J. Wind Eng. Ind. Aerodyn. 157 (2016) 47–62

Contents lists available at ScienceDirect

Journal of Wind Engineering and Industrial Aerodynamics

journal homepage: www.elsevier.com/locate/jweia

Partial turbulence simulation method for predicting peak wind loads on small structures and building appurtenances

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ARTICLE INFO

Article history:
Received 1 April 2015
Received in revised form
1 August 2016
Accepted 6 August 2016

Keywords:
Low-rise Building
Partial turbulence simulation
Pressure coefficient
Wind load

ABSTRACT

Large-scale wind tunnel testing is preferred for small structures and building appurtenances for maintaining modeling accuracy and minimizing Reynolds number effects. In these circumstances the ability to obtain a large enough turbulence integral scale is usually compromised by the limited dimensions of the wind tunnel. So, it is not normally possible to fully simulate the low frequency end of the turbulence spectrum. In this paper the approach is taken of dividing the turbulence into two distinct statistical processes, one at high frequencies which can be simulated in the wind tunnel, and one at low frequencies which can be treated in post-test analysis using the assumptions of quasi-steady theory. In this Partial Turbulence Simulation (PTS) method the contribution of both the high and low frequency turbulence on the wind loads on structures is included by using the probability of load from each of the two processes, with one part coming from the wind tunnel data representing the high frequency component and the remainder from the assumed probability distribution (taken in this paper as Gaussian for generic boundary layer flow) of the missing low frequency component. The two processes are approximated as independent of each other. The efficacy and validity of the method and its various assumptions are assessed by comparing predicted local peak pressure coefficients from tests on large scale models of the Silsoe cube and Texas Tech University (TTU) building in the Wall of Wind facility at Florida International University (FIU) with the corresponding full-scale data. Generally good agreement was found between the model results and full scale, particularly when comparing the highest overall peak pressure coefficients. These results, although limited to peak local pressures on the two test buildings for which good full scale data are available, are encouraging and invite further experiments to explore the range of applicability of the PTS method. This method, although developed in the Wall of Wind facility at FIU, can be equally used in conventional boundary layer wind tunnels and has the potential to enhance the ability of existing boundary layer wind tunnel facilities to predict full scale wind loads.

1. Introduction

Boundary layer wind tunnel testing has been generally accepted as a useful tool for evaluating wind loads on structures. For tall buildings the model scales used are typically in the range of 1:300–1:600. At these scales it is possible in typical sized wind tunnels to simulate the wind velocity profile, turbulence intensity and turbulence integral scale such that all represent well the corresponding values at full scale. However, for small structures like low-rise buildings, and for building appurtenances, the model scales used are often larger, in the range of 1:10 – 1:100 in order to keep Reynolds numbers high enough to avoid adverse scale effects (Kargarmoakhar et al. 2015), better replicate the effects of architectural features, and to be able to obtain adequate spatial resolution of pressures taps. For some tests even larger scales are desirable. At these large model scales the ability to obtain a large enough turbulence integral scale in the wind tunnel is compromised by the limited dimensions of the wind tunnel (Stathopoulos and Surry, 1983). As a result many of the model tests on these structures have been undertaken with less than ideal simulation of the turbulence integral scale.

Both small-scale and large-scale turbulence play an important role in the development of the peak wind pressures. The small scale turbulence interacts directly with the turbulent shear layers and vortices that originate at the edges of the roof and walls and then pass over the roof and wall surfaces. The configurations and strengths of these shear layers and vortices, which directly affect the suctions on the building surfaces, can be significantly altered by the small scale turbulence. Therefore accurate simulation of

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http://dx.doi.org/10.1016/j.jweia.2016.08.003
0167-6105/

high frequency turbulence is necessary in order to correctly model flow separation and reattachment (Asghari Mooneghi, 2014; Asghari Mooneghi et al. 2014; Banks, 2011; Irwin, 2009; Kopp and Banks, 2013; Kumar and Stathopoulos, 1998; Melbourne, 1980; Richards et al. 2007; Saathoff and Melbourne, 1997; Tieleman, 2003; Yamada and Katsuchi, 2008). The large scale turbulence tends to cause low frequency fluctuations in the oncoming wind speed and direction, which then cause low frequency movements and changes in strength of the shear layers and vortices. Notionally these low frequency fluctuations may be treated using the quasi-steady approximation, i.e. as if they are similar to changes in mean wind speed and direction, and this approach is explored in this paper.

While the focus in this paper is on buildings it is worth noting that similar issues of turbulence simulation have also arisen in sectional model testing of bridges, typically done at scales in the range 1:30–1:100. The use of partial simulation of turbulence for bridges can in fact be traced back to the 1980′s. Davenport and King (1984) used grid generated turbulence, deficient at low frequencies, on sectional models so as to include the aerodynamic effects of turbulence. The missing low frequency component of turbulence was compensated for analytically, essentially using quasi-steady assumptions. Also, Wardlaw et al (1983) reported results of experiments on the effect of grid generated turbulence on bridge decks. The integral scales were less than at full scale implying that only the high frequency component was simulated. Irwin (1998) described the requirement for spectrum matching for bridges (essentially Eq. (18) of the present paper) when using partial turbulence simulation. It was applied in sectional model tests of the Second Severn Bridge (Macdonald et al. 2002) and much better agreement with full scale observations of vortex excitation was obtained when partial turbulence simulation was used as compared to smooth flow.

