

In the above references, the flutter suppression methods are based on the structural mechanics. Modifying the flow around the bridge deck or generating stabilizing aerodynamic forces from the flow is another approach to the flutter problem.

The researches on aerodynamic control by using winglets and flaps or being called control surfaces were proposed and developed (Kobayashi *et al.* 1992a, b, 1996, 1998, 2001 and 2005). An extensive theoretical study on the active control of bridge flutter using a model similar to that proposed by Kobayashi was presented (Wilde *et al.* 1998, Preidikman and Mook 1998, Nissen *et al.* 2004). They also translated their active model to a passive one (Wilde *et al.* 1999). This model consists of two control surfaces attached to both edges of the deck and a pendulum placed inside the deck. The maximum improvement of the flutter speed is 43%. The buffeting effect was not considered yet. Omenzetter *et al.* (2000, 2002a, b) also proposed the passive flap control with springs and supplementary cables. They showed the numerical result, but the experimental study was not yet shown. Shubov (2004) proposed the system with a spring-mounted aerodynamic plate. He did not show the detailed analysis.

Kobayashi and Nagaoka (1992a) investigated that the active flaps could increase the flutter speed. The flaps were driven by actuators at the same frequency as the vibrating bridge, but the phase was adjusted so that the flaps produced positive aerodynamic damping. They reported that flap motion with no phase shift from bridge motion had some stabilizing effects. The flap motion with no phase shift can be given by the mechanical driving system which is driven by the motion of the bridge deck. This means that wind-induced oscillations of a bridge deck may be controlled by a mechanical driving of flaps. This study investigates the efficiency of passive flaps (mechanically driven flap) for controlling of flutter and buffeting of a bridge deck. A flap is mechanically controlled after a pitching motion of the deck and the aerodynamic damping or suppressing aerodynamic force is produced.

2. Static considerations on the aerodynamic effects of flaps for a bridge deck

Flutter and buffeting of a bridge deck appear in relatively high wind speed. In buffeting analysis, the quasi-static aerodynamic force is sometimes allowed. In this section, the static aerodynamic controlling forces by flaps are considered. A bridge deck section in this paper is a shallow box girder and is aerodynamically treated as a flat plate. Controlling flaps at both edges of a bridge deck are also assumed to be flat plates. Thus the numerical model of the bridge deck with the controlling flaps is described as shown in Fig. 1.

By using the classical thin airfoil theory (Aderson 1984), the static aerodynamic lift L and the aerodynamic moment M are

$$L = 1/2\rho U^2(2b)[C'_L\alpha + C'_{L\beta}\beta + C'_{L\gamma}\gamma]$$
$$M = 1/2\rho U^2(2b)^2[C'_M\alpha + C'_{M\beta}\beta + C'_{M\gamma}\gamma] \tag{1}$$

In which ρ = air density, U = wind speed, α = angle of attack of the bridge deck, β = angle of the trailing edge flap and γ = angle of the leading edge flap. Coefficients are the slopes of the aerodynamic force coefficients. They are explained as follows

$$C'_L = 2\pi \quad C'_{L\beta} = 2(\theta_0 + \sin\theta_0) \quad C'_{L\gamma} = 2(-\theta_0 + \sin\theta_0)$$
$$C'_M = (1/2)\pi \quad C'_{M\beta} = -(1/2)[-\theta_0 + (1/2)\sin 2\theta_0] \quad C'_{M\gamma} = -(1/2)[-\theta_0 - (1/2)\sin 2\theta_0] \tag{2}$$

where $\theta_0 = cos^{-1}\ c$ and c indicates the location of a hinge of the flap as shown in Fig. 1.

It is assumed that the flaps are mechanically driven after the pitching displacement (torsion) of the bridge deck. The flap angles are in proportion to the magnitudes of the pitching displacement α. The proportion ratios of the leading flap and trailing flap are set equal but with opposite sign. In such a case, the flap angles are explained as follows

$$\beta = -G\alpha \qquad \gamma = G\alpha \tag{3}$$

where G is the amplification factor transmitting the bridge deck angles to the flap angles. The positive value of G gives the turning down of the leading flap and the turning up of the trailing flap by the head up rotation of the bridge deck.

