Effects of Gap-width on a Twin-deck Bridge: Part 1 – Vortex Shedding Excitation

*C.H. Fok[1,2)], K.C.S. Kwok[1,2)], P.A. Hitchcock[1)] and X.R. Qin[3)]
[1)] *CLP Power Wind/Wave Tunnel Facility, HKUST, H.K.S.A.R., P.R. China*
[2)] *Department of Civil Engineering, HKUST, H.K.S.A.R., P.R. China*
[3)] *Institute of Mechanical Design and Its Theory, School of Mechanical Engineering, Tongji University, Shanghai, P.R. China*

Abstract. Simultaneous pressure measurements were carried out on a rigid sectional model of a twin-deck cable-stayed bridge for five configurations with different gap-widths. Bridges featuring a twin-deck configuration have a high potential to be widely employed in future super long-span bridges (Miyata et al., 1999). The current research was divided into two parts. In Part 1, information of the sectional model and experimental techniques are discussed in detail. A comprehensive research effort was undertaken with the goal of studying the effects of gap-width on vortex shedding mechanisms of a twin-deck bridge in a nominally smooth flow. In Part 2, the effects of gap-width on the aerodynamic admittance functions are investigated.
Keywords: gap-width; long-span bridge; pressure measurement; vortex shedding; twin-deck bridge.

1. Introduction

Vortex shedding excitation is a common type of wind effect that needs to be considered when designing long-span bridges (Kobayashi et al., 1992; Kawatani et al., 1993 and 1999; Larsen et al., 2000), and it can induce significant lock-in type oscillations. It may happen at a relative low or moderate wind speed when the vortex shedding frequency is close to a natural frequency of the bridge. For long-span bridges, the nature of this phenomenon is basically governed by the aerodynamic geometry of the deck, the wind speed and the angle of wind incidence. As mentioned by Kwok (1977), Bearman and Davies (1975) suggested that this kind of wind effects is highly dependent on the shape of the afterbody and a twin-deck configuration makes the mechanisms even more complicated.

For a twin-deck bridge, the action of the discrete gusts generated from the near wake region of the upstream deck impinging onto the downstream deck is likely to significantly increase the degree of excitation (Larsen et al., 2004). This may potentially cause serious fatigue problems for various structural components and adverse perceptive effects on the bridge users. This paper aims to investigate the effects of gap-width on vortex shedding mechanisms in a nominally smooth flow. The presentation and discussion of the findings obtained from the pressure and wake flow measurements of a twin-deck bridge form the basis of this paper.

2. Wind Tunnel Tests

The sectional model of a twin-deck bridge simulated the two parallel carriageways linked together by reinforced concrete cross-girders at 18m intervals across a centre gap separating the decks. The corresponding combined deck width and depth are 53.3m and 3.5m, respectively. Rigid model pressure tests were carried out using a sectional 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 sectional 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 sectional model was approximately 80 Hz and the very high damping ensured negligible model vibrations during the tests. The central 1m portion of the model was installed with seven pressure-tapped strips and each strip comprised 64 pressure taps distributed around the twin-deck bridge. The tap locations together with the response coordinate system are shown in Fig. 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 pressures of the sectional model, allowing simultaneous pressure measurements at 448 locations on the deck surface. The wind tunnel tests presented in this paper were conducted in a nominally smooth flow and only the bare deck configuration was considered, i.e. components such as parapets, guide-vane and stay-cable anchor were not installed. Five test configurations of gap-width (b) to total chord (B) ratios of 0%, 2.5%, 16.1%, 26.8% and 35.1% were investigated. The test configurations are denoted as Gap1, Gap2, Gap3, Gap4 and Gap5, respectively.

