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The new flutter derivatives extraction system for considering the coupled force

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ABSTRACT

The flutter derivatives used for aeroelastic analysis are generally extracted by free or forced vibration methods. However, the free vibration method has the problem that the length of the vibration signal becomes shorter as the wind speed increases. The bridge section model moves only with a prescribed motion in the forced vibration method, so fluid-structure interaction cannot be considered. A new excitation system was developed and verified to solve these problems. By periodically applying sinusoidal force to the system, it was possible to solve the current problems. In this paper, the new method was verified through wind tunnel tests. An aeroelastic test using the new method was performed for a rectangular section (width/depth ratio = 20).

1. INTRODUCTION

The flutter derivatives are used for the aeroelastic analysis of long-span bridges. Coefficients are generally extracted by the experimental method. Free or forced vibration methods are commonly utilized. However, these two methods have some limitations. The free vibration method has the problem that the length of the vibration signal becomes shorter as the wind speed increases. In the forced vibration method, the bridge section model moves only with a prescribed motion. Therefore, fluid-structure interaction cannot be considered. A new extraction system, named force-controlled excitation system, was developed to solve these problems. By periodically applying sinusoidal force to the spring supporting system, it was possible to solve the signal length problem and consider the structure-fluid interaction. In addition, it is possible to extract the flutter derivatives in the steady-state state assumed by Scanlan (1978). In this paper, the new method was verified through wind tunnel tests. An aeroelastic test was performed with a rectangular section (width/depth ratio = 20).

2. Proposed Force-Controlled Excitation (FCE) system for Bridge Deck-Section

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Models

2.1 Concept of FCE

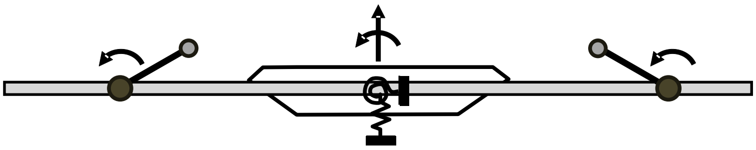

Fig. 1 Basic sketch of FCE system

The FCE system mounts a bridge section model using a spring supporting system and applies a sinusoidal force to the system to move in a steady-state state. Using the spring supporting system makes it possible to move in two degrees of freedom caused by interaction. Four rotary motor and pendulum devices are used to apply a sinusoidal force to the system, as shown in Fig. 1. The amount of force applied can be adjusted by adjusting the pendulum's rotation frequency, weight, and installation position.

2.2 Analysis Procedure

The sectoral shape was selected as the shape of the pendulum, as shown in Fig. 2. As the sectoral pendulum rotates, a force is applied to the system in the direction of the red arrow in Fig. 2.

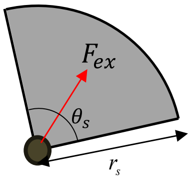

Fig. 2 The shape of the selected pendulum for the MCE system

To excite the system in the vertical direction, sectoral pendulums are initially set in the same position and rotated in opposite directions. In that case, only the vertical force remains as in Eq. (1).

$$L_{ex}(t) = \frac{16}{3} m_s r_s \frac{sin(\theta_s/2)}{\theta_s} \omega_{ex}^2 \, cos(\omega_{ex} t) \tag{1}$$

where, L_{ex} = excitation lift force, m_s = mass of each pendulum, r_s = radius of the pendulum, ω_{ex}= excitation angular frequency

Rotational excitation is possible if the pendulums have a phase difference of 180 degrees and rotate in the same direction. Only moment force remains as in Eq. (2).

$$M_{ex}(t) = -\frac{16}{3} m_s r_s \frac{sin(\theta_s/2)}{\theta_s} \omega_{ex}^2 \, cos(\omega_{ex} t) r_{mor} \tag{2}$$

where, M_{ex}= excitation moment force, r_{mor}= the distance between the center of the system and motor

The flutter derivatives can be obtained from the system's response that changes according to the wind speed if the excitation force applid to the system can be accurately calculated. The equation of motion in this system can be expressed as Eq. (3). The right side of Eq. (3) can be composed of the applied force($\mathbf{F_{ex}}$) and the wind force ($\mathbf{F_{ae}}$).

$$\mathbf{M}\ddot{\mathbf{X}} + \mathbf{C}\dot{\mathbf{X}} + \mathbf{K}\mathbf{X} = \mathbf{F_{ae}} + \mathbf{F_{ex}} \tag{3}$$

where, $\mathbf{M}, \mathbf{C}, \mathbf{K}$= mass, damping, and stiffness matrices of the target bridge system, respectively, $\mathbf{X}, \dot{\mathbf{X}}, \ddot{\mathbf{X}}$ = the displacement, velocity, and acceleration vectors of the system

The equation error estimation (EEE) method is utilized for identifying the system's mass, damping, and stiffness matrix through the experiment in the no-wind state. For using the EEE method, four accelerations are installed in the FCE system, and the velocity and displacement data are reconstructed based on acceleration information. The same procedure is repeated in the wind state to calculate the differences in the damping and stiffness matrices. Flutter derivatives are extracted from these differences.

