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Wind resource assessment using airborne LiDAR data and smoothed particle hydrodynamics

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ABSTRACT

The increasing availability of airborne Light Detection And Ranging (LiDAR) data provides new opportunities for environmental simulations. This paper proposes a new method for wind resource assessment by using wind simulation over 3D geometry extracted from classified LiDAR data. The simulation of wind flow is performed by using Smoothed Particle Hydrodynamics (SPH) in two phases for each time-step, firstly over low-resolution Digital Elevation Model (DEM) data, and secondly over high-resolution LiDAR data. Inlet wind particles depend on the logarithmic wind profile, where the morphometric aerodynamic roughness length is considered. The estimated wind power is integrated over a given timespan, resulting in wind energy potential. The simulated velocities were validated with annual measurements, where an agreement of 80.72% and 90.81% was achieved for ~0.5 km^2 sized urban and rural areas, respectively. The cumulative wind energy potential at 20 m above surface height is at 7.62 GWh and 56.613 GWh for the given areas, respectively.

1. Introduction

Knowledge of the wind flow at a given geographic location complements numerous applications in climate modelling, urban planning, environmental modelling and other applications (Blocken, 2014). Moreover, wind energy is becoming a suitable alternative energy source, providing extensive mitigation of anthropogenic emissions from nonrenewables (Barthelmie and Pryor, 2014). However, there are still fundamental problems of identifying suitable locations for the installation of wind power systems over complex terrain or within urban environments. Wind resource assessment is a viable solution for the given problem, as it provides the per-annum outlook of the characteristic wind energy potential at a specific location. The structure and depth of ABL (Atmospheric Boundary Layer) (Manwell et al., 2009) needs to be considered when dealing with the estimation of a spatio-temporally dependent wind flow in order to assess the energy potential.

Various methods have been developed for wind resource assessment using geographic data by statistical analysis of wind speed using Weibull or Rayleigh distribution. Although this does not capture the turbulent behaviour affecting the wind over more complex geometry completely, it provides an adequate solution over large-scale geographic areas (Sliz-Szkliniarz and Vogt, 2011; Mohammadi et al., 2014; Karthikeya et al., 2016). In recent years, preprocessed remote sensing data such as Digital Elevation Model (DEM) or Digital Terrain Model (DTM) have been used extensively, together with Geographic Information System (GIS) (Sliz-Szkliniarz and Vogt, 2011; Palaiologou et al., 2011; Grassi et al., 2014; Siyal et al., 2015) for wind resource assessment. Many of these methods considered low-resolution DEM data for wind resource assessment over a large geographic area, together with aerodynamic roughness length z_0 from available databases, e.g. CORINE land cover (EEA, 2009), European wind atlas (Mortensen and Petersen, 1998), and Davenport-Wieringa roughness classification (Wieringa, 1992). The z_0 parameter is imperative for wind flow assessment in the inner ABL when using a logarithmic wind profile in order to estimate wind speed at different heights. Since the fast progression of laser-based active remote sensing technologies such as Light Detection And Ranging (LiDAR), it is possible to obtain an accurate 3D geometric description of a given geographic area. The airborne LiDAR device is mounted on an aircraft, where the scanner

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emits laser pulses towards the surface. Based on the time difference between the emission and the absorption of the pulse at the scanner, the position where the pulse hit the surface can be estimated accurately (Petrie and Toth, 2008). The result is a topologically unstructured point cloud consisting of millions of 3D points, which can be preprocessed adequately by using a topological structure. With high-resolution surface data availability, morphometric approaches have been used for estimating z_0 automatically (Holland et al., 2008; Millward-Hopkins et al., 2011; Dallman et al., 2013). Millward-Hopkins et al. (2013a, b) have developed a new morphometric model that considers heterogeneous height and surface area density, and have applied it successfully over low-resolution large geographic area for wind resource assessment. Millward-Hopkins et al. (2013c) also considered their morphometric model for more accurate wind resource assessment based on analytical Wind Atlas methodology over high-resolution urban geometry extracted from airborne LiDAR data.

