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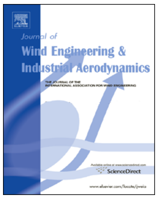

Harmonic buffeting in a high-altitude ridge-mounted triblade Horizontal Axis Wind Turbine

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ABSTRACT

In the context of high-altitude mountain ridges, harvesting energy with wind turbines presents new challenges. The results of a computer model solving the Reynolds-Averaged Navier–Stokes equations for incompressible flows above such a ridge are presented in the context of a case study. A theoretical blade-element model of a triblade Horizontal-Axis Wind Turbine (HAWT) was implemented. By combining both models we show that a wind turbine placed at such a location may receive less dense incoming air with repercussions on power output, as well as other unforeseen effects due to airflow negative vertical incidence such as the appearance of harmonic cyclic torque both in the turbine main shaft and nacelle yaw-control system.

1. Introduction

Along with the price increases for petroleum-derived fuels, on- and offshore wind turbine installations are becoming a familiar sight in Europe and other continents. Some variations in spatial distribution are emerging, however. In the year 2000, 85% of wind generation capacity in Europe was concentrated in three countries: Denmark, Germany and Spain. This is no longer the case, rather the tendency in recent years is towards increasing development in southern and eastern European countries, accompanied by a continuing development of onshore installations in Northern European countries such as Germany and Sweden (The European Wind Energy Association (EWEA), 2012).

Since modern wind turbines are a considerable investment to their owners and expected to function for long periods of time, the importance of being able to model cyclic forces applied on real wind turbines is accepted (Muhammad and Ristow, 2010). Most modern wind turbines are of the Horizontal-Axis Wind Turbine (HAWT) type, in which a windward-facing triblade rotor turns on a horizontal axis, while a control mechanism turns the complete rotor head assembly on a vertical (yaw) axis, keeping it constantly pointed into the wind. For this reason, building computer models to calculate steady and cyclic forces affecting a HAWT is a field that has attracted some attention since real-world applications of wind turbines have become widespread. Once such a model has been built and validated, we can estimate the resulting effects on machine integrity (Quarton et al., 1996).

However, such models tend to hypothesize an ideal situation in which the wind turbine is situated on a flat surface and within a fluid structure that can be approximated using the power law. Models then focus on variations within wind structure such as wind shear (Shen et al., 2011) and unsteady flows (Bermúdez et al., 2000). This may be a good approximation for offshore installations or those in flat countries under some conditions, under which the Prandtl log profile law may be used to model the boundary layer

$$\frac{v(z)}{v_0} \approx \frac{1}{\kappa} \cdot \ln\left(\frac{z}{z_0}\right)$$

with κ the von Kármán constant, v_0 reference incident wind speed (m/s) and z_0 the surface roughness length (m). Some authors, such as van den Berg (2004), note that this assumption may not always be valid, for instance during nighttime.

On the other hand, geographical conditions in Southern Europe are often quite different from those encountered in Northern Europe: instead of the flat shallow seabeds or wide-open plains typical of northern wind farms, the terrain presents a more varied topography. Southern European wind farms such as Rivesaltes

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(Roussilon, France) or Collet dels Feixos (Catalonia, Spain) tend to group wind turbines along ridges in order to maximize exposure.

The demographic pressure and economic activities along the coastline have a tendency to displace wind energy installations further inland and into the more mountainous regions. Visual impact and concerns raised by their effect on wildlife (Barrios and Rodriguez, 2004) are of importance in areas with economies based on tourist activities.

In this paper, our objectives are to build and validate a wind pattern modeling technique applicable to sharp mountain ridges, and thus obtain the cyclic forces received by a triblade HAWT placed in such a situation. At this time the actual wind flows encountered by wind turbines in mountain sites have been less studied in the literature. Taylor and Lee (1984) and Taylor and Teunissen (1987) concentrated on relatively low hills (specifically Askervein Hill, 116 m high). More recently, Bitsuamlak et al. (2004) discuss numerical models of complex terrain, but without coupling them with a HAWT model.

This is why in Section 2 we present a study that combines two distinct computer models. The first is a regional wind circulation Computational Fluid Dynamics (CFD) model that produces a simulation of wind flow. Its results are then used as inputs for the second model, a Blade Element Model (BEM) of a wind turbine that predicts yaw and tilt torque as well as overall power output under simulated field conditions. The influence of the HAWT on wind circulation is neglected; the two models are thus one-way coupled.

In Section 3, we present the results obtained by the combined computational model, as applied to an actual case study. They may help site engineers' awareness of situational differences between an installation site in a geographically flatter region, and a projected mountain ridge installation, with a view to better protect the investments made.

Finally, in Section 4, we develop a theoretical model to interpret and put these results into a wider perspective.

