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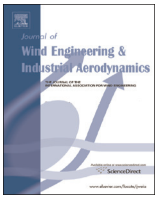

A study of tornado induced mean aerodynamic forces on a gable-roofed building by the large eddy simulations

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ABSTRACT

A tornado simulator was built and tornado-induced mean aerodynamic forces on a gable-roofed building were numerically studied. Simulated mean flow fields and mean forces acting on a building model showed satisfactory agreement with those from experiments verifying the accuracy of the tornado simulator. Around the world experimental tornado simulators are very limited which makes estimating tornado induced forces much difficult. Therefore, examining whether or not there are any relationships between tornado induced forces and straight-line wind induced forces is the target of this study. After checking mean wind profiles below the height of building in tornado flow fields, a kind of spiral was found. This spiral is unique compared with profiles in traditional wind tunnel. Therefore a concept of volume averaged velocity was proposed and found to be the linkage between tornado induced mean forces and straight-line wind induced mean forces, i.e. removing tornado induced atmospheric pressures, the building in tornado experiences similar responses with those in wind tunnel if the direction of volume averaged velocity is same. Based on this finding, a method estimating the tornado-induced mean aerodynamic forces using the straight-line wind tunnel is proposed and the results transformed from the data base of the straight-line wind tunnel show satisfactory agreement with those directly calculated in the tornado simulator.

1. Introduction

Straight-line wind induced aerodynamic forces have been extensively studied in past decades experimentally and numerically [see, e.g. Hoxey and Richards (1993), Mochida et al. (1993), Tamura et al. (1997, 2001, 2008), Kopp and Chen (2006), Blocken et al. (2007), and Yang et al. (2008)]. Tornado-induced forces are not studied as extensively as those by the straight-line wind. Tornadoes are among the most violent storms occurring in the atmospheric boundary layer. Thousands of tornadoes are reported every year and they cause incredible amounts of damage as well as significant numbers of fatalities, e.g. in 2011, more than 1000 tornadoes occurred in the U.S., due to which at least 550 people were perished, as reported by Doswell et al. (2012). Therefore it is important to take proper consideration of tornado-induced wind loads and tornado-borne debris for wind resistant design of structures. More and more attentions were paid to reveal the complicated flow structures [see, e.g., Ward (1972), Church et al. (1979), Monji (1985), Lee and Wilhelmson (1997a, 1997b), Lewellen et al. (2000), Hangan and Kim (2008), Matsui and Tamura (2009), Tari et al. (2010), Ishihara et al. (2011), and Maruyama (2011)]. With the improvement of understanding about tornado-like flow fields, estimation of tornado-induced aerodynamic forces on structures is now becoming a new goal.

Considering the difficulty of observing tornados in nature, laboratory simulations are now the main approach for studying the tornado-induced aerodynamic forces and three types of tornado simulators are used. The first type is the Ward-type simulator developed by Ward (1972) which could only be used to study the stationary tornado. Jischke and Light (1983) applied the Ward-type simulator to study the interaction between tornado flow fields and structures and proposed that an addition of swirl to the flow significantly changes the forces acting on the model. Mishra et al. (2008) also applied Ward-type simulator to generate a single-celled tornado-like vortex and studied the wind loading on a cubical model. It was found that the pressure distributions and forces exhibit quite different characteristics in comparison with those from wind tunnel. Rajasekharan et al. (2013a) performed an experimental investigation using the tornado simulator at Tokyo Polytechnic University which is also a Ward type simulator and obtained a better understanding of the effects of building location with respect to vortex. Rajasekharan et al. (2013b) then analyzed

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Nomenclature

$C_{F_{it},v_{H,\,max}}$	total force normalized by $v_{H,\,max}$
$C_{F_{ip},v_{H,\,max}}$	force due to pressure drop normalized by $v_{H,\,max}$
$C_{F_{iw},v_{H,\,max}}$	force due to direct impact of wind normalized by $v_{H,\,max}$
C_{F_{iw},V_H}	force due to direct impact of wind normalized by V_H
C_{F_{iw},V_v}	force due to direct impact of wind normalized by V_V
$C_{F_{i,e.b.}}$	force due to direct impact of wind at the end bay region normalized by V_H
d	diameter of the updraft hole
F_{ip}	forces associated with the tornado-induced pressure drop
F_{iw}	forces caused by the direct impact of wind upon the structure
F_{im}	impactive forces caused by tornado-borne missiles
$F_{i,e.b.}$	time averaged aerodynamic forces at the end bay region
h	height of the inlet layer
Q	flow rate
r_c	radius at which v_c occurs
$r_{H,\,max}$	radius at which $v_{H,\,max}$ occurs
Re_b	reynolds number for the building model
Re_t	tornado reynolds number
V_T	translating speed
V_v	volume averaged wind speed
V_H	wind speed at m.e.h.
v_c	maximum tangential velocity in the quasi-cylindrical region
v_{xH}	time-averaged radial velocity
v_{yH}	time-averaged tangential velocity
v_{zH}	vertical velocity at m.e.h.
$v_{H,\,max}$	maximum tangential velocity, at m.e.h.
λ_L	tornado size scale
λ_{vel}	velocity scale
λ_B	ratio of the building size to the size of the tornado
θ_H	angle of attack at m.e.h.
θ_S	angle of attack at surface
θ_v	volume averaged angle of attack
Ω	volume occupied by the building model
m.e.h.	mean eave height
e.b.	end bay region

