ICWE 16
August 27-31, 2023
FLORENCE - ITALY
16th International
Conference on
Wind Engineering

Coupled Flutter Investigation of a Flexible Suspended Footbridge

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SUMMARY:
Flexible suspended footbridges are relatively more vulnerable to flutter than suspension road bridges due to their lightweight, flexible, and slender structural features. A precise investigation of the flutter characteristics is necessary to ensure proper flutter stability of the flexible suspended footbridge. The flutter behavior and mechanism of the flexible suspended footbridge were verified via wind tunnel tests and time-domain analyses on a solid deck section where flutter occurred. It was deduced that the decrease of torsional damping due to the torsional-driven vertical vibration and coupled aeroelastic force induced the torsional flutter.

Keywords: flexible suspended footbridge, coupled flutter mechanism

1. GENERAL INSTRUCTIONS

Flexible suspended footbridges mainly rely on cables supporting the segmented narrow deck along the bridge. The flexible suspended footbridges are intentionally designed with low stiffness and damping ratios to cause a certain level of vibration for the enthusiasm of pedestrians. For this reason, the flexible suspended footbridges are susceptible to significant vibrations by dynamic loads (Jiménez-Alonso et al., 2016). Accordingly, flutter instability becomes one of the issues in the design of the structure (Li and Li, 2020).

This study investigated the mechanism of flutter instability for a flexible suspended footbridge with a solid deck. A series of vibration tests were conducted to investigate the occurrence of coupled flutter and its characteristics. The time-domain aeroelastic analysis based on Fourier series approximation was implemented to demonstrate the coupled-flutter-prone mechanism observed in the 2D wind tunnel tests.

2. EXPERIMENTAL INVESTIGATION

A prototype bridge was chosen to investigate the aerodynamic characteristics of the flexible suspended footbridge. The bridge is flexibly suspended by a series of cables with a span length of 303 m with a deck width of 1.85 m, resulting in a span-to-width ratio of 164.

Aerodynamic sectional model tests were performed in an open-circuit Eiffel-type wind tunnel at

Seoul National University, South Korea. The geometric scale of the tested section model was determined as 1/12. The section model had a width of 0.154 m, a height of 0.15 m, and a length of 0.9 m. Figure 1 shows the plan view of the solid deck section models. The model was elastically suspended using four linear springs and a bracket that could simulate 2 DOF motions. The section model test was performed at a wind attack angle of $0°$ under uniform flow conditions. The dynamic parameters applied to the vibration test are as follows: m=3.642 kg/m, I=0.048 kg·m^2/m, f_h=1.885 Hz, f_α=3.077 Hz, ξ_h=0.250 %, ξ_α=0.175 %.

Figure 2 shows the maximum displacements during the measured time of 60 seconds for each tested wind speed on a prototype scale. The maximum responses increased slightly as the wind speed increased to 15.2 m/s, but they increased sharply from the next testing speed of 16.4 m/s. The dominant frequency of the vertical motion suddenly shifted to the torsional motion frequency, as shown in Figure 3. The dominant frequencies for each DOF were identified by the fast Fourier transform (FFT) of response time histories at each tested wind speed. Notably, the apparent shift of vertical motion from its origin to torsional frequency demonstrates the torsional mode-driven coupled flutter behavior.

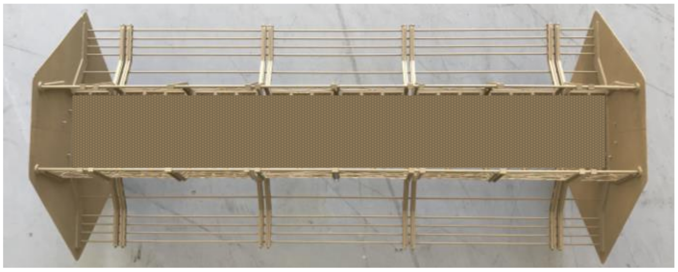

Figure 1. Plane view of section model (solid deck)

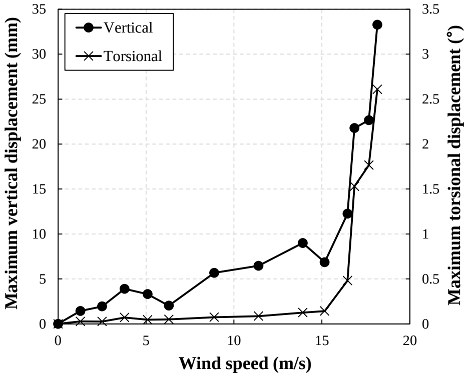

Figure 2. Maximum vertical and torsional displacement

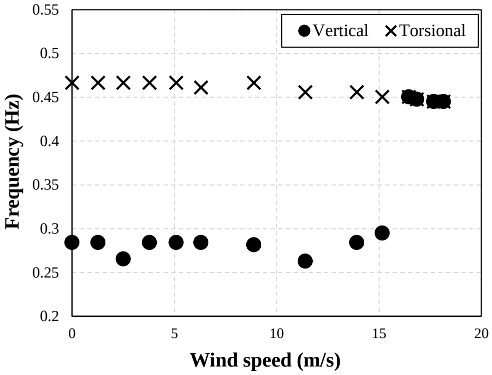

Figure 3. Dominant motion frequencies for each DOF

3. ANALYTICAL INVESTIGATION OF TEMPORAL FLUTTER BEHAVIOR

2DOF time-domain analysis was performed based on the same dynamic properties to investigate the mechanism by which the dominant frequency transits from f_h to f_α in the vertical motion and the process of generating the initial vibration at the flutter wind speed, which is difficult to observe in the experiment, was investigated through time-domain analysis. Truncated Fourier series approximation (Park et al., 2014), which approximates the transfer function with Fourier series to satisfy the causality condition, was used for time-domain analysis. Based on linearized forms of the aerodynamic lift and moment equation defined by Simiu and Scanlan (1996), the flutter derivatives extracted from the experiment were used for analysis.

