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# Span-wise correlation of wind-induced fluctuating forces on a motionless flat-box bridge deck

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ABSTRACT

A detailed wind tunnel test has been carried out on a motionless flat-box bridge deck model with three special grid-generated wind fields using an electronically scanned pressure transducer system, enabling almost instantaneous capture of 372 pressure tap signals from 6 sections of 62 different spacing taps at each section. A very complete analysis has been performed on the pressure signals, and fluctuating forces through weighted integrations of pressure at each section were formed. The integral scales of fluctuating force were found to be dependent mainly on the integral scale of turbulence and the size of deck. The root coherence of buffeting force relied chiefly on integral scales of force and the separation of two sections, and the span-wise correlation of the fluctuating forces were larger than those of wind turbulence. An empirical model of root coherence for the fluctuating lift for a flat-box deck has been developed and proved to be feasible and effective for fitting the test data. The fitted parameters can be defined by simple expressions related to the oncoming turbulence and the size of deck, and thus it has practical applications. The proposed model can fully explain the character of low frequency curves in the root coherence.



## 1. Introduction

Research on bridge buffeting analysis in the frequency-domain was initiated by Davenport (Davenport, 1961a, 1961b, 1962a, 1962b) in the early sixties last century. The quasi-static linear theory was employed in Davenport's theory to establish the buffeting force and aeroelastic damping, and the buffeting response was analyzed mode by mode based on the strip theory of aerodynamics. The concept of span-wise coherence was introduced to consider the effectiveness of the temporal and span-wise cross-correlation of buffeting loading, which was assumed to be the same as that of wind turbulence and was described by a simple exponential function. This format is not the best model for the root coherence of fluctuating forces and wind, because the experimentally measured root coherence does not approach one for zero frequency at large separations (Bowen et al., 1983) and the function does not fit the phenomenon of "low frequency curves" in the typical root coherence (Toriumi et al., 2000) where the maximum root coherence occurs at a certain low frequency, not at zero frequency.

The coherence structure of fluctuating forces (pressure) does not follow the same pattern as that of the surrounding wind turbulence. Firstly, integral scales of force are larger than those of fluctuating wind and this was pointed out firstly by Nettleton on an airfoil in the grid-generated turbulence as reported by Etkin (1972), then Hjorth-Hansen et al. (1992), Jakobsen (1997) and Larose (2003). This characteristic of low frequency curves in root coherence (co-coherence) was observed directly in wind tunnel tests (Hjorth-Hansen et al., 1992, Larose 1992, 1997, Flay and Vickery, 1995, Jakobsen 1997, Kimura et al., 1997, Matsumoto et al., 2003, Zhu et al., 2009, 2013, Le et al., 2011, Ito et al., 2014, 2015 and Li et al., 2015) and from field measurements at the West Gate Bridge (Melbourne, 1982), the Ikara Bridge (Sankaran and Jancauskas, 1993) and another cable-stayed bridge (Niihara et al., 1998).

Although many root coherence models concerning fluctuating wind forces have been proposed in the past thirty years, the Davenport-type model is still adopted in many specifications and codes (e.g. Ministry of Communication of PRC, 2004 and European Committee for Standardization, 2005) due to its simplicity. A few

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models of force root coherence (e.g. Larose, 1992, 1997 and Kimura et al., 1997) are based on the von Karman spectrum of wind turbulence and consist of complex functions, like Bessel functions. Other root coherence models using the basic exponential form (e.g. Hjorth-Hansen et al., 1992, Flay and Vickery, 1995, Jakobsen, 1997 and Ito et al., 2014, 2015) are convenient for application but cannot explain the "low frequency curves" phenomenon due to the forms of models themselves. Among them, the model suggested by Flay and Vickery in 1995 was used at University of Western Ontario, and the empirical root coherence function of lift proposed by Ito et al. was proved to be appropriate for rectangular boxes and flat boxes (Ito et al., 2014, 2015). Zhu et al., (2009, 2013) presented a new model by a simple combination of rational fractions with two variables of a deck-width-related reduced frequency and a reduced span-wise separate distance normalized by an average span-wise integral scale of longitudinal and vertical fluctuating wind velocities. This new model is able to fit the "peak" phenomenon in low reduced frequency zone occurred in the test results, as well as peaks in high reduced frequency zones generated by vortex shedding. However, the fitted parameters in the model follow the complex pattern, and they have no physical meaning.

