J. Wind Eng. Ind. Aerodyn. 103 (2012) 73–85

Contents lists available at SciVerse ScienceDirect

Journal of Wind Engineering and Industrial Aerodynamics

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

Development and implementation of an urban wind field database for aircraft flight simulation

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ARTICLE INFO

Article history:
Received 14 July 2011
Received in revised form
9 December 2011
Accepted 14 February 2012
Available online 28 March 2012

Keywords:
Building
Wakes
Simulation
Aircraft
Database

ABSTRACT

Surveillance applications of unmanned aerial vehicles (UAVs) within urban areas is made difficult by turbulent winds generated by buildings. A methodology is proposed by which wind data is pre-calculated using computational fluid dynamics and stored in a database. To capture the relevant wind field features a first generation database is proposed using three independent variables for single building simulations and seven independent variables for simulations of two buildings in close proximity (canyons). The current generation of the database is shown to be capable of simulating the relevant wind effects generated within small to moderately populated urban environments. A selection algorithm is described which determines if an aircraft is located within a region significantly influenced by the building turbulence, and if so, applies the wind data from the database. The flight data of a fixed wing UAV through a sample urban environment is used to illustrate the implementation of the database and the selection algorithm. Results show that building wake effects on aircraft position and control effort can be captured by the proposed methodology without the need to simulate the entire urban domain.

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1. Introduction

There exists significant research interest with regards to the flight of unmanned and micro aerial vehicles (UAVs and MAVs) in urban environments. Such research has been motivated by numerous potential applications such as reconnaissance and surveillance (Hegazy et al., 2004), human risk-reduction and military operations (Mullens et al., 2003; Peot et al., 2005) and law enforcement (Murphy and Cycon, 1998). With the low weight of such aircraft acceptable flight performance is a concern due to the turbulent wind generated around urban structures. The wakes developed by urban structures have been studied by numerous researchers and been shown to depend on both wind conditions and building configuration (Baik and Kim, 1999; Kastner-Klein et al., 2004; Hunter et al., 1990; Kovar-Panskus et al., 2002; Oke, 1998). Thus a given series of buildings can create several unique flow structures, each of which will pose a different challenge to aircraft flight and must be considered independently.

The general characteristics of urban winds are influenced by meteorological, aerodynamic, and heat related factors (Boris, 2005; Britter and Hanna, 2003). On the city scale the dominant effect of an urban area on the winds developed is the transition from the rural to the urban boundary layer. Researchers have shown that the differences between the rural and urban boundary layers are due primarily to urban heating and aerodynamics (Sorbjan and Uliasz, 1982; Counihan, 1967; Hildebrand and Ackerman, 1984; Martilli, 2002). Although buoyancy effects due to the urban heat island effect can create significant vertical air motion, of more interest to vehicle flight within an urban environment is aerodynamic turbulence. As air flows past buildings large wakes, dynamically shed vortices, and complex recirculation zones can be generated which significantly influence small aircraft.

Primarily motivated by pollutant dispersion, numerous efforts to understand and model the causes and characteristics of these types of urban flow have been made. The QUIC-URB code at the Los Alamos National Laboratory uses empirical algorithms and mass conservation to avoid solving the energy or momentum transport equations directly. Although based on the Röckle model which assumes only two flow regimes (skimming and isolated flow), the code is able to determine wind fields suitable for particle dispersion within the order of minutes for large urban areas of several square kilometres. Alternatively, numerical simulations of the complete Navier–Stokes equations can be performed (thus solving the momentum and energy transport equations in addition to continuity). For example, Boris (2005), Murakami et al. (1999), Oliveira and Younis (2000), Patnaik et al. (2005); Panaik et al. (2003), and Yee et al. (2007) have used

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0167-6105/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jweia.2012.02.010

numerical simulations to predict the flow characteristics in large urban areas and around specific building structures. In general these approaches acknowledge the costly and time consuming nature of simulating large urban areas and the sensitivity of important flow characteristics to the selection of a turbulence model. These studies are unique to a particular city and a new simulation must be done for each combination of city and atmospheric conditions considered.

Studies done using CFD (Computational Fluid Dynamics) to parametrize the flow around various single building and urban canyon geometries have also been done (Baskaran and Kashef, 1996; Chang and Meroney, 2001; Kastner-Klein et al., 2004; Lakehal and Rodi, 1997; Lien and Yee, 2004; Patnaik et al., 2005; Zhang et al., 1996). These studies have found that the flow is a function of several key parameters such as building spacing (i.e., canyon width or depth), differences in rooftop height, and the orientation of the building with respect to the freestream wind direction. In many cases these simulations have been compared to experimental data (Kovar-Panskus et al., 2002; Meroney et al., 1999; Smith et al., 2001). The numerical simulations have been shown to be sufficiently accurate to capture the variations in flow regimes as a function of the critical configuration variables.

