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Suppression of bridge flutter by passive aerodynamic control method

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교량 플러터의 공기역학적 수동제어

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Abstract

In this study, a new passive aerodynamic control method is proposed. Control plate which is oscillated by TMD-like mechanism makes flutter stabilizing airflow. Effectiveness of proposed model is verified by experimental and analytical study. In addition, various parameters of the proposed system are investigated. Applicability to long span bridge is also examined. According to the research results, proposed model is very effective in suppressing flutter, and it also shows remarkable robustness.

1. INTRODUCTION

In general, wings or control plates have been used in aerodynamic control of bridge flutter. Most of aerodynamic control methods upto nowe are active, while a few of them are passive. Passive aerodynamic control of bridge flutter is more attractive in practical point of view.

Wilde et al.[1] successfully translated their active model to passive one. However, the controller is still difficult to implement to real bridges because, for successful control, it needs either a pendulum with extremely heavy mass, a long natural period and large damping, or a pendulum that is tuned for very narrow frequency range. On the other hand, Preidikman and Mook [2] conducted research on similar model to Wilde's, yet it is limited to theoretical works.

In this study, a new passive aerodynamic control method for bridge flutter is proposed. The method uses TMD mechanism in order to activate the control plates, which modify airflow around the deck section. Wind tunnel test is performed to verify the effectiveness of the controller and to measure unsteady aerodynamic forces required in analysis. Equation of motion for the proposed system is derived. The section equipped with controller is analyzed for various cases to examine applicability to real structures. Finally, this study will apply the proposed controller to a long span suspension bridge and will investigate its effectiveness.

2. PRESENT METHOD

Flutter occurs due to interactions between structure and wind. The basic idea of aerodynamic flutter control is to modify wind forces itself rather then to increase structural stiffness or damping. In this study, a new passive aerodynamic controller is designed to activate control plates properly according to the motion of bridge deck without external power supply.

Sato et al. [3] experimentally studied the active aerodynamic control system which made three slits on the flange of deck, and small plates controlled by each separated servo motors oscillate through those slits. What is noticeable in Sato et al.'s study is that the amplitude of control plate displacement gives little effect on flutter velocity. One of the successful control patterns in Sato's study can be applicable to present passive control system.

Figure 1 shows mechanism of the proposed passive aerodynamic control method in this study. Key idea of this system is to properly activate the control plates according to the bridge deck motion. Constant phase angle between the control plate and deck motion should be kept for successful control. The followings are brief description of actual mechanism of this system. There are two slits on bottom flange of deck, and the control plates oscillate through those slits. When the bridge deck keeps horizontal state, control plates do not move and keep its equilibrium position. But when the deck is oscillated by wind, control plates move up or down according to motion of the deck, and it changes airflow. Seesaw-like rod inside the deck activates control plates. Its mechanism is similar to TMD. Phase

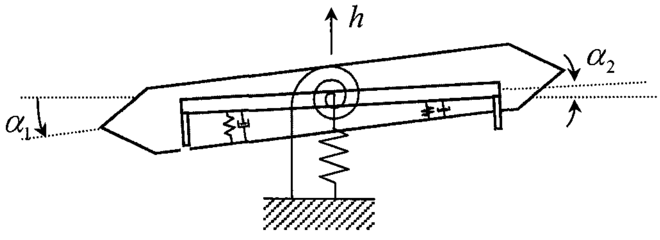

Figure 1: Control mechanism of the proposed system

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angle between deck and control plate can be adjusted by mass and stiffness of the rod. Because the inertia force of TMD is not used for direct vibration control but for moving control plates in order to make aerodynamic control effect, the mass ratio of this system can be greatly reduced in comparison with traditional TMD for structural control. This is one of the great advantages of the proposed system.

3. ROBUSTNESS OF THE SYSTEM

Structural properties of controller, stiffness and damping, can be changed from its design value during installation or operation, and such change affect the control performance of the system. Especially frequency ratio between controller and deck is strongly affected by changing the stiffness of controller. Therefore robustness for variation of structural properties should be investigated.

As shown in Figure 1, bridge deck section with controller (seesaw-like rod and control plates) can be modeled as three degrees of freedom system. Vertical and torsional displacements of the deck section are indicated as h and α_1 respectively, and torsional displacement of the controller is α_2. The equation of motion for free vibration of the proposed system can be easily derived.