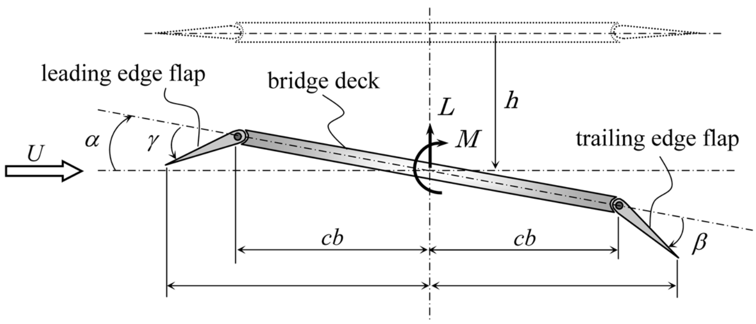


Fig. 1 A flat plate with flaps at leading and trailing edge

In these flap angles, the aerodynamic forces become

$$L = 1/2\rho U^2(2b)[C'_L\alpha + (-C'_{L\beta} + C'_{L\gamma})G\alpha]$$
$$M = 1/2\rho U^2(2b)^2[C'_M\alpha + (-C'_{M\beta} + C'_{M\gamma})G\alpha] \quad (4)$$

Let us consider the numerical example. Let us take the total deck width $2b$ = 207 mm and flap width $(1 - c)b$ = 30 mm. In this case, c = 0.71 and θ_0 = 44.8 degrees. The slops of the coefficients of aerodynamic forces become

$$C'_{L\beta} = 2.97 \quad C'_{M\beta} = 0.14 \quad C'_{L\gamma} = -0.15 \quad C'_{M\gamma} = -0.14 \quad (5)$$

Substituting these values in the aerodynamic forces, we obtain

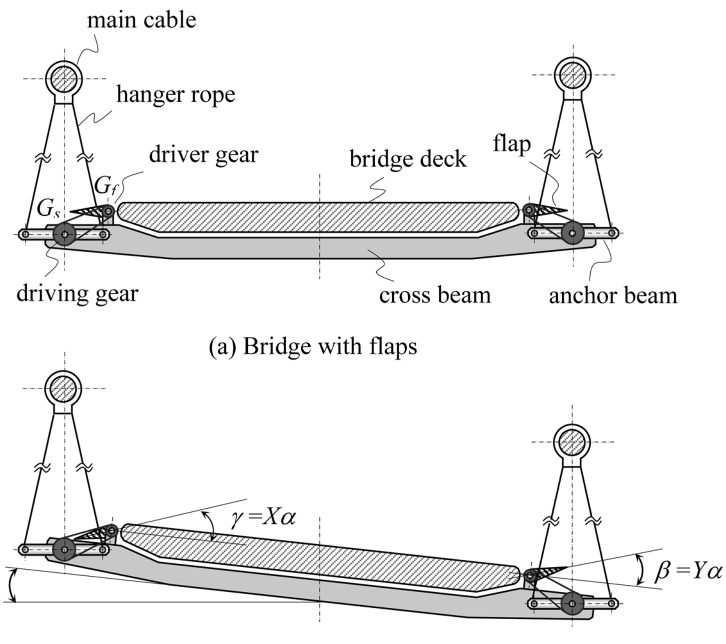
$$L = 1/2\rho U^2(2b)[(2\pi - 3.12G)\alpha]$$
$$M = 1/2\rho U^2(2b)^2[(C'_M\alpha + C - C'_M\beta + C'_{M\gamma})G\alpha] \quad (6)$$

The positive G value gives the reduction of the lift force and the aerodynamic moment. If the amplification factor G is selected as 2.0, the lift force becomes to zero. If the amplification factor G is selected as 5.6, no aerodynamic moment appears in any angle of attack of the bridge deck system. It is known that for a long-span bridge with a shallow deck, divergence phenomenon, a static aerodynamic instability, may take place in high wind speed. As the flap rotation by G = 5.6 gives no aerodynamic moment in any angle of attack and no divergence appears in the bridge deck. Of course positive smaller amplification factor than 5.6 can reduce the aerodynamic moment and help the stability of the bridge deck system in high wind. If the amplification factor G is selected as 5.6 in order to reduce the aerodynamic moment to zero, the magnitude of the induced lift by the rotation of the deck and the flaps at G = 5.6 is almost doubled compared to the case without flap angle. The lift force may have less influence for the system stability than the aerodynamic moment does. The dynamic stability is usually achieved by controlling the aerodynamic moment.

