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Investigations of aerodynamic effects on streamlined box girder using two-dimensional actively-controlled oncoming flow

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ABSTRACT

The aerodynamic behavior of a streamlined box section model is characterized in an actively controlled wind tunnel with multiple fans and vibrating airfoils in Miyazaki University, Japan. A series of single pseudo harmonic fluctuating wind flows with discrete frequencies are generated. The aerodynamic admittance components obtained via a cross-spectral identification method for different incoming flows present obvious deviations between each other. This indicates the probable dependence of aerodynamic admittance on the characteristics of oncoming flow, which implies the limitation of conventional buffeting theory. More attention is focused on the relationship between aerodynamic forces and wind turbulence components, along- and across-wind cross-wind, in pseudo sinusoidal flow conditions. It is found that the across-wind turbulence has dominant influences on lift and pitching moment forces. With the strengthening of along-wind turbulence, the lift force increases, while the drag and pitching moment forces vary with different trends in different frequency ranges. Moreover, the contribution of along-wind turbulence to lift and pitching moment forces is considered to be negligible compared with that of the cross-wind turbulence, while for the drag force, the two turbulence components present comparative contributions.

1. Introduction

Buffeting is a kind of stochastic forced vibration caused by the turbulence existing inherently in natural wind. Buffeting is hence inevitable for any bridges exposed to natural wind. To ensure safety of construction for long-span bridges, buffeting analysis needs to be refined. Many previous studies have made great contributions to the development of buffeting theory (e.g. Von Karman and Sears, 1938; Davenport, 1962; Scanlan, 1978b; Sarkar, et al., 1994; Larose, et al., 1997; Diana, et al., 1998; Chen and Kareem, 2002). For the consideration of non-stationarity and incomplete spanwise coherence of natural turbulence, aerodynamic admittance was employed to modify the quasi-steady aerodynamic forces. In buffeting analysis, Sears's function for a vertical wind gust (Von Karman and Sears, 1938) and Devenport's formula for an along wind gust (Davenport, 1962) are usually employed. The accuracy of the result depends largely upon the accurate estimation of aerodynamic admittance. Wind tunnel testing is the most common method for investigating the effects of wind on long-span bridges. Some studies focusing on aerodynamic admittance have been conducted in conventional boundary-layer wind tunnels (Sarkar, et al., 1994; Larose, et al., 1997). Considering the limitations of the passive turbulence generation method, such as adjustment of wind power spectral density and the integral length scale, a few actively controlled wind tunnels have been proposed.

The original active turbulence generator in an atmospheric boundary wind tunnel was built with vibrating grids (Lin and Wan, 1972), shown as Fig. 1. Prof. Cermark realized the first real actively controlled wind tunnel with several active horizontal or vertical vanes, illustrated in Fig. 2, and reported that actively controlled vanes can easily produce higher turbulence intensity (more than 10%) and a larger integral scale (several meters) compared with traditional passive wind tunnels (Cermark and Peterka, 1978; Cermark, 1987; Cermark et al., 1992, 1995; Cermark, 1995). The vibrating horizontal vanes can strengthen the turbulence intensity and integral scale of oncoming fluctuating wind, especially in the vertical direction (Kobayashi and Hatanaka, 1992; Kobayashi et al., 1994). Prof. Diana has investigated the aerodynamic effects on some typical bridge cross sections utilizing the sine- wave wind generated in an active vane wind tunnel (Diana et al., 2002, 2010; Cigada et al., 2002), shown in Fig. 3. In order to produce a smooth sine-wave wind, the testing models were located near the vibrating vanes, and only the vertical component of oncoming fluctuating wind was considered in these serial tests.

Multiple-fan wind tunnels are relatively fine active generation wind tunnels in Japan. In the active wind tunnel in Miyazaki University, 99 fans arranged in a 9 wide by 11 high matrix have

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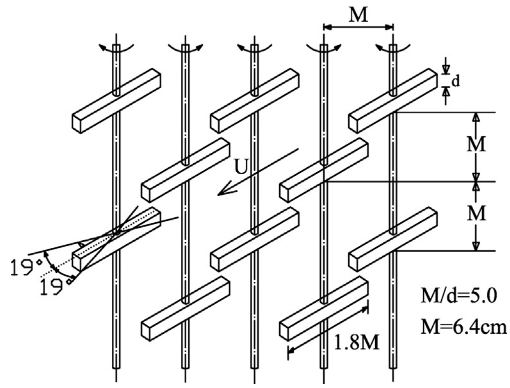

Fig. 1. Vibrating grids (Lin and Wan, 1972).