The aforementioned related state-of-the-art methods for wind resource assessment, for the most part, do not consider high-resolution wind flow simulation using Computational Fluid Dynamics (CFD). Over the past few years, the use of Eulerian CFD has grown substantially within the field of Computational Wind Engineering (CWE). Reynolds Averaged Navier Stokes (RANS) with realisable k-ε and Large Eddy Simulation (LES) are one of the most representative turbulent models when simulating wind flow within the ABL layer over complex 3D geometry (Hussein and El-Shishiny, 2009; Wakes et al., 2010; van Hooff and Blocken, 2010; Milashuk and Crane, 2011; Blocken et al., 2012; Janssen et al., 2013; Flores et al., 2013, 2014; Toparlar et al., 2015). Many of these methods also consider standard wall functions with sand-grain roughness length, being related to aerodynamic roughness length (e.g. from Davenport-Wieringa classification (Wieringa, 1992)) as proposed by Blocken et al. (2007).

This paper presents a novel method for the purpose of wind resource assessment for a given geographic area by using the high-resolution geometry and morphometrically estimated z_0 from classified LiDAR data. The wind flow simulation is performed by using weakly compressible Smoothed Particle Hydrodynamics (SPH) done with DualSPHysics (Crespo et al., 2015) with a LES turbulence model. The wind energy potential at a given height is then estimated by integrating the estimated wind power for each meteorological time-step (e.g. 1 h) over a given timespan, based on simulated velocities over the input geometry. The main novelties in relation to state-of-the-art that are covered by the proposed method are as follows:

- more accurate wind resource assessment by using CFD over morphometric z_0, as opposed to analytical wind atlas methodology,
- higher computational efficiency is gained by simulating wind flow for each meteorological time-step in two interchangeable phases, firstly over the low-resolution DEM, and afterwards over the high-resolution preprocessed LiDAR data. The wind velocities are estimated likewise by two different approaches. In the first phase the average wind velocities are estimated by using logarithmic wind profile, typical meteorological year (TMY) and morphometric z_0. These velocities are then used as initial conditions to the second phase, where the wind power is based on simulated wind velocities at a given height.
- and showing suitability of using SPH for high-resolution wind resource assessment.

The paper is structured as follows. The next section describes the proposed method in detail, from preprocessing the input data to the proposed wind resource assessment method. The experiments are provided in the 3rd section, where the proposed method was performed over urban and rural LiDAR scanned areas. Furthermore, the simulated wind velocities were validated with measurements within the considered LiDAR scanned areas, while the advantages of the given method are shown in comparison to the analytical Wind Atlas approach. The last section concludes this paper.

List of symbols	
Δt	Meteorological data time-step
κ	von Kármán constant
$\mathbf{v}_z$	Velocity at given height z
c_i	i-th cell within the grid
F	Wind front cuboid dimensions
G	2.5 grid from classified LiDAR data
G^{DEM}	2.5 grid representing DEM
G_{diag}	Length of diagonal over G
res	Resolution of a given grid
z	Height
z_0	Aerodynamic roughness length
z_d	Displacement height
z_{ref_d}	Reference displacement height
z_{ref}	Reference height
Abbreviations	
ABL	Atmospheric Boundary Layer
CFD	Computational Fluid Dynamics
CWE	Computational Wind Engineering
DEM	Digital Elevation Model
DTM	Digital Terrain Model
GIS	Geographic Information System
IDW	Inverse Distance Weighting
LES	Large Eddy Simulation
LiDAR	Light Detection And Ranging
RANS	Reynolds Averaged Navier-Stokes
SPH	Smoothed Particle Hydrodynamics
TMY	Typical Meteorological Year

2. Methodology

The overview of the proposed method can be seen in Fig. 1, where the method is divided roughly into the preprocessing and simulation phases. At first, a low and the high-resolution computational domains are established by using DEM and a preprocessed LiDAR point cloud as 2.5D grid structure, respectively. The above-ground heights can be estimated using DTM. Then, the aerodynamic roughness length z_0 and zero-plane displacement z_d are estimated with a morphometric approach. For each meteorological time-step, the SPH-based simulation is firstly performed in the low-resolution computational domain that is constructed using the DEM of the LiDAR scanned area's surroundings. The logarithmic wind profile is used for initializing wind particles' velocities at the given domain inlet by using z_0, z_d, and TMY of the long-term meteorological measurements. Afterwards, the simulation is performed in the high-resolution computational domain that is based on 2.5D grid. In this domain the wind particles are initialized using the logarithmic wind profile and average velocities from the simulation performed a priori in the low-resolution computational domain. Finally, the wind energy potential is estimated at a given height for each 2.5D cell.

The proposed method is described in more detail in the continuation. The next subsection describes the preprocessing phase of the remote sensing data, morphometric z_0 and meteorological measurements. The second and third subsections provide descriptions of the used SPH methodology for wind flow simulation and the established boundary conditions within the computational