All these wind tunnel tests mentioned do not separate the influences of the intensity and integral scale of turbulence, so the coherence structure of fluctuating force may be not accurate enough. In the present study, three special grid-generated wind fields were built. One pair of grid sets gave similar integral scales of turbulence but different turbulence intensities, while another pair of grids gave almost the same turbulence intensities but different integral scales of turbulence. Experiments were carried out using these grids and a very complete analysis was performed on the pressure signals and the fluctuating forces which were determined through weighted integrations of the pressures at each section. Finally an empirical model on root coherence of fluctuating lift for flat-box girder is proposed and it captures the characteristic of low frequency curves in root coherence well. The coefficients in this model have physical meaning and are developed from simple expressions in order to encourage their practical application.

## 2. Outline of Xiangshan Harbor Bridge

Xiangshan Harbor Bridge is a sea-crossing bridge of the Zhejiang coastal motorway in Zhejiang Province of China. The total length of the bridge is 6.723 km and the span arrangement of the main bridge is 82+262+688+262+82 m which contains a total of four carriageways in dual directions. The main bridge is a double-tower cable-stayed bridge with two inclined cable planes and a flat closed steel box deck, as shown in Fig. 1. The central height of the deck is 3.5 m and the diamond-shaped concrete towers are 226.5 m high and have a 173.1 m high part above the bridge deck. To improve the flutter critical wind speed and to mitigate any vortex-excited resonances, the width of the deck increased to 34.0 m from 32.0 m in the origin design scheme, and the nose angle of the two side wind fairings was also decreased to $38^0$ from $56^0$ based on the wind tunnel test results.

**Fig. 1.** Xiangshan Harbor Bridge.

## 3. Experimental setup

### 3.1. Measurement system

In selecting the model scale, it is important to minimize the influence of wind-tunnel walls and excessive blockage of the test section. Selecting the model scale should also consider measurement and installation errors.

The sectional model was constructed at a geometric scale of 1:45 and the width ($B$) and depth ($D$) of the model were 775.6 mm and 77.8 mm respectively in a compromise of the above effects. The configuration of the model cross section is shown in Fig. 2(a). The model length ($L$) was designed as 1.74 m after balancing many factors, such as the size of working section of the wind tunnel and the blockage ratio, having a sufficiently large aspect ratio (length-to-width) of the model and the model stiffness. The width-to-depth ratio was 9.71 which is a typical ratio in modern practical bridge engineering projects.

There were 6 pressure measurement sections in the span-wise direction of the model and each section had 62 pressure holes with different spaces because of the rapid change of pressures occurring at surfaces close to the edges of the model or from large curvatures of the model region. The details of the pressure holes in the cross section are given in Fig. 2(b).

The pressure integration technique is often used to determine the overall aerodynamic forces from surface pressure information. The process of pressure integration is shown in Fig. 2(c). The structural coordinate system is $o\bar{x}\bar{y}$ and the angle between the mean wind $U$ and the $o\bar{x}$-axis in the structural coordinate system is

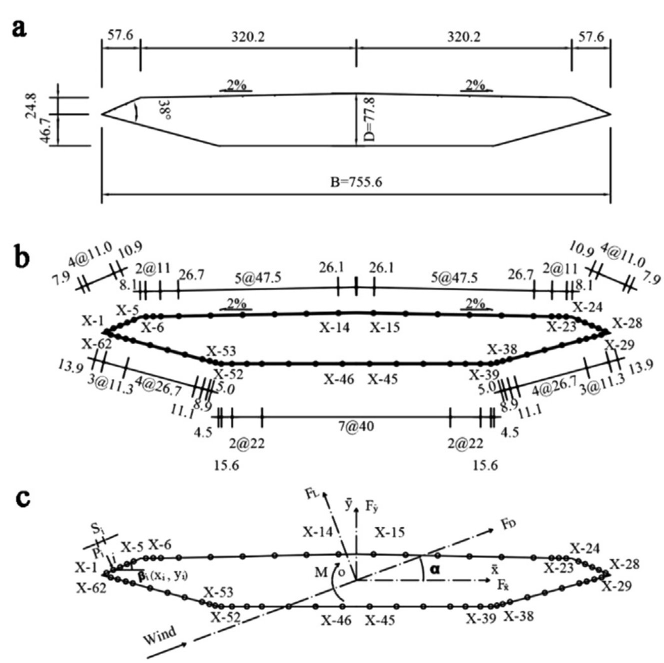


**Fig. 2.** Shape of the experimental model showing the pressure tap locations (unit in figures: mm). (a) Overall dimensions of the model cross section. (b) Details of the pressure tap locations. (c) The process of pressure integration.