For the proposed system, phase angle between α_1 and α_2 under harmonic excitation can be derived from the equation of motion for free vibration. The derived equation of phase angle is

$$\theta = \arg\{r^4 - r^2 + (2\zeta_2 r)^2 + i(2\zeta_2 r)\} \tag{1}$$

where, r : frequency ratio between controller and deck, $_2$: damping ratio of controller.

According to the Sato's experiment on active control [3], phase angle between deck and control plate should be ranged from 90° to 270° for successful control. That is, present passive aerodynamic control system operates properly only if phase angle is ranged between 90° and 270°. To make effective phase angle, mass and stiffness of controller should be properly tuned to that of bridge deck.

Using Equation (1), phase angles of the proposed system are evaluated according to various frequency ratio and damping ratio of controller. The result is shown at Figure 2. Grey area represents controllable region. Since the proposed system is controllable only if frequency of the controller is smaller than that of deck, the system can be easily designed. Furthermore phase angle of the proposed system is not altered even though frequency and damping of the controller are greatly changed during operation. Therefore it can be said that the proposed system has strong robustness for variation of structural properties.

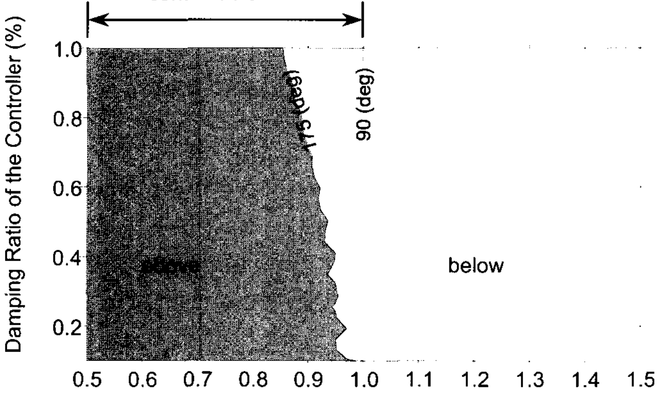

Figure 2: Contour of phase angle for various frequency ratio and damping ratio of controller

3. AEROELASTIC ANAYSIS OF BRIDGE FLUTTER

It is assumed that aerodynamic effects by the control plates are included in the measured unsteady aerodynamic forces of deck because the aerodynamic forces generated by control plates can not be separated from those of deck. Therefore controller is coupled with deck structurally, not aerodynamically.

In this study, multi mode flutter analysis [4] is used. The displacements can be expressed by summation of finite number of modes. Since the aerodynamic forces are velocity and displacement dependent, aerodynamic force at i^{th} mode can not be decoupled for each mode. Therefore off-diagonal terms in the aerodynamic force matrix will not vanish. By rearranging velocity dependent terms and displacement dependent terms, and then rewriting in matrix form, final equation of motion for flutter is obtained as follows.

$$\mathbf{M\ddot{u}} + \mathbf{C\dot{u}} + \mathbf{Ku} = \mathbf{A_C\dot{u}} + \mathbf{A_K u} \tag{2}$$

where **M**, **C**, **K** are diagonalized mass, damping and stiffness matrix, and $\mathbf{A_C}$, $\mathbf{A_K}$ are velocity and displacement dependent aerodynamic force matrix respectively.

In solving the complex eigenvalue problems in Equation (2), *p-K* method, numerical method for tracing the eigenvalue of each mode, is used. In addition, variable-step size algorithm is added to *p-K* method in order to correctly trace the path and to enhance accuracy. Damping ratio and frequency can be calculated from the solution. After calculating solutions up to certain velocity ranges, we can get flutter onset velocity by finding the velocity where the sign of damping ratio changes.