the effect of ground roughness on the internal pressures developed inside a building model exposed to a stationary vortex. The second type is the tornado simulator developed in Iowa State University (ISU) which could simulate both stationary and translating tornadoes. The details of this type of simulator have been introduced in Haan et al. (2008). Haan et al. (2010) then presented transient wind loads on a one-story, gable-roofed building in a laboratory-simulated tornado and showed that the tornado-induced lateral forces were about 50% larger than those by ASCE 7-05 and uplift forces in tornado were two or three times as large as those by the provision. Yang et al. (2010, 2011) experimentally quantified the characteristics of the wind loads on a gable-roofed building and a high-rise building using the ISU tornado simulator, from which the significant difference between tornado induced forces and straight-line wind induced forces was discussed. The last one is the torando simulator developed in WindEEE (Wind Engineering, Energy and Environment Research Institute) Dome at Western University as reported by Refan (2014). However, the tornado simulators around the world are limited, therefore it is meaningful to propose a method estimating tornado-induced forces by the wind tunnel.

There are very few numerical researches associated with tornado-induced forces so far. Wilson (1977) firstly applied a two dimensional numerical model to examine the effects of tornadoes on buildings, in which only horizontal forces were calculated. However, flow fields in tornado are three dimensional and the lift force regarded as an important factor causing the damage of buildings could not be calculated by this two-dimensional numerical simulator. Alrasheedi and Selvam (2011) applied a three-dimensional model to compare the wind loads from tornado and those from straight-line winds. They concluded that it is not sufficient to estimate the wind loads using wind tunnels; however, tornado-like flow fields in their study were provided from a Rankine combined vortex model. Therefore, a three-dimensional numerical simulation about the tornado-induced aerodynamic forces on buildings with flow fields directly generated from a three-dimensional numerical tornado simulator is needed to be carried out.

In this study, tornado-induced mean forces acting on a gable-roofed building are calculated numerically by large eddy simulations in a three-dimensional model and a method estimating tornado-induced mean forces by aerodynamic coefficients from wind tunnels is proposed. In Section 2, the setups of a numerical tornado simulator and a numerical wind tunnel are introduced. Accuracies of the numerical tornado simulator and the numerical wind tunnel are validated in Section 3, where the flow fields as well as the mean forces acting on a building model are investigated. In Section 4, a method evaluating the tornado-induced forces on the building through the straight-line wind tunnel is proposed.

2. Numerical models

In this section, the governing equations and the solution scheme are firstly outlined, followed by the introduction of the gable-roofed building model. Then the setups for the numerical tornado simulator and the numerical wind tunnel are introduced, including its geometry, mesh and boundary conditions.

2.1. Governing equations and solution schemes

In this study, large eddy simulation (LES) is adopted, in which large eddies are computed directly, while the influence of eddies smaller than grid spacing is modeled. Boussinesq hypothesis is employed and standard Smagorinsky–Lilly model is used to calculate the subgrid-scale (SGS) stresses.

The governing equations applied in LES model are obtained by filtering the time-dependent Navier–Stokes equations in Cartesian coordinates (x, y, z) and expressed in the form of tensor as follows:

$$\frac{\partial \rho \tilde{u}_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial \rho \tilde{u}_i}{\partial t} + \frac{\partial \rho \tilde{u}_i \tilde{u}_j}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\mu \frac{\partial \tilde{u}_i}{\partial x_j}\right) - \frac{\partial \tilde{p}}{\partial x_i} - \frac{\partial \tau_{ij}}{\partial x_j} \tag{2}$$

where $\tilde{u}_i$ and $\tilde{p}$ are the filtered velocities and pressure, respectively, μ is the viscosity, ρ is the density, τ_{ij} is the SGS stress, which is modeled as follows: