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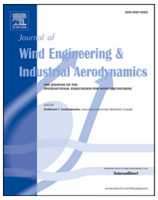

Effects of turbulence on the mean pressure field in the separated-reattaching flow above a low-rise building

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ABSTRACT

The effects of upstream turbulence in the atmospheric boundary layer flow on the mean surface pressure distribution within the separated flow above a typical low-rise building roof are investigated experimentally. Time-averaged Navier-Stokes equations are used to evaluate the pressure gradients from planar particle image velocimetry data. The pressure fields are reconstructed by integrating the pressure gradients using an analytic interpolation approach. This reconstruction approach is validated by successfully matching the reconstructed pressure to Bernoulli's equation along a streamline far from the body and with pressure measurements on the surface of the body. Through this process, the mean pressure field can be directly explained from the mean velocity and turbulence fields near the roof. For high turbulence intensity levels, the maximum suction coefficient on the roof surface was found to be increased. Such increased magnitudes are directly related to the reduced size of mean separation bubble in higher turbulence, more rapid variation of the velocity magnitude near the leading edge, and enhanced variation of the turbulence stresses. On the other hand, a higher rate of surface pressure recovery is found in the leeward portion of the separation bubble, which is mainly due to the more rapid variation of the turbulence stresses.

1. Introduction

Free-stream turbulence is known to affect the mean flow around two-dimensional (2D) rectangular prisms. For the separated and reattached flow near the leading edge, investigations over several decades (e.g., Kiya and Sasaki, 1983; Saathoff and Melbourne, 1997) have shown that increased free-stream turbulence intensity reduces the mean separation bubble length, x_r, on both the upper and lower surfaces. On the other hand, altering the length scale of turbulence has not been found to affect the length of the separation bubble as significantly as turbulence intensity (e.g., Hillier and Cherry, 1981; Nakamura and Ozono, 1987), at least over the range examined.

These findings have significant implications for the separated and reattached flow near a low-rise building roof, where large suctions can induce uplift failures in high winds. In order to investigate the influence of turbulence in the atmospheric boundary layer (ABL), Akon and Kopp (2016) conducted roof surface pressure measurements of a geometrically-scaled, low-rise building together with planar particle image velocimetry (PIV) measurements in a boundary layer wind tunnel. Near the height of the building, the turbulence intensity in their simulated ABLs ranged from 10% to 30% while the integral length scale ranged from 6 to 12 times of building height. Note that the turbulence intensity is defined as $I_u = \sqrt{\overline{u'u'}}/\overline{u}$, while the integral length scale is defined as $L_{ux} = \overline{u}\int_0^\infty \overline{u'(t)\,u'(t+t_*)}/\overline{u'u'}\,dt_*$, where $\overline{u}$ is the mean stream-wise velocity, u' is the fluctuating component, t denotes time and t_* is the time lag. The general effects of turbulence intensities and length scales on the mean reattachment length on the upper surface of the roof was found to be similar to the cases for 2D rectangular prisms. The distributions of mean pressure coefficients, $\overline{Cp}$, on the roof surface were found to be primarily dependent on the reattachment length, x_r, but also on the turbulence intensity. The minimum value of the mean pressure coefficient, $\min(\overline{Cp})$, was found to asymptotically decrease for increased turbulence intensity. By further plotting the reduced mean pressure coefficients, $Cp^* = \left(\overline{Cp} - \min\left(\overline{Cp}\right)\right)/\left(1 - \min\left(\overline{Cp}\right)\right)$, as originally defined by Roshko and Lau (1965), against the normalized distance from the roof leading edge, x/x_r, they found that the mean pressure distributions beneath the separated flow are not self-similar because of the dependence on the turbulence intensity, I_u. In particular, they found that the value of Cp^* decreases at the reattachment point, $x/x_r = 1$, for increased values of I_u, indicating that the pressure takes relatively longer to recover with respect to the reattachment point (which decreases for increased

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Nomenclature

Cp	Pressure coefficient
Cp_e	Estimated pressure coefficient
Cp^*	Reduced pressure coefficient
f	Frequency
H	Height of the low-rise building model, $H = 8$ cm
I_u	Turbulence intensity of streamwise velocity component
L_{ux}	Integral length scale of streamwise velocity component
p	Pressure
p_∞	Ambient static pressure
r	Radial distance on the xz-plane, i.e., $r = \sqrt{x^2 + z^2}$
S_{uu}	Auto-spectra of streamwise velocity component
u	Streamwise velocity component (with direction parallel to x-coordinate)
$\mathbf{u}$	Velocity vector, $\mathbf{u} = u\mathbf{i} + v\mathbf{j} + w\mathbf{k}$
u_H	Upstream streamwise velocity at roof height
u_{ref}	Reference velocity
w	Vertical velocity component with direction parallel to z-coordinate
x	x-coordinate of the space
x_r	Reattachment length of the mean separation bubble
$\mathbf{x}$	Space vector. $\mathbf{x} = x\mathbf{i} + y\mathbf{j} + z\mathbf{k}$
z	Vertical coordinate of the space
ν	Kinematic viscosity of air
α	Coefficient associated with x-derivative of the analytic support, Φ
β	Coefficient associated with z-derivative of the analytic support, Φ
Φ	Analytic support
ρ	Density of air
σ	Support size of the radial analytic function Φ
$\boldsymbol{\tau}$	Turbulence stress tensor with component $\tau_{ij} = \overline{u_i'u_j'}$
$\overline{a}$	Time average of a
a'	Temporal fluctuation of a, i.e., $a' = a - \overline{a}$
$\min(a)$	Minimum value of a
$\max(a)$	Maximum value of a

values of I_u).

