Wind Turbine Wake Encounter by Light Aircraft

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I.Introduction

The wakes generated by wind turbines have similar, but not identical, characteristics to aircraft wakes. They can also be hazardous to passing-by flying vehicles as in the case of aircraft wake encounters. Fixed-wing aircraft wake vortices and aircraft encountering the wake generated by another aircraft have been well studied [1–4]. There are also clear definitions of the separation time or distance criteria used for the prevention of aircraft wake encounters between fixed-wing aircraft [5, 6]. Rotorcraft far wakes were also investigated using flight tests [7] and flyby light detection and ranging (LIDAR) measurements [8]. There is some guidance for helicopter wake encounters, for example, the three-rotor-diameter separation distance described in [5]. For the case of a landing aircraft encountering helicopter wakes at a low altitude and a low speed, engineering wake modeling and piloted flight simulations were used to study the encounter severity [9]. Wind turbine wake encounters are far less studied [10, 11]. In the UK, wind turbines are being proposed and built close to aerodromes, hence the need to assess their impact, in particular to light aircraft and helicopters [12].

There are similarities between helicopter and wind turbine wakes, and some helicopter wake models can be adapted