Through the mechanical driving of flaps the static torsion deformation by the aerodynamic moment is also suppressed. The possibility of suppression of the aerodynamic torsion oscillation is expected. If the torsion response is suppressed, the flutter of the bridge deck can be suppressed. The above mentioned equations are based on the flat plate theory. Applying to arbitrarily shaped bridge deck systems, the coefficients in Eq. (5) will be determined empirically.

3. Bridge deck with mechanically driven flap

In the above section the static effect of flaps whose angles are set through the deformation angle of the bridge deck were showed. If the leading edge flap is turned down and trailing edge flap is turned up when the bridge deck displaces head up, the magnitudes of the aerodynamic lift and the moment are reduced in case $0 < G < 4.0$. From this result it is expected that the flap has also the reduction effect for dynamic exciting forces. Here the bridge deck system with flaps is proposed for the purpose of control of the wind-induced oscillation.



(b) Deformation of bridge and flaps

Fig. 2 Bridge deck with mechanically driven flap

Turning the flap mechanically in proportion to the bridge deck torsion displacement is easily realized in a suspension bridge. Fig. 2 shows the bridge deck system having flaps which are mechanically driven after the rotational motion of the deck. The flap is fixed with a hinge at the longitudinal edge of the bridge deck. Two hanger cables from a main cable are fixed to an anchor beam at its ends. A cross beam of the deck system is fixed to the anchor beam with a hinge.

The gears G_s and G_f are fastened to the anchor beam and flap, respectively. Both gears are connected by a driving belt. When a bridge deck causes a torsion motion in its natural oscillation mode, hanger ropes almost keep their vertical figure. The relative rotation angle is transmitted to the rotation of the flap through the driving belt with a given amplifying factor $G = R_s/R_f$ where R_s and R_f are the radiuses of the gear G_s and G_f, respectively. Thus the flap is driven just after the pitching motion of the bridge deck mechanically.

The same mechanism of flap driving system is installed at the leeward side of the bridge deck. When the flaps are driven through the above mentioned manner, if we set the head up motion of the bridge deck as α, the turning down of leading edge flap is $\gamma = G\alpha$ and the turning up the trailing edge flap is $\beta = -G\alpha$. The same flap motions are seen when the wind direction is reversed.

Such driving system is installed at the position of every hanger cable where a flap is thought to be required for the control of bridge deck oscillation. The length of a fraction of the flap corresponds to the distance between the hanger ropes. The flaps are installed avoiding the center of the main span of suspension bridge. Because the short hanger ropes near the center of a main span of a suspension bridge rotate with the rotational motion of the bridge deck, the relative rotation angle between the anchor beam and the cross beam is difficult to be appeared.

If the different amplification factors among the leeward and the windward flaps are required, wind-detecting apparatus is used and driving mechanism is switched to the other one following the wind direction. The friction damping by the mechanism is also expected as a stabilizing effect for the aerodynamic responses.

4. Wind tunnel test

4.1 Wind tunnel model

To investigate the effects of the mechanically driven flap on the controlling of wind-induced oscillations, the two dimensional wind tunnel tests were done using a two-dimensional bridge deck model with flaps. The cross sectional shape of the model and flaps are shown in Fig. 3(a). The spring-mounting of the model is shown in Fig. 3(b). The driving system of the flaps in the wind tunnel test is different a little from the above-mentioned system in an actual bridge. The model is fixed with the hinge at H_a of the supporting frame and elastically supported by the pitching springs k_a from the frame only allowing a pitching oscillation about the hinge H_a. The frame is supported by the vertical spring k_h which allows only vertical motion of the frame including the model. The connecting rods AC and BD inhibit the sway motion and rotation of the frame. Thus the model has two degrees of freedom of oscillation, heaving and pitching.