2. Material and methods

Our target is to build a wind circulation computer model for an orographically complicated terrain. Such terrain presents a challenge in that fluid circulation must be modeled for larger mountain valleys with lengths of several km, but also in sufficient detail to reproduce well smaller scales in the vicinity of the HAWT itself.

Topographical data is taken from the Space Shuttle Radar Topography Mission (Farr et al., 2007) This data set presents $1 \times 1^{\circ}$ (latitude $\times$ longitude) height grids, which at our latitudes give a horizontal resolution of 68 m in the East–West direction, and 93 m North–South. This is the best resolution obtainable to us without resorting to interpolation. In order to make efficient use of available computing power, nested meshes on three levels were used, with successive horizontal mesh sizes of 81.981×111.194, 34.130×46.292 and 6.826×9.258 m. Each successive mesh has shared points (both on the border and within the mesh volume) with the previous mesh so as to ensure flow continuity.

So as not to produce low-quality (deformed) mesh elements, vertical mesh resolution is limited by horizontal resolution. For this reason, all meshes have a vertical resolution of 25 m, thus giving us several vertical data points in the vicinity of the HAWT. Since high-altitude flows are considered less expensive to model from a computation standpoint, a uniform vertical resolution is used from the level of the terrain within the 2–3 m range above sea level (a.s.l.) up to an upper limit of 7.5 m.

Based on our previous work (Ward and Jorba, 2011), we implement a mesh optimization technique to treat the problem of mesh element deformation that appears in complex terrain forms.

Air pressure, temperature and density components are calculated using the ISA Standard Atmosphere Model (derived from the U.S. Standard Atmosphere, 1976 and Talay, 1975) as pressure input. The temperature gradient (standard: 0.0065 K/m, local: 0.00609 K/m) is adapted to local conditions through analysis of nearby decade-long instrumental temperature records, and used to adjust local air density.

The Reynolds-Averaged Navier–Stokes equations for incompressible flow were modeled using the well-known standard $\kappa - \epsilon$ turbulence model (Jones and Launder, 1972). No temperature variations or heat exchange were considered within the fluid, thus simplifying the model since buoyancy did not need to be handled.

The boundary layer was modeled in two ways. In a first approximation, a simple slip boundary condition was used, maintaining zero normal gradient at the ground interface. A second method was then implemented, modeling surface roughness with the k_s method. Since our target were high-altitude HAWT installations, typical ground surfaces in the vicinity of the HAWT are either short grass typical of the alpine mountain stage, or snow and ice. In either case, surface roughness lengths in the 0.002–0.5 m range are to be expected (Singh and Singh, 2001). $z_0 = 0.01$ m was chosen as reference value, giving roughness height $k_s = 30 \cdot z_0 = 0.3$ m and roughness constant $C_s = (9.793/k_s) \cdot z_0 = 0.33$ (dimensionless) as suggested by Blocken, et al. (2007).

Finally, the PISO method (Issa, 1986) was used for the numerical solver using the open-source OpenFOAM toolkit.

As for the second computer model (modeling the HAWT itself), many HAWT modeling techniques have been proposed. The earliest Blade Element Model (BEM) (Glauert, 1935) has been criticized for its relatively poor comparison with experimental data (Smulders et al., 1981; Helmis et al., 1995). Modern techniques such as the vortex method (Afjeh and Keith, 1986), potential methods (Bermúdez et al., 2000), particle methods (Voutsinas et al., 1995) or, more recently, a lattice method proposed by Pesmajoglou and Graham (2000), take into account wake structure to better approximate forces acting on each turbine blade segment. Combined methods have also been proposed, for example (Conway, 2002; Dobrev et al., 2007).

These methods present the advantage of modeling the wind turbine not as an isolated element, but as one more aerodynamic influence within a global flow, and may be seen as a modern continuation of the actuator disk model proposed originally by Froude (1889) and adapted to wind turbines by Betz (1920). A related development has been the actuator line method (Sorensen and Wen, 2002) and object of recent studies such as Troldborg (2008), or the actuator surface (Masson and Watters, 2008).

Methods such as finite elements and multi-body systems to take structure deformation during operation into account (see review of the field in Passon and Kühn, 2005) have been in use since the late 2000s to model HAWTs themselves and immediately surrounding airflow. However, these models suppose a regular environment for the HAWT in order to simplify calculations. We cannot do so, and for this reason think that the blade element model is the most reasonable choice for situations that present a complex input flow such as a high-mountain ridge.

On the other hand, the geographic situations considered often present transportation issues due to narrow roads with curves, and for this reason we hypothesize maximum blade length of 25 m. Larger physical HAWT sizes would not be transportable since individual turbine blades must be shipped as a complete assembly. For this reason we build a standard BEM model based on an existing type of HAWT, the Enercon E48. This class of triblade HAWT with 48 m rotor diameter and 800 kW maximum power output is small by modern standards. But it is also at the larger end of the range of machines that could realistically be transported up to installation sites.