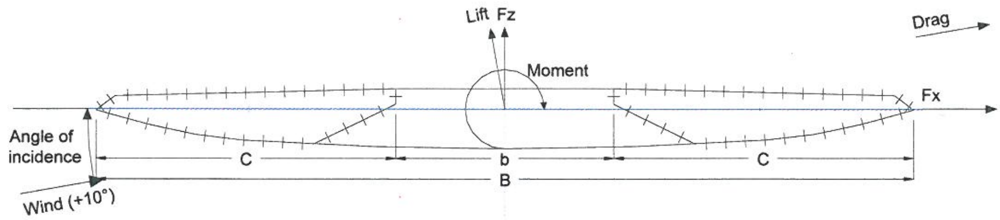

Fig. 1. Positions of the pressure taps and the response coordinate system

3. Results and Discussions

3.1. Data Verification

The oscillatory motion of a bridge can be induced by the shedding process of the vortices generated around the deck surfaces. Vortex shedding is commonly described by the non-dimensional Strouhal Number which is a function of vortex shedding frequency (f_s) and mean speed of the approaching wind flow (U), as shown in Eq. 1, where H is the depth of the deck which is equal to 3.5m in prototype scale.

$$St = \frac{f_s H}{U} \tag{1}$$

Strouhal Number for the twin-deck bridge can be determined from the spectra of either its wake flow or integrated lift force. Before proceeding, it is worth comparing the results between these two measurement techniques to verify that the spectral peak on the lift spectrum of the twin-deck bridge is associated with vortex shedding. Time histories of the wake flow were measured by mounting a Cobra probe downstream of the bridge deck at an angle of wind incidence of 0° in the smooth flow. This enabled the vortex shedding frequency to be determined from the wake flow spectrum. Fig. 2 shows a typical example of the wake spectrum of Gap4. Compared with the spectrum of the free stream flow, the spectral peak shown in the wake spectrum is evidently caused by vortex shedding which corresponds to a Strouhal Number of 0.23.

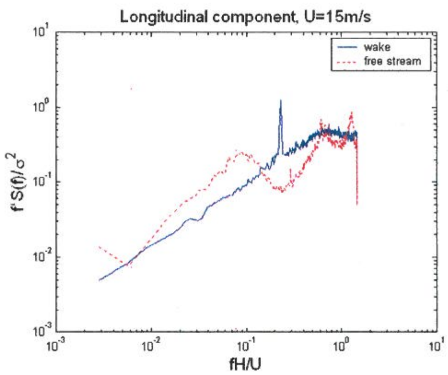

Fig. 2. Wake flow spectrum of Gap4 at 0° angle of wind incidence

In order to investigate the effects of gap-width on vortex shedding mechanisms, the normalized spectra of the lift force at 0° angle of wind incidence for each of the tested configurations are plotted against the reduced frequency, fH/U, as shown in Fig. 3. It can be seen that there are spectral peaks for test configurations (Gap2, Gap3, Gap4 and Gap5) with a centre gap, which is believed to be associated with the vortex shedding. The Strouhal Numbers of these configurations can then be determined from the corresponding reduced frequencies of the spectral peaks, which are generally consistent with those determined from the wake flow measurements, as shown in Fig. 4. This, in turn, verifies the accuracy and validity of the Strouhal Numbers determined from the peaks on the lift spectra of the twin-deck bridge.

3.2. Effects of Gap-width

This section aims to investigate the relative contributions by various potential sources of vortex shedding around the twin-deck bridge under study. There are basically three possible mechanisms from which vortex shedding can be initiated. Vortices may be expected to be shed from the trailing edges of both the upstream deck and downstream deck forming the well-known von Karman vortex streets. For the purpose of identification, vortex shedding mechanisms corresponding to the upstream and downstream deck are referred to as the "first source" and "second source", respectively. At a certain wind speed, effective energy transfer from the regular vortex patterns can potentially cause significant cross-wind response and results in the so-called wake excitation. The "third source" of vortex shedding is associated with the centre gap of the twin-deck bridge. The downstream deck immersed in the wake of the upstream deck is subjected to turbulence buffeting induced by the vortices shed from the upstream deck. As a consequence, the cross-wind excitation may be enhanced by the buffeting action of the discrete gusts. These discrete gusts contain a distinctive frequency signature associated with vortex shedding from the upstream deck (first source) and the centre gap (third source) may enhance the regularity and/or the strength of the vortices shed from the upstream deck (first source).

Gap1, i.e. the zero gap-width configuration, is not subjected to the "first source" or "third source" of excitation which are respectively due to the upstream deck and the centre gap, respectively. The whole structure works as a singe bluff body and the only relevant source of excitation is the "second source" which is associated with the vortices shedding from the trailing edge of the deck. However, as shown in Fig. 3, there is no apparent spectral peak in the lift spectrum for Gap1, i.e. the energy is distributed over a broad range of frequencies. Therefore, this deck configuration is apparently relatively insensitive to this vortex induced cross-wind excitation mechanism.