The flap installed at the leading edge of the model has a driving arm FH_γ at its end of the rotation axis of the flap as shown in the figure. The vertical tie bar EF connects between a given point of the driving arm and the frame. The pitching motion of the flap is given by the pitching motion of the bridge deck through the driving arm. The magnitude of the turning angle and turning direction of the leading edge flap depend on the location of the tie bar EF as follows

$$\beta = Y\alpha; Y = -(cb+l_2)/l_2$$
$$\gamma = X\alpha; X = (cb+l_1)/l_1 \qquad (7)$$

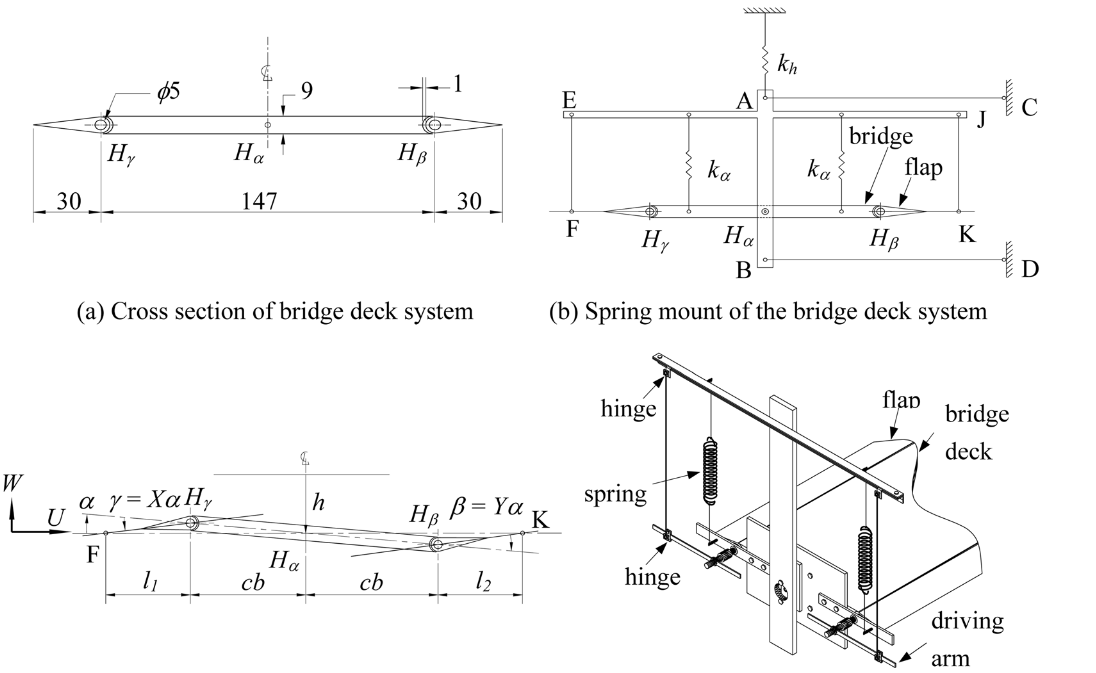
If $l_1 = l_2$ and G = $(cb+l_1)/l_1$, the controlling angles are $\beta = -G\alpha$, $\gamma = G\alpha$.

Thus the control manner as has been described in the above section is realized in this model. During a heaving motion of the model-mounted system, this driving arm does not move. The trailing edge also has the same mechanism. Fig. 3(c) explains the flap displacement when the angle of attack of the bridge deck is given. Fig. 3(d) shows the sketch of the flap driving mechanism.

The model dimensions and dynamic properties are shown in Table 1 in which the weight of the

Table 1 Model dimensions and dynamic properties

Length × Width × Depth (mm)		408 × 207 × 9
Width of flap (mm)		30
Weight (kg/m)		4.28
Moment of Inertia (kgm^2/m)		0.015
Frequency (Hz)	Heaving	1.00
	Pitching	1.25
Damping ratio	Heaving	0.005
	Pitching	0.025



(a) Cross section of bridge deck system (b) Spring mount of the bridge deck system

(c) Flap angles due to deformation of the bridge deck (d) Sketch of the flap driving mechanism

Fig. 3 Wind tunnel model

model includes the mass of the frame. The damping ratios are measured when the flaps are fixed.

Vertical wind gust is actively simulated in the Eiffel type wind tunnel based on Karman's spectrum with turbulence intensity of 5% (Kobayashi *et al.* 1992, 1994). Horizontal wind has no turbulence.

