Sectional Pressure Tests of a Twin-deck Bridge:
Part 1: Experimental Techniques and Effects of Angle of Wind Incidence

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Abstract. Simultaneous pressure measurements of 448 channels were conducted on a stationary deck section model of a twin-deck bridge. Bridges featuring a twin-deck structure have a high potential to be widely employed in future super long-span bridges. The current research was divided into two core parts and experiments were carried out in a smooth flow and a turbulent flow. In Part 1 of this study, information of the section model and experimental techniques are discussed in detail and the effects of angle of wind incidence on the deck of design configuration are analyzed. In Part 2, the effects of different gap-widths of the twin-deck configuration on the aerodynamic performances of the bridge are investigated.
Keywords: aerodynamic forces; cable-stayed bridge; force correlation; pressure distribution; pressure measurement; twin-deck;

1. Introduction

Long-span suspension and cable-stayed bridges are susceptible to vibrations induced by the natural wind. One of the essential requirements of modern bridge design is to avoid significant levels of wind-induced vibrations. There are several mechanisms, in various wind speed ranges, which can cause significant oscillation of the deck of long-span bridges. Therefore, it is very important for engineers to fully understand the wind effects on the bridge deck. In this study, the bare deck design configuration of a twin-deck bridge was used to investigate the fundamental flow excitation mechanisms. The effects of angle of wind incidence on the mean and fluctuating pressure distribution, and the aerodynamic forces and moment were analyzed. The corresponding span-wise correlation was also analyzed to compare with the structure of the approach wind.

2. Wind Tunnel Experiments

2.1. Stationary Section Model

The section model of the twin-deck bridge simulated the two side-by-side carriageways linked together by reinforced concrete cross-girders at 18m intervals across the 14.3m gap separating the decks. The corresponding combined deck width and height are 53.3m and 3.5m, respectively. Rigid model pressure tests were carried out using a section model in the high-speed test section of the CLP Power Wind/Wave Tunnel Facility at The Hong Kong University of Science and Technology. A 3m long rigid model with length scale of 1:80 was used to simulate the aerodynamic geometry of the bridge. The section model was stiffened by sets of guy-wires located at appropriate positions along the deck span and supported by end-plates at the ends for angle adjustment. The natural frequency of the section model was approximately 80 Hz and the very high damping ensured negligible model vibrations during the tests. The 1m center portion of the model was installed with 7 pressure-tapped strips and each strip comprised 64 pressure taps distributed around the twin-deck. The tap locations together with the response coordinate system are shown in Figure 1. The strips were spaced at 1/8, 1/4, 1/2, 1, 2 and 4 times of the chord length (C) of a single deck, which remained a constant parameter, to investigate the span-wise correlation and coherence of the forces and the pitching moment. A total of 28 multi-channel electronic pressure scanners were utilized to measure the surface pressure of the section model, allowing simultaneous pressure measurements at 448 locations on the deck surface. The pressure taps were connected to the pressure transducers via flexible tubing. Only the bare deck configuration was considered and no aerodynamically sensitive components such as parapets, guide-vane and stay-cable anchor were installed.

The test wind speed was 15m/s and the surface pressures were measured for 21 angles of wind incidence of $\pm 10^{\circ}$ at 1° intervals. All pressure data were sampled for a period of 135 seconds at a sample rate of 400 Hz.

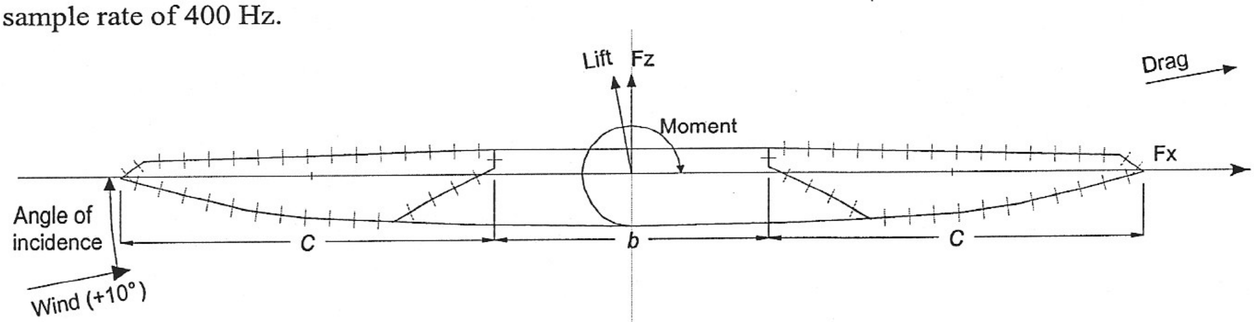


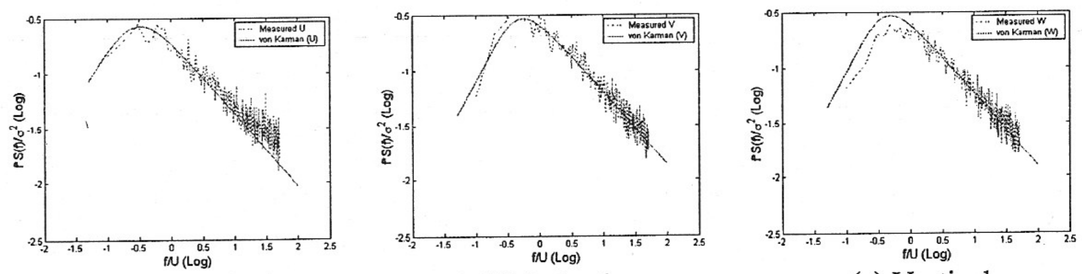
Figure 1: Positions of the pressure taps and the response coordinate system.

2.2. Flow Characteristics

The tests were conducted in a smooth flow and a turbulent flow. A TFI cobra probe, which is capable of measuring the three-components of velocity and local static pressure simultaneously, was used for the measurements of wind velocity and turbulence characteristics. Time history records were obtained for spectral analysis and correlation estimates. Correlation measurements were conducted by employing two probes simultaneously, with one probe mounted on a fixed support and the other on a traverse mechanism. The characteristics of the flow fields are summarized in Table 1. The equivalent prototype turbulence length scales were determined by fitting the von-Karman turbulence spectral models [1] as shown in Figure 2.

Table 1: Characteristics of flow fields employed.

	I_u (%)	I_v (%)	I_w (%)	L_{ux} (m)	L_{vx} (m)	L_{wx} (m)
Smooth	<1	-	-	-	-	-
Turbulence	17.4	17.9	15.6	35	15	17



(a) Longitudinal (b) Lateral (c) Vertical

Figure 2: Power spectral density of wind velocity fluctuations: (a) Longitudinal component (U); (b) Lateral component (V); (c) Vertical component (W).

3. Results and Discussions

3.1. Aerodynamic Forces and Moment

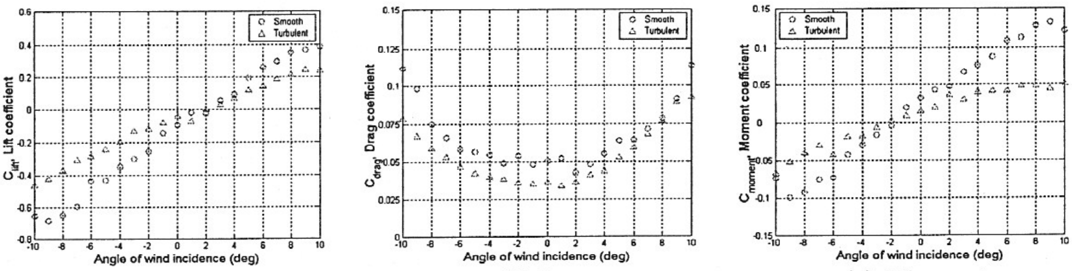
Figure 3 shows the results of the static aerodynamic coefficients as a function of the angle of wind incidence, which are defined as follows:

$$C_L = \frac{F_L}{\frac{1}{2}\rho_a U^2 B}; \qquad C_D = \frac{F_D}{\frac{1}{2}\rho_a U^2 B}; \qquad C_M = \frac{M}{\frac{1}{2}\rho_a U^2 B^2}$$

where F_L, F_D and M are the mean values of lift, drag and moment per unit length of the bridge deck respectively, calculated by spatial integration of the mean pressure distribution; ρ_a is the air-density, U is the test mean wind speed; and B is the total chord length of the deck (53.3m in prototype scale).

The magnitude of the lift, drag and moment were found to increase gradually with the angle of wind incidence, as might be expected. The smallest value of drag occurred at around 0° and its distribution with respect to the angle of wind incidence is quite symmetrical. Moreover, its magnitude in smooth flow is always larger than that in the turbulent flow, especially at large negative angles.

For the lift and moment, the slopes of the curves are positive. Generally, their magnitudes in smooth flow are larger at large angles of wind incidence.



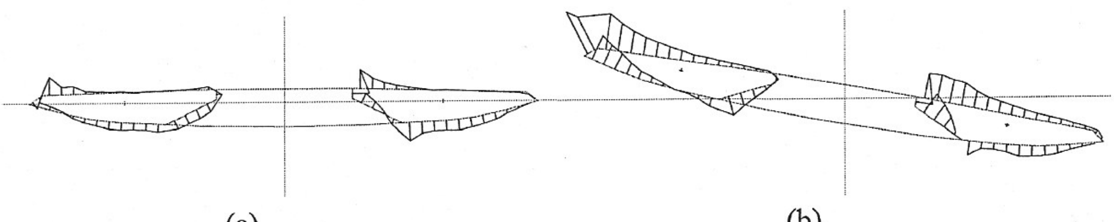
(a) Lift (b) Drag (c) Moment

Figure 3: Static aerodynamic coefficients of (a) Lift; (b) Drag; and (c) Moment of the twin-deck bridge as a function of angle of wind incidence.

3.2. Stream-wise Pressure Distribution

The distribution of the mean pressure coefficients at 0° and $+10^\circ$ is depicted in Figure 4. For the results of 0°, the flow over the top and bottom surfaces of the upstream deck appears to be largely attached flow. The resultant surface pressures are mildly negative. The non-streamlined windward portion of the downstream deck exposed to the approach wind is marked by positive surface pressures. The flow separates at the windward corner of the top surface and appears to reattach shortly afterward. The flow also separates at the transition point on the bottom surface with no apparent reattachment thereafter, where the surface pressures remained negative.

The mean pressure distribution at $+10^\circ$ characterises the increase in magnitude of the aerodynamic forces and moment when compared to that at 0°. Flow separations are evident at the leading edges of the top surfaces of both decks, as indicated by the large negative local pressures, and there is no apparent flow reattachment. Positive pressures are recorded on the bottom surfaces of both decks where they are exposed to the approach wind due to the tilt of the decks. The flow separates at the transition points on the bottom surfaces with the surface pressures remaining negative thereafter [2]. This results in an increase of the aerodynamic forces and hence the pitching moment about the rotational center. Similar phenomena occur for the negative angles of wind incidence, which also resulted in increased aerodynamic forces and moment.



(a) (b)

Figure 4: Mean pressure distribution at: (a) 0°; and (b) $+10^\circ$; in the turbulent flow (flow from left to right). The depth of the deck equals 1.0 C_p and negative pressures are away from the surface.

3.3. Span-wise Correlation of the Aerodynamic Forces and Moment

It was found that the span-wise correlations of the aerodynamic forces and moment at different angles of wind incidence are generally similar to each other, as depicted in Figure 5, indicating that the span-wise correlations are generally independent of the angle of wind incidence. A similar trend is evident in smooth flow, although the correlation in the turbulent flow is much higher. Moreover, it can be seen that the forces and moment are more correlated along the bridge span than the fluctuations of the approach wind, which was attributed to non-negligible secondary cross flows by Larose et al. in 1998 [3 & 4]. The interaction between the flow and the bridge deck, which gives rise to the flow separations and reattachment discussed in the previous section, is also believed to be responsible for the generation of the spatially correlated forces and moment. Further discussion of the correlation of span-wise forces will be given in Part 2 of this study.

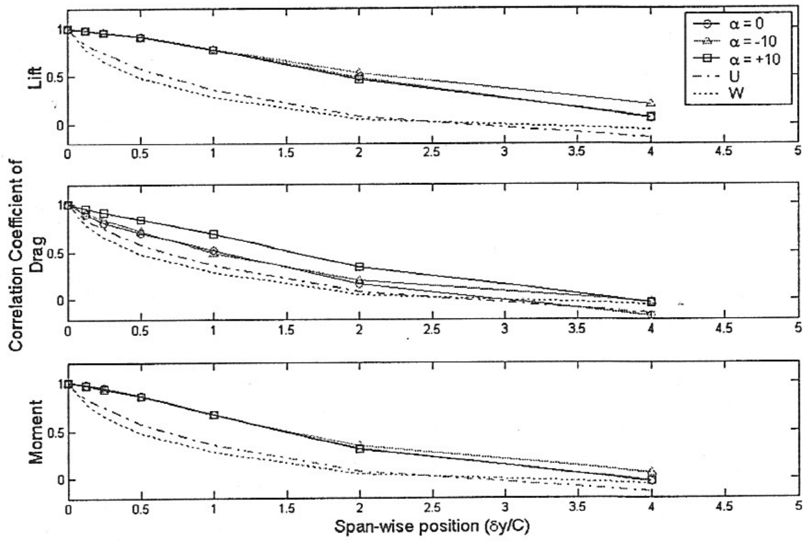


Figure 5: Span-wise correlation coefficients of the aerodynamic forces and moment (solid lines) and the wind velocity fluctuations of the U and W components (dashed lines) in the turbulent flow.

4. Conclusions

The experimental technique and results of the pressure measurements on a section model of a twin-deck bridge were presented in this paper. The tests were carried out in a smooth flow and a turbulent flow at 21 angles of wind incidence.

It was found that the magnitude of the aerodynamic forces and moment generally increased with the angle of wind incidence due to the increase in the projected area of the deck, normal to the approach flow. Furthermore, the slopes of the curves of the lift and moment coefficients are positive with respect to angle of wind incidence. The span-wise correlation coefficients of the aerodynamic forces and moment were found to be generally independent of the angles of wind incidence in both smooth and turbulent flow.

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