5. EXPERIMENTAL VERIFICATIONS

Figure 3 shows detailed dimension of the model used in experiment. Two control plates that oscillate through slits in bottom flange are supported by Seesaw-like rod. Spring mount was designed movable to adjust the frequency of the controller. The slits were sealed with thin film when control plates were not used. Frequency ratio of controller to deck was 0.845. Maximum outer displacement of control plate

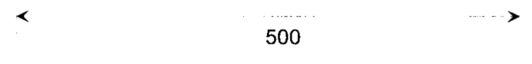

Figure 3: Model for wind tunnel test

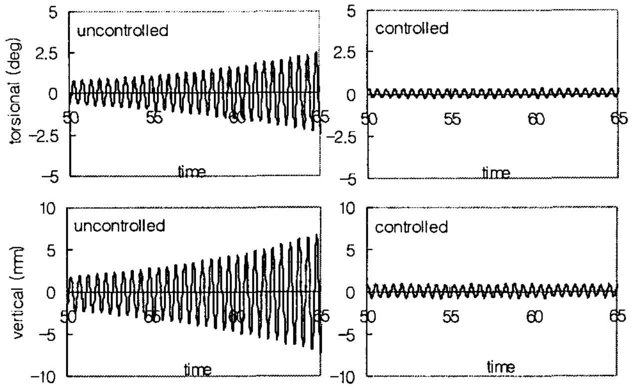

Figure 4: Uncontrolled and controlled time response (smooth flow, U/fB = 6.57)

from bottom flange of deck was limited to 10mm.

Two kinds of experiment were performed. The first one was test for response measurement. Time series response of deck and control plate was measured by varying wind speed. The second one was test for pressure measurement. For measuring pressure, 36 pressure holes were made on the upper and bottom flange of deck. The pressures were measured while the deck was under sinusoidal motion driven by external motor

Table 1: Measured flutter onset velocity

flow	attack angle	w/o (U/fB)	w control (U/fB)
Smooth	0°	6.5	< 9.3: stable control > 9.3: with impact (upto 10.7)
	+3°	5.9	6.9
	-3°		7.5
Turbulent	0°	6.4	7.9 (experiment limit)

In the response measurement test, torsion-dominant flutter occurred in uncontrolled model but coupled flutter occurred in controlled model. Test results are summarized in Table 1. The uncontrolled non-dimensional flutter velocity was 6.5, yet controlled one was increased to more than 10.7. Increase ratio of flutter velocity was 64.6%. The non-dimensional velocity of the experiment was limited to 10.7 because of safety of model. Stable control was obtained until non-dimensional velocity 9.3, and control with irregular impact of the controller was recorded from 9.3 to 10.7(experiment limit).

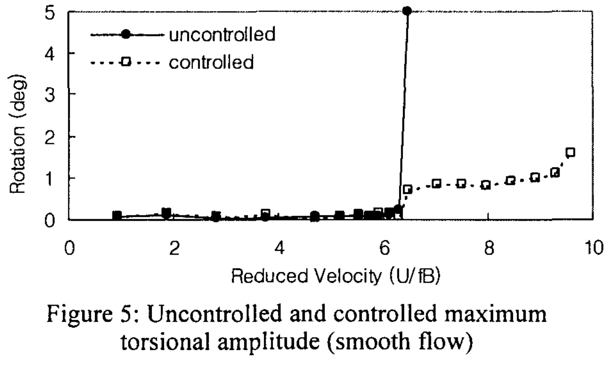

Figure 5: Uncontrolled and controlled maximum torsional amplitude (smooth flow)

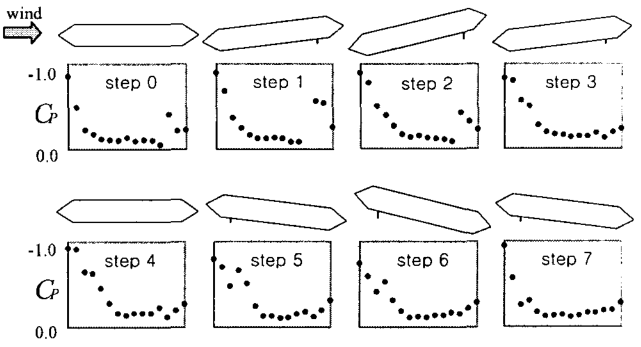

Figure 6: Pressure coefficient of bottom flange at controlled case (U/fB = 9.39)

Control effects of the proposed system can be found in Figures 4 and 5. Figure 4 shows uncontrolled and controlled time response under smooth flow at non-dimensional velocity 6.57. While deck displacement diverged in uncontrolled case, the displacement was limited to constant in controlled case. Figure 5 shows uncontrolled and controlled maximum torsional responses under smooth flow.

Distribution of measured pressure coefficient on the bottom flange of the deck during one cycle of torsional vibration is given in Figure 6. Whereas pressure coefficients of upper flange keep almost constant, those of bottom flange vary with rotating deck. Flutter derivatives are calculated from the measured pressure.

6. COMPARISON OF RESULTS

Table 2 summarizes the experimental and analytical results. Analytical prediction shows good agreement with experimental study. Discrepancy between experimental and analytical result at high mass ratio is mainly due to the limitation of experiment.

Table 2: Comparison of experimental and analytical results

	mass ratio	w/o (U/fB)	TMD only		TMD + control plate	
			U/fB	increase	U/fB	increase
Exp.	4.5%	6.5	8.9	36.9%	> 9.3 (10.7)	> 43.1% (64.6%)
Anal.	4.5%	6.85	9.01	31.5%	14.08	105.5%
	1.0%		7.79	13.7%	13.33	94.6%
	0.1%		7.04	2.8%	11.08	61.8%
	0.0%		-	-	10.89	59.0%

It is also revealed in Table 2 that control is mainly done by aerodynamic effect. When control plates are attached, control performance is noticeably high in comparison with TMD only control. Even though the mass ratio of controller is as small as 0.1%, the increase of flutter velocity is as much as 61.8%. Therefore the mass of TMD can be minimized only to operate the control plates.

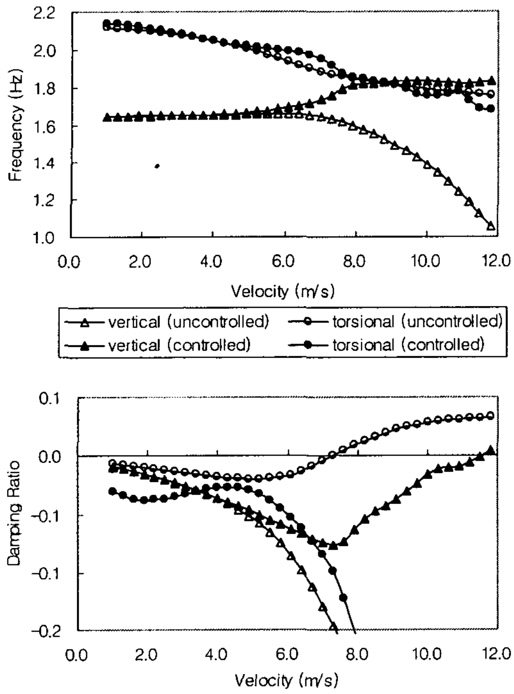

Figure 7: Frequencies and damping ratios of bridge According to wind velocity

7. APPLICABILITY TO LONG SPAN BRIDGES

For studying applicability of the proposed system to long span bridge, a long span suspension bridge is adopted as numerical example. Center span length of the bridge is 3000m, and side span length is 1000m each. Width of the deck is assumed as 30m.

Figure 8 shows improvement of flutter velocity with respect to the change of controlled length in center span. The controller is assumed to be installed from middle of center span. Flutter onset velocity increases 51% when 60% of center span equips controller.

8. CONCLUDING REMARKS

According to the experimental and analytical study, the proposed controller is very effective in suppressing flutter. Since control of the proposed system is mainly done by aerodynamic effect, the system can be operative with relatively much lower mass ratio in comparison with traditional TMD. The proposed system shows remarkable robustness for variation of structural properties because the system is controllable only if frequency of controller is smaller than that of deck. The proposed passive controller not only compensates the defects of active controller, but also shows good control performance. It can be used as an effective control method for bridge flutter.

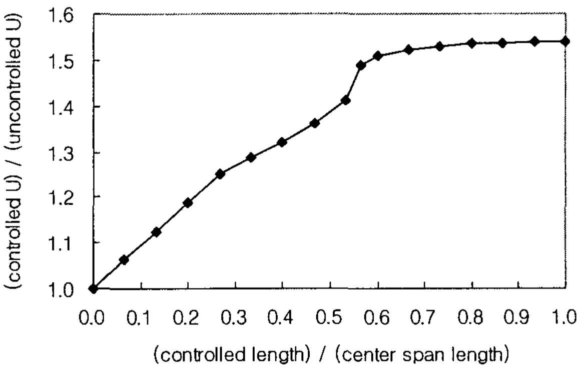

Figure 8: Improvement of flutter velocity with respect to controlled portion in suspension bridge

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