4.2 Measured static aerodynamic force coefficients by flap

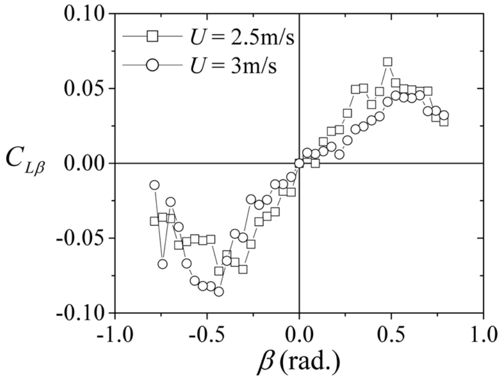
The static aerodynamic force coefficient by flap was measured in a smooth wind when the angle of attack of the bridge deck is 0 degree. The results are shown in Fig. 4. The force coefficients are almost linear among the flap angle -0.3 ~ 0.3 radians. The slopes of the coefficients (derivatives) of the lift and moment among these angles were estimated and compared with the theoretical values on flat plate. The results are shown in Table 2.

Very small lift slope is obtained from the trailing edge flap. It is assumed to be caused by the following reasons. The trailing flap is in a region of the separated flow different from the theoretical flow. In addition, the small gap between the deck and the flap also reduced the aerodynamic force by flap.

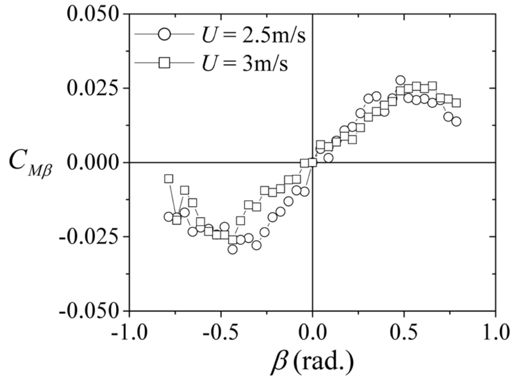
4.3 Wind-induced responses

4.3.1 Improvement of critical wind speed in a smooth flow

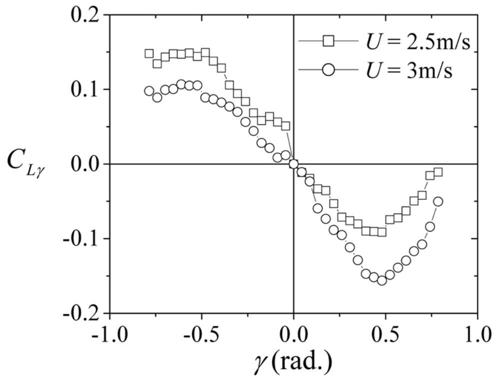
When the flaps are mechanically driven pitching frequency and damping are measured. The



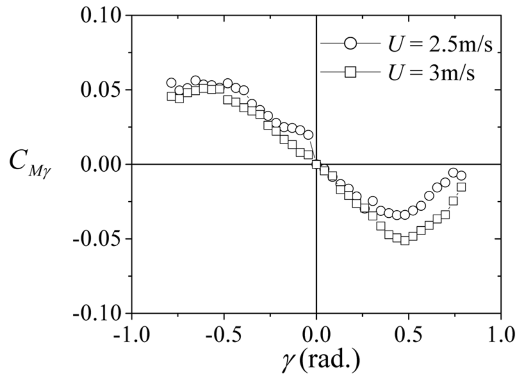
(a) Lift coefficient by trailing edge flap



(b) Moment coefficient by trailing edge flap



(c) Lift coefficient by leading edge flap



(d) Moment coefficient by leading edge flap

Fig. 4 Static aerodynamic force coefficients by flaps

Table 2 The slopes of lift and moment coefficient

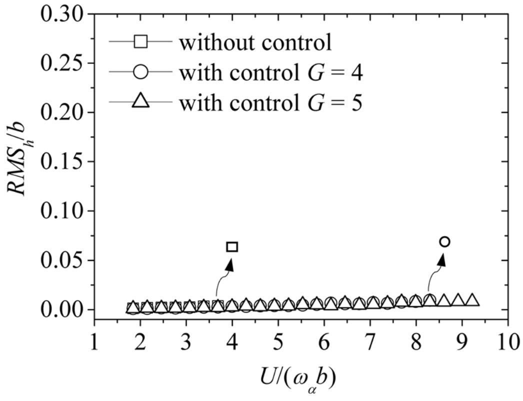
Coefficient	$C'_{L\beta}$	$C'_{M\beta}$	$C'_{L\gamma}$	$C'_{M\gamma}$
Theoretical	2.97	0.14	-0.15	-0.14
Measured	0.13	0.06	-0.31	-0.11

frequency and damping in each case of control are shown in Table 3. Compared to the case of no control, i.e., G = 0 with a damping ratio of 0.025 in pitching motion, the driving of flaps increase the pitching damping a little. Accordingly, corresponding theoretically determined flutter speed deviates about up to 10% from that of the case of G = 0.

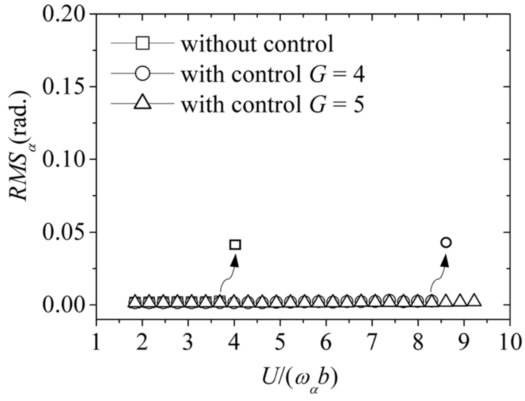
The response amplitude of the model in the smooth flow was measured. The result is shown in Fig. 5. The critical speed is defined by the wind speed at which the pitching response exceeds 10 degrees in *RMS*. The model without flap control met flutter at $U/(\omega_\alpha b)$ = 3.90. If the model was controlled with G = 4.0 the flutter speed was increased up to $U/(\omega_\alpha b)$ = 8.60. This wind speed is larger than the theoretical divergence one of $U/(\omega_\alpha b)$ = 5.74. The reduction effect of the aerodynamic moment by flap control could also suppress the divergence phenomenon. Increasing the flap motion

Table 3 Results of damping and frequency in smooth flow test

G	f_h (Hz)	f_α (Hz)	ξ_h	ξ_α
-1.4	1.00	1.33	0.0050	0.036
0	0.99	1.25	0.0047	0.025
2.3	1.01	1.26	0.0053	0.026
3.0	0.99	1.27	0.0052	0.025
4.0	0.98	1.30	0.0054	0.027
5.0	1.02	1.32	0.0048	0.029



(a) Heaving response



(b) Pitching response

Fig. 5 Response in smooth flow

to G = 5.0, flutter speed is increased more than the maximum operating speed of the wind tunnel ($U/(\omega_\alpha b)$ = 8.60).

4.3.2 Improvement of critical wind speed in a turbulent flow

The damping ratios of the model in this test were almost the same as the case in the smooth flow tests. The control effect of flap control with G = 5.0 was investigated in a turbulent flow. The results are shown in Fig. 6. The flutter motion of the model without control takes place at $U_{flt}/(\omega_\alpha b)$ = 3.69. This speed is improved to $U_{flt}/(\omega_\alpha b)$ = 6.45 by flap control with G = 5.0. Compared with the case in the smooth flow, improving effect of the critical speed in the turbulent flow was reduced. The suppression of the buffeting may be required for the high effectiveness on the critical speed. Small pitching gust response is seen in high wind speed. The flutter speed is lowered by the turbulence. The flap motion by G = -1.4 is considered to give a reversal effect for the aerodynamic response. Experimental result by the G = -1.4 in Fig. 6 shows the flutter appeared at a little lower speed compared with the case without control.

4.3.3 Suppression of gust response by passive flaps

An example of the time history of the response of the model with and without flap control in a turbulent flow is shown in Fig. 7. Wind speed is just below the flutter speed for the model without control. The gust response in heaving and pitching of the model without control was shown with the