With the capability of PIV measurements, our goal now is to look into the more detailed influences of ABL turbulence on the flow field variation near the roof. From the Navier-Stokes equations, the flow field can be directly connected to the pressure field so that the influence of turbulence on the pressure field can be examined. By defining the pressure coefficient, Cp, as

$$Cp = \frac{p - p_\infty}{0.5\,\rho u_{ref}^2}, \tag{1}$$

and normalizing the velocity vector, $\mathbf{u}$, by the reference velocity, u_{ref}, the gradient of the mean pressure coefficient can be written as:

$$\nabla\overline{Cp} = -2\left[\left(\frac{\overline{\mathbf{u}}}{u_{ref}}\right)\cdot\nabla\left(\frac{\overline{\mathbf{u}}}{u_{ref}}\right) + \nabla\cdot\left(\frac{\boldsymbol{\tau}}{u_{ref}^2}\right) - \frac{\nu}{u_{ref}}\nabla^2\left(\frac{\overline{\mathbf{u}}}{u_{ref}}\right)\right]. \tag{2}$$

Here ρ denotes the density of the air, p denotes the pressure, p_∞ is the ambient static pressure and ν is the kinematic viscosity. The overbars in Eq. (2) denote the time average, while $\boldsymbol{\tau}$ denotes the turbulent stress tensor with components $\tau_{ij} = \overline{u_i'u_j'}$ with the prime denoting a fluctuating component.

This Eulerian approach to pressure gradient evaluation, along with methods of pressure integration have been explored by many researchers and is recently reviewed by van Oudheusden (2013). The central difference scheme, which is of second order accuracy and relatively simple in operation, is usually used in determining the velocity gradients on the right hand side of Eq. (2) (e.g., Murai et al., 2007; de Kat and van Oudheusden, 2012). On the side of pressure integration, however, greater attention is needed. Space-marching techniques for pressure integration are relatively straightforward and fast (e.g., Baur and Kőngeter, 1999; van Oudheusden et al., 2007). However, at times ‘memory’ effects of integrated results along the integration path can occur (e.g., de Kat et al. (2008)), which means the pressure integration can be path dependent with errors from either discretization or measurement (e.g., Sciacchitano and Wieneke, 2016) being accumulated along the integration path (Ettl et al., 2008). Because of these drawbacks for space-marching schemes, other types of optimization methods for pressure integration may be preferable. The most common approach is to solve the Poisson equation for pressure with standard numerical techniques (e.g., Gurka et al., 1999; de Kat and van Oudheusden, 2012). Note that boundary conditions of mixed type, i.e., a combination of Dirichlet and Neumann, are required for solving Poisson equations (van Oudheusden, 2013). In addition to these techniques, algorithms in CFD have also been used to determine pressure from measured velocity data. For example, Jaw et al. (2009) calculated the pressure distribution through the SIMPLER algorithm, in which continuity is satisfied and no boundary conditions are required. In contrast to these methods, in the current work we are applying the analytic interpolation approach proposed by Ettl et al. (2008). The goal of this method is to keep the local details of integration while providing a globally optimized solution. This method has other advantages, such as no requirements for entire boundary conditions and the ability to remove bad gradient data.

An overview of this paper is as follows. The planar PIV and surface pressure measurements of the flow fields around a low-rise building under various terrain roughness conditions, as measured by Akon and Kopp (2016), are used as the input for analytic interpolation technique. Following a description of the method, the mean pressure fields are obtained from the measured mean velocity fields. The roof surface pressures estimated from velocity fields are then compared to the measurements. Effects of turbulence in the ABL on the mean roof surface pressure distributions are, hence, examined directly.

2. Atmospheric boundary layer (ABL) flow simulation with various terrain roughness conditions

Six upstream terrain conditions were used for generating the turbulent atmospheric boundary layer (ABL) flows. While the measurements are briefly reviewed here, full details can be found in Akon and Kopp (2016). These ABL turbulent flows are simulated in the high-speed test section of Boundary Layer Wind Tunnel II at the University of Western Ontario (UWO), which offers a fetch of 39 m for flow development and a cross-section of 3.36 m in width and 2.05 m in height at the test location. At the upstream end, three spires, with a height of 1.22 m and a base width of 0.1 m, are placed. Sets of roughness blocks are distributed along the floor between the upstream end and the test location. By altering the heights of the roughness blocks, three distinct ABL turbulent flows, which are called ‘Flat’, ‘Open’ and ‘Suburban’ in this paper, are generated. By further placing a barrier of 0.38 m (15 inch) height immediately after the spires, along with the same sets of roughness blocks mentioned earlier, another three sets of ABL flow are generated with altered integral scales. In summary, the measurements were conducted with a total of six terrain roughness conditions. Three of them, with 15 inch barrier at the upstream end, are labelled as ‘F15’, ‘O15'and ‘S15’ for Flat, Open and