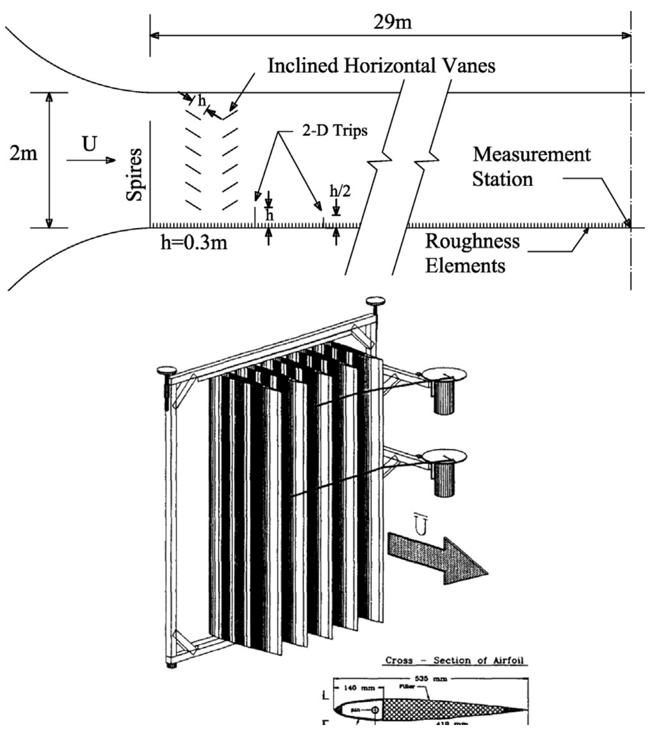

Fig. 2. Active horizontal or vertical vanes in wind tunnel. (Cermark and Peterka, 1978; Cermark, 1987; Cermark et al., 1992; Cermark, 1995).

been used to generate oncoming flows with good simulation of some important wind field parameters, such as spectrum function, turbulence intensity and integral scale (Nishi et al., 1997, 1999; Cao et al., 2002). This wind tunnel can effectively simulate the average wind and turbulence profiles and reasonably represent the wind-time history of sine-wave and broadband turbulent wind with different integral scales (Nishi et al., 1997, 1999; Cao et al., 2002). Up to now, the testing techniques of an active wind tunnel provide a chance to further recheck the validation of traditional aerodynamic theory.

2. Preliminary investigation

In the wind tunnel of Miyazaki University, some preliminary studies have been conducted (Zhao et al., 2011). A series of single harmonic fluctuating winds were generated to research the relationship between aerodynamic forces induced by sinusoidal fluctuating wind with discrete dominant frequency and broadband turbulence. The 99 fans in the wind tunnel can be programmed independently to deliver variable flows, and hence phase shifts can be introduced among the fans, allowing broadband turbulence to be generated. The single harmonics can be obtained when the 99 fans rotate with the same frequency and phase. A high-precision three-component force balance was used to test section model aerodynamic loads. The balance ranges are ± 20 N (F_x, F_y) and ± 2 N m (M_z) with a measurement accuracy of 1‰. Synchronous acquisition equipment was adopted to measure the turbulent wind and aerodynamic load at the same time. The geometric configuration of the section model is streamlined box shaped. The measured frequency of the whole system after installation of the section model is 24 Hz in the weak-axis direction and 44 Hz in the strong-axis direction. Thus, the system′s natural frequency is much larger than the dominant frequency of sinusoidal flow. The results are shown in Fig. 4, including the PSD (S_u and S_w) of along- and across-wind turbulences (Fig. 4(a)) and corresponding PSD (S_L and S_D) of aerodynamic forces (Fig. 4(b)). The black curves represent the PSD of a broadband oncoming turbulence and corresponding PSD of aerodynamic forces, while the other colored curves represent the single harmonics. For theoretical sinusoidal wave, the PSD is going to infinity at the single dominant frequency and at all the other frequencies is zero. The discrete harmonics referred to in this paper are not true sinusoidal signals but narrowband, as shown in Fig. 4(a). Hence the signal analysis techniques used are the same with those used for broadband spectrum signals. In the following, such narrowband turbulences are denoted as single pseudo harmonics for more rigorous.

It can be found that when both the along- and across-wind turbulences are properly simulated, such as the sinusoidal flow in the frequency range of 2–4 Hz in Fig. 4, the aerodynamic forces match well with those of the broadband turbulence. For simplicity, when S_u and S_w at predominant frequency of single harmonics coincide with the corresponding value of the broadband turbulence, the S_L and S_D match well. This probably illustrates that the principle of superposition of aerodynamic forces for sinusoidal flows applies in some specified frequency range. It is noteworthy that the principle of superposition of aerodynamic forces for sinusoidal flows does not mean the superposition of different curves in of values, but means the feasibility of a combination of discrete predominant frequencies of a series of single pseudo harmonics into a natural broadband form.

Fig. 5 shows one of the testing results containing the time history of low-frequency sinusoidal flow and the corresponding spectrum of turbulent wind. Compared with the cross-wind turbulence (w-turbulence), the along-wind turbulence (u-turbulence) has an absolute advantage with an energy ratio of about 1200:1 (Fig. 5(b)). This implies that the active wind tunnel with only multiple-fan equipment could not produce sufficient across-wind turbulence. Combined with the results shown in Fig. 4, we can see that the insufficient simulation of across-wind turbulence may possibly result in significant effects on buffeting forces. In other words, an active wind tunnel that can only generate longitudinal compression wave is not suitable for the simulation of aerodynamic forces of long-span bridges.

In the wind tunnel tests carried out by Diana et al. (2002), a new experimental technique based on the use of an active turbulence generator was applied to measure a complex aerodynamic admittance function. In contrast with the preliminary experiment carried out in Miyazaki University with insufficient simulation of w-turbulence, the testing models here were located near the vibrating vanes that produced smooth sine-wave wind, and only the vertical component of oncoming fluctuating wind was considered in these serial tests.

However, the contribution of u-turbulence and w-turbulence to aerodynamic forces has not yet been clarified. Based on the limitations of the existing active wind tunnels, Miyazaki University′s wind tunnel is equipped with additional active vibrating