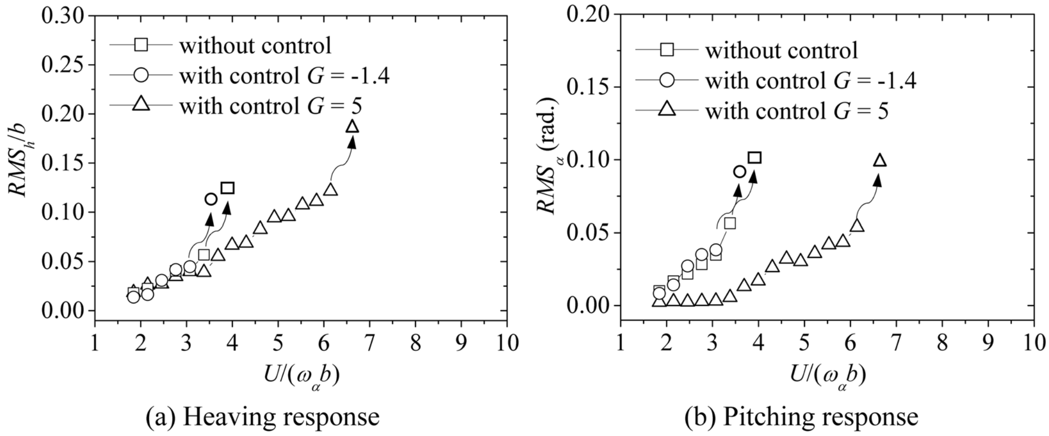


Fig. 6 Response in turbulent flow

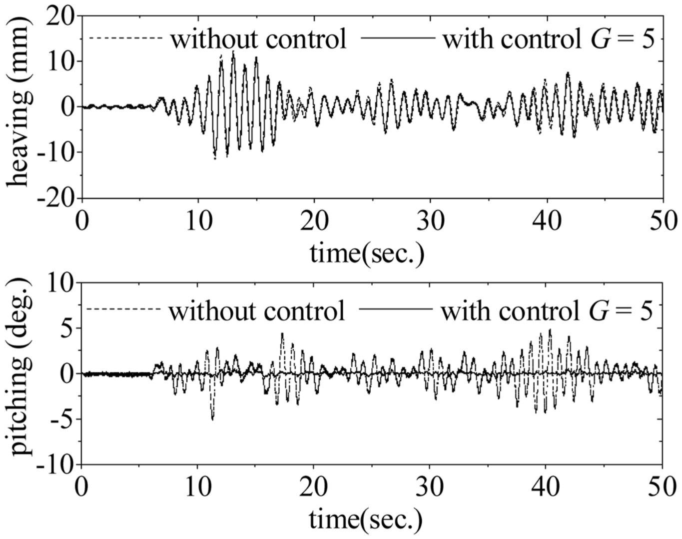


Fig. 7 Time trace, without control G = 0 and with control G = 5 at $U/(w_a b)$ = 2.76

dotted lines. If the model is controlled, the flaps are driven with the amplification factor of G = 5.0, pitching response was suppressed, however almost no effect on the heaving response is seen. As has been investigated in the static consideration, this control gives almost zero aerodynamic moment but lift force still exist. As a result, the pitching response was suppressed and heaving was not.

4.3.4. Effect of the amplification factor G on the critical speed

The critical speed was checked with different G values. The result is shown in Fig. 8. With positive amplification factor G, the critical wind speed is increased with the increase of the amplification factor. In the smooth flows, G = 5.0 gives very high critical speed. The reverse effect is observed with negative gear ratio G. The turbulence also affects on the controlling of the critical speed. Some improvements may be investigated in future.

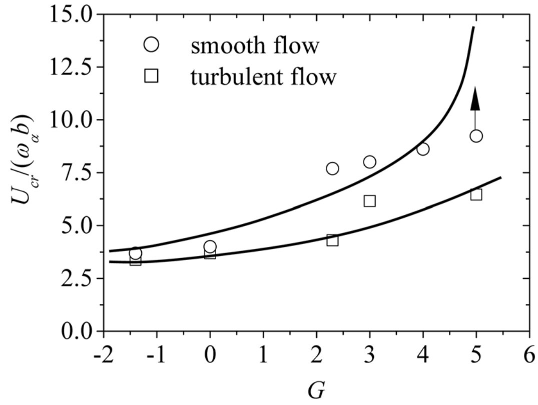


Fig. 8 Effect of G on control

5. Conclusions

In order to suppress the wind-induced motion of a bridge, a bridge deck with mechanically driven flaps were proposed. Flaps are turned mechanically their angles in proportion to the pitching angle of the bridge deck. The driving system of the flap is easily installed in a suspension bridge. Experiments on flutter and buffeting control of bridge deck by flaps were performed. The following results were found:

a. The mechanical control by flaps with $\beta = -G\alpha$, $\gamma = G\alpha$ by G = 5.0 in a smooth flow improved the flutter speed above 2.5 times (the maximal workable wind speed of the wind tunnel) and suppressed the divergence phenomenon up to its wind speed.

b. In a turbulent flow, control by G = 5.0 also improved the flutter speed about 2 times and suppressed the divergence phenomenon up to its wind speed. Buffeting in pitching motion was effectively suppressed but heaving motion was not.

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