Spectral peaks are clearly evident in all other test configurations with a centre gap demonstrating that this twin-deck bridge is susceptible to vortex shedding. The Strouhal Number and, hence, the vortex shedding frequency, gradually increased with increasing gap-width due to the change of flow regime around the twin-deck bridge with different gap-widths. The pressure data obtained for Gap4 in the smooth flow are considered to be representative results illustrating the effects of gap-width on the vortex shedding mechanism. The characteristics of the fluctuating pressures around the deck surface and the corresponding pressure spectra at locations is believed to be potential sources of vortex shedding are shown in Fig. 5. These are locations at the trailing edge of the upstream deck and windward surface of the downstream deck. It can be seen clearly that the fluctuating pressures at these locations are mainly associated with the vortex shedding mechanism as indicated by the spectral peaks centred at a reduced frequency of 0.27 which is consistent with the Gap4 Strouhal Number obtained from the lift force spectrum depicted in Fig. 3. Similar findings were obtained for the other test configurations with a centre gap. Therefore, it is evident that the vortex shedding of this twin-deck bridge is mainly governed by the "first source" and "third source" of vortex shedding which are respectively the wake excitation of the upstream deck and vortex induced turbulence buffeting on the downstream deck.

It should also be stressed that the significance of vortex shedding does not always increase with increasing gap-width. It is apparent that vortex induced response of the twin-deck bridge is mainly contributed by the wake excitation of the upstream deck and vortex induced turbulence buffeting on the downstream deck. Both the wake excitation and the turbulence buffeting in particular are influenced by the gap-width. For small gap-widths (such as Gap2), the turbulence buffeting action may not be fully initiated due to the proximity of the downstream deck to the upstream deck, such that the formation of vortices in the wake is not well-developed. However, as the gap-width is increased, from Gap4 to Gap5, there is a noticeable decrease in the lift force associated with vortex shedding of the upstream deck as shown in the lift spectra shown in Fig.3, possibly due to a loss in the coherent structure of turbulence buffeting on the downstream deck as the discrete gusts travel downstream. When the two decks are separated sufficiently far apart, the excitation mechanism is expected to be dominated by the aerodynamics of the two decks individually.