Application of this type of wind field data to small aircraft flight poses significant challenges due to the mobility of aircraft (i.e., they can be deployed over a wide range of city environments) and the manner in which aircraft dynamics are treated. Research by Orr et al. (2005) and Stoor et al. (2006) investigate methods by which UAVs can navigate a collision-free path in an urban environment while taking building generated turbulence into consideration. Orr et al. (2005) uses a single CFD simulation to model the flow in and around a complete urban environment composed of multiple buildings and canyons. At each instance in time the aircraft dynamic model incorporates local winds from the numerical simulation at the aircraft's centre of gravity into the calculations. Two simulations are performed including and excluding the effects of building generated turbulence. When these results are compared they show a significant deviation in the resulting flight paths, where when local turbulent wind is considered many of the desired waypoints cannot be reached.

Although the use of simulations of entire urban areas can be effective, if the prevailing winds change or the aircraft is deployed in an alternate urban environment these simulations must be re-done. In some cases this is not practical and so Galway et al., 2011 and Galway et al. (2008) have suggested the use of a database of smaller, parametrized simulations. This database consists of common urban structures for which numerous geometric building configurations and wind conditions can be more easily simulated. These can be assembled to match the urban environment under investigation thus allowing the local turbulent winds to be applied to the aircraft. Additionally, the manner in which these winds are incorporated is expanded to include unmanned vehicles whose size is on the order of the turbulent wind structures. Local winds at the center of gravity and their variation along the dimensions of the aircraft are applied when evaluating the aircraft dynamics.

This paper describes the development of this wind field database. The manner in which urban environments are parametrized, the current scope of the database and its scalability, as well as the implementation of the wind data into the flight simulations is detailed. The use of wake boundaries is also described as a means of reducing the complexity of the flight simulations through a judicious application of local wind data from the database.

2. Urban parametrization

The variables defining both the building configuration and the prevailing wind condition are chosen such that as many of the flow structures observed can be captured within the simulations. For example, a single building within a constant freestream wind has been observed to produce complex arch and shear layer vortices as well as separation regions on both the sides and top of the building (Martinuzzi and Tropea). In order to capture the variations in strength, size, and development of these flow structures the single building database is defined by three independent variables. The first is the length to width ratio (L/W, where by convention $W \leq L$) which is varied between values of 1 and 3 as this represents a majority of buildings within common urban centres. The orientation of the building with respect to the freestream wind is the second variable. This can have a dramatic effect on the existence of certain flow structures such as recirculation on the building sides (where for some values of θ_w this recirculation can be eliminated effectively making the building more aerodynamic). The remaining variable is the Reynolds number reflecting the freestream wind value and which has a significant effect on the strength and size of any turbulence generated.

The current generation of the database also contains canyon simulations. These are defined as configurations of two buildings where the resulting turbulence generated cannot be accurately simulated by combining two individual building simulations. This is necessary to capture details such as the transition from wake interference flow to skimming flow as well as the development of canyon vortices. Due to the additional complexity the number of independent variables required to define the database is increased. The two variables characterizing the freestream wind (i.e., Re and θ_w) are the same as for the single building cases. However, the building geometry is now slightly more complicated in the variety of variables that can affect the wake properties. As shown in Fig. 1, each building's length to width ratio needs to be defined, while the addition of a second building requires the specification of the height of each building. These values are used in three parameters defining the canyon configuration space. First is the parameter $\Delta H/D_{avg}$. This is limited to values below unity since when $\Delta H/D_{avg} > 1$ a significant portion of the wake is influenced by only the taller of the two buildings. The average height of the buildings, H_{avg}, is used in two parameters. The first, H_{avg}/D_{avg}, represents the depth of the canyon. Larger values represent building configurations with deeper canyons which can effect the size and strength of any vortices developed. The

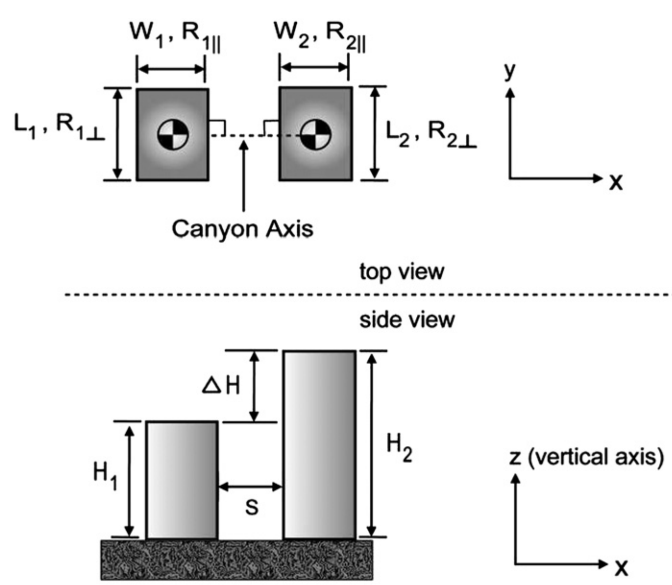

Fig. 1. Canyon geometry variables.

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