The flutter wind speed was compared for cross-validation of the experimental and time domain analysis results. Analysis was performed by giving initial displacements of 1 mm and 0.01 degrees. As a result of the time domain analysis, the coupled flutter was predicted to occur at 16.5 m/s, which is similar to the flutter wind speed (16.4 m/s) observed in the experiment. Since the flutter phenomenon was consistent in the two methods, it was determined that the flutter phenomenon observed in the experiment could be sufficiently explained through time-domain analysis.

Figure 4 (a) shows the vertical and torsional vibration signals at the flutter wind speed(16.5 m/s). The vertical vibration of the f_h components(0.283 Hz) gradually damped out in the initial 15 seconds. After that, the vertical vibration of the f_α component(0.446 Hz) was continuously generated. The occurrence of this vibration pattern can be explained by self-excited lift force. The self-excited lift force drawn in Figure 4 (b) was classified into the direct force and the coupled force. Here, the direct force means the lift force caused by vertical motion, and the coupled force means the lift force caused by torsional motion. The direct force gradually decreased, whereas the coupled force continuously increased. This is a chain action caused by a large torsional vibration. The large torsional vibration made a significant self-excited lift force of the natural torsional frequency component, which caused vertical vibration of the natural torsional frequency component. Due to this positive feedback phenomenon, coupled flutter eventually occurred.

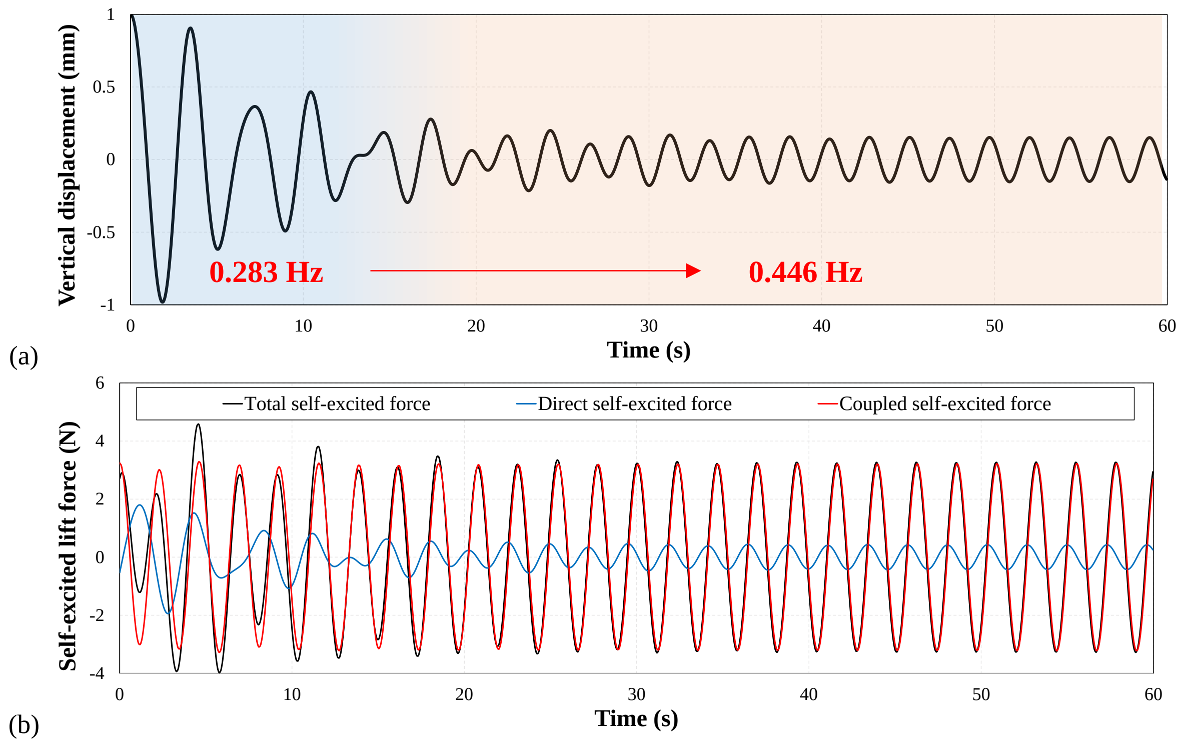

Figure 4. Time histories (U = 16.5 m/s) of: (a) vertical displacement; (b) self-excited lift force

4. CONCLUSIONS

Torsional-induced vertical vibration by the aeroelastic coupling effect was the leading cause of coupled flutter occurrence of the flexible suspended footbridge. Since the aeroelastic coupled force dominated the self-excited lift force as the wind speed increased, the vertical vibration also oscillated with the torsional natural frequency. Based on these results, torsional vibration should be suppressed first to suppress this type of coupled flutter.

ACKNOWLEDGEMENTS

This research was conducted with financial support from Ulsan City and the Korea Agency for Infrastructure Technology Advancement (KAIA) grant funded by the Ministry of Land, Infrastructure and Transport (Grant RS-2023-00250727) through the Institute of Construction and Environmental Engineering at Seoul National University and technical support from CABLEBRIDGE

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