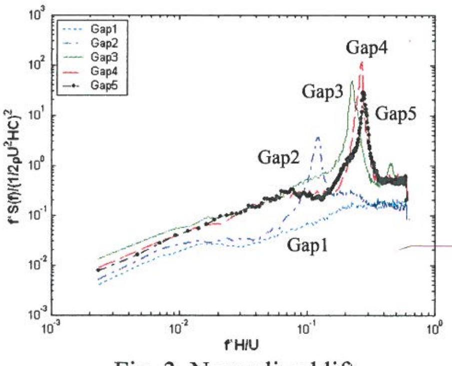

Fig. 3. Normalized lift spectra of the tested configurations

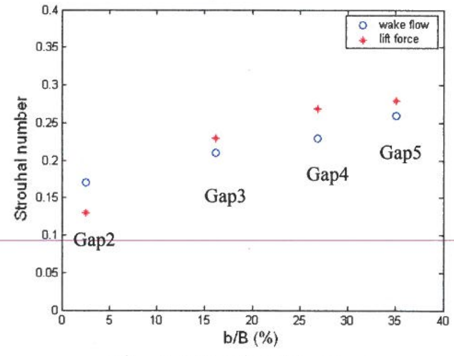

Fig. 4. Strouhal Numbers of the tested configurations

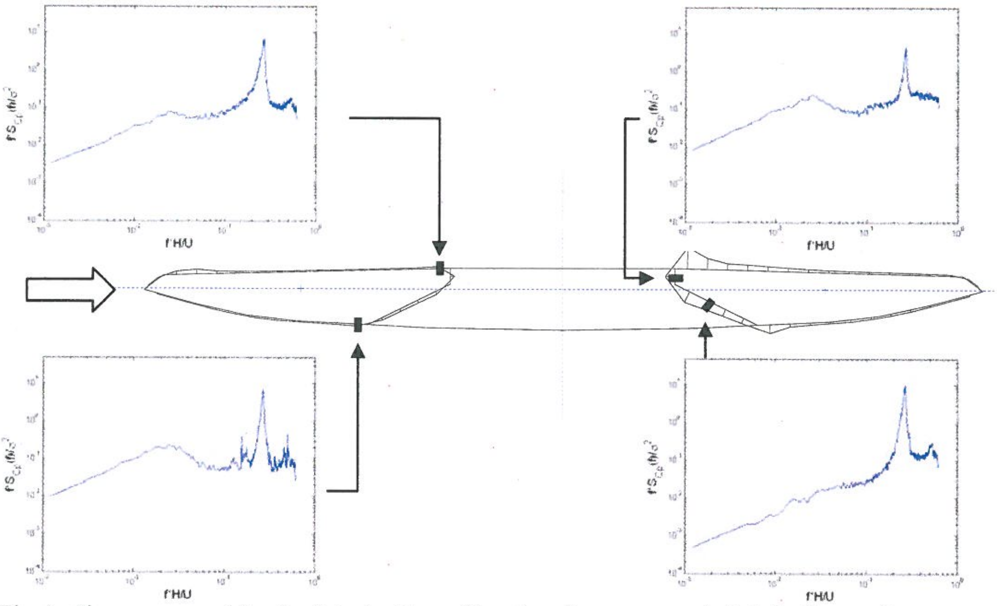

Fig. 5. Fluctuating pressure (standard derivation of local surface pressure) distribution and pressure spectra on Gap4 at 0° angle of wind incidence in the smooth flow (The depth of the deck equals 1.0Cp)

4. Conclusions

The experimental technique and results of the pressure measurements on a sectional model of a twin-deck bridge were presented in this paper. The main aim of this paper is to investigate the effects of gap-width on vortex shedding mechanisms in a nominally smooth flow. The analyzed results demonstrated that the twin-deck is susceptible to vortex shedding. It is also shown that the Strouhal Number and, hence, the vortex shedding frequency, gradually increases with increasing gap-width due to the change of flow regime around the twin-deck with different gap-widths.

5. Acknowledgements

This research is supported by the Research Grants Council of Hong Kong (Project: CA02/03.EG03) and the HKUST Targets of Opportunities Fund (Project: TOOF03/04.EG01). The authors gratefully acknowledge the contributions of the Highways Department of the Hong Kong SAR.

6. References

Bearman, P.W. and Davies, M.E. (1975), The flow around oscillating bluff structures, Proceedings of the 4th International Conference on Wind Effects on Buildings and Structures, September, London, Cambridge University Press.

Kawatani, M., Kim, H., Uejima, H. and Kobayashi, H. (1993), Effects of turbulent flows on vortex-induced oscillation of bridge girders with basic sections, Journal of Wind Engineering and Industrial Aerodynamics, Vol. 49, pp. 477-486.

Kawatani, M., Toda, N., Sato, M. and Kobayashi, H. (1999), Vortex-induced torsional oscillations of bridge girders with basic sections in turbulent flows, Journal of Wind Engineering and Industrial Aerodynamics, Vol. 83, pp. 327-336.

Kobayashi, H., Kawatani, M. and Kim, H. (1992), Effects of turbulence characteristics on vortex-induced oscillation of rectangular cylinders, Journal of Wind Engineering and Industrial Aerodynamics, Vol. 41, pp. 775-784.

Kwok, K.C.S. (1977), Cross-wind response of structures due to displacement dependent excitations, Ph.D. Thesis, Department of Mechanical Engineering, Monash University, Victoria, Australia.

Larsen, A., Esdahl, S., Andersen, J.E. and Vejrum, T. (2000), Storebelt suspension bridge - vortex shedding excitation and mitigation by guide vanes, Journal of Wind Engineering and Industrial Aerodynamics, Vol. 88, pp. 283-296.

Larsen, A., Hui, M.C.H., Savage, M. and Larsen, S.V. (2004), Investigation of vortex response of a twin box bridge section at high and low Reynolds number, Proceedings of the 5th International Colloquium on Bluff Body Aerodynamics and Applications, Ottawa, Canada, pp. 249-252.

Miyata, T, Fujisawa, N. and Yamada, H. (1999), Long-span bridges and aerodynamics, Japan, Springer, pp. 3-19.