Comparison with full-scale data is the ultimate test of the validity of scale model testing in wind tunnels. Studies by a number of researchers on comparisons of mean pressure coefficients have demonstrated good agreement in many cases. However, discrepancies have been observed for the peak suction pressures, mainly in regions of (1) flow separation near the leading edges of the roof, and (2) conical vortices near the windward roof corners for oblique wind azimuth angles (Cheung et al. 1997; Cochran and Cermak, 1992; Okada and Ha, 1992; Surry, 1991). In wind tunnel studies on the Texas Tech University (TTU) test building (Lin et al. 1995; Okada and Ha, 1992; Surry, 1991; Tieleman et al. 1996) good agreement between the laboratory and field data was found for mean pressures. However, the agreement for the peak and root-mean-square (RMS) point pressures was found to be less satisfactory at critical locations in the roof corner region. A similar result was obtained by Richards et al (2007) when comparing 1:40 scale wind tunnel results with full-scale data on the Silsoe cube. One of the main reasons of this discrepancy was attributed to mismatches in the turbulence spectrum, i.e. not enough content at low frequencies and too much at high frequencies. Recent studies suggest that in addition to properly simulating the longitudinal turbulence intensity (Hillier and Cherry, 1981; Melbourne, 1980, 1993; Saathoff and Melbourne, 1989), the simulation of lateral (Letchford and Mehta, 1993; Richards et al. 2015; Tieleman, 2003; Tieleman et al. 1996; Zhao, 1997) and vertical (Wu et al. 2001) turbulence intensities can affect results for the peak-suction pressures especially near a roof corner. If the overall longitudinal and transverse turbulence intensities are matched on the model, but the integral scale is too small, then the high frequency part of the spectrum has too much power. To correctly match the spectrum at high frequencies in this situation, it is required that the model turbulence intensity be smaller than at full scale (Asghari Mooneghi et al. 2015; Banks, 2011; Richards et al. 2007; Yamada and Katsuchi, 2008) but then the question arises as to how to account for the missing low frequency content.

This paper presents a theoretical and experimental approach to account for the effects of the low frequency fluctuations in the wind flow. It assumes that all the effects of the high frequency fluctuations are captured by measurements in a wind flow that has the high frequency part of the turbulence spectrum at the right energy level. The effects of low frequency fluctuations are then accounted for analytically using quasi-steady theory.

As already noted quasi-steady theory has been used before to examine the buffeting response of bridges (Davenport and King, 1984). It has also been used by Diana et al (1999) to investigate the turbulence effects on flutter. In their analytical model the total response was decomposed into components with different frequencies in order to incorporate frequency dependent characteristics. Chen et al (2000) developed a time domain analysis framework for predicting the flutter and buffeting responses of bridges under turbulent winds which included the nonlinear aerodynamics with respect to the effective angle of incidence. In their approach, the turbulence was again divided into low frequency and high frequency components with the low frequency turbulence being expressed using the quasi-steady approximation.

In the context of testing small structures ASCE/SEI 49–12 (2012) discusses the need for additional interpretation of wind tunnel data when the complete spectrum of wind turbulence is not simulated, but does not define a methodology. An aim of the present research is to explore methodology for achieving an appropriate interpretation. There are two versions of the presently proposed method. The simplified version is called the “Partial Turbulence Simulation (PTS)” method in which just the effect of missing low frequency longitudinal turbulence is considered. The extended version of PTS is called 3 Dimensional Partial Turbulence Simulation (3DPTS) which simulates the additional effects of the missing low frequency lateral and vertical fluctuations. The 3DPTS method requires a number of additional tests using small incremental wind azimuth and pitch angles centered on the mean wind vector of interest. To assess the accuracy of both the PTS and 3DPTS methods, pressures on large-scale models of the Silsoe cube (Richards and Hoxey, 2012) and TTU building (Levitan and Mehta, 1992a and 1992b) were measured in the Wall of Wind (WOW) facility at Florida International University (FIU) with only the high frequency part of the turbulence spectrum simulated experimentally. Then the effects of the missing low frequency fluctuations were incorporated analytically by analyzing the experimental data using the PTS and 3DPTS methods to predict the full scale pressure coefficients. The final results were compared with the pressure coefficients obtained from field data on the respective prototypes in the real atmospheric flow with full turbulence spectrum.

2. Theory

2.1. Small and large scale turbulence

The aerodynamic behavior of a bluff structure such as a building is governed by the state of flow separation around it which is greatly affected by the oncoming flow turbulence. As indicated earlier, it is known that small-scale turbulence interacts in important ways with the shear layers and vortices cast off from a body immersed in turbulent air flow. On the other hand, very large-scale turbulent eddies, much bigger than the body, can be expected to have a somewhat similar effect to a change in the mean flow velocity vector. This suggests that if a sufficient range of the small-scale turbulence can be simulated in a wind tunnel then it might be possible to include the large-scales later in post-test analysis using quasi-steady assumptions.