3. Validation of FCE system through wind tunnel tests

3.1 Target model

A rectangular section with a width/depth ratio of 20 (BD20) was selected as the target bridge model to verify the FCE system. The reason for choosing BD20 is that Matsumoto (1993)'s study showed that constant flutter derivatives were extracted regardless of the vibration mode. Therefore, it is possible to compare and verify the flutter derivatives extracted by the FCE system with the results of the existing literature. The dynamic properties used in the experiment are shown in Table 1. The specifications of the used fan-shaped pendulum are as follows; mass = 0.102 kg, radius = 9 cm, central angle = 30 degrees.

Table 1. Dynamic properties of BD20

Length	0.9 m
Width	0.3 m
Mass	8.2 kg/m
Mass moment of inertia	0.194 kg·m^2/m
Natural vertical frequency	2.6 Hz
Natural torsional frequency	4.2 Hz

3.2 Test results

The wind tunnel experiments were conducted by excitation in vertical and torsional directions using the FCE system. The excitation frequency of pendulums was fixed at 3Hz. Although the excitation force was 1DOF, the system’ response was 2DOF due to the coupled force. For example, vertical amplitude occurs in the rotational excitation, as shown in Fig. 3(a).

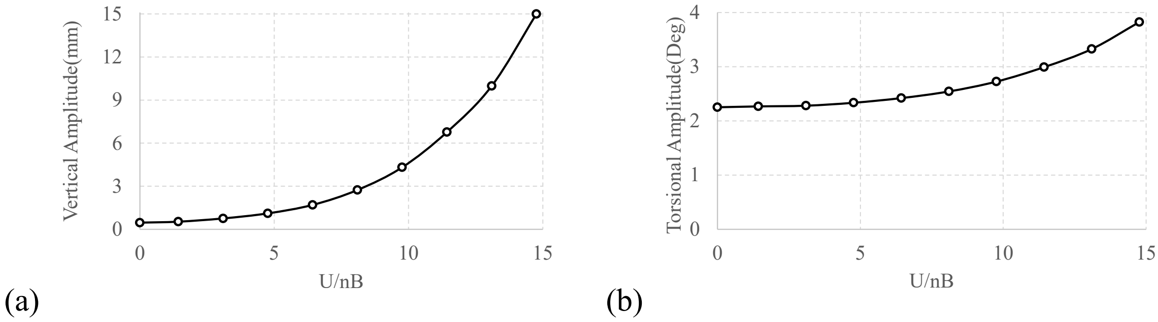

Fig. 3 Measured displacement amplitude according to the reduced velocity in the rotational excitation; (a) vertical direction (b) torsional direction

The flutter derivatives can be obtained from the change in displacement amplitude and the phase difference between excitation force and displacement. Among the coefficients obtained in the experiment, the A_2 and H_1 were compared with the results of Kyoto University in Fig. 4. It can be seen that the trend and magnitude of values agree well.

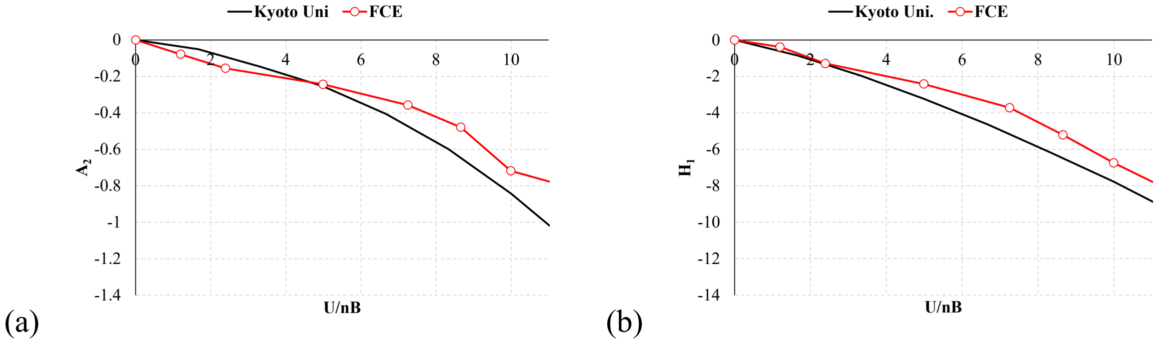

Fig. 4 Comparison of flutter derivatives; (a) A_2 (b) H_1

4. Conclusion

The FCE system that can extract flutter derivatives by maintaining a steady-state state without constraining the system's displacement was developed to consider the fluid-structure interaction. The system was verified through a wind tunnel experiment using a BD20 section model. As a further study, it is necessary to conduct an FCE experiment on a bridge section model where a lot of coupled force occurs due to interaction to see the difference with the flutter derivatives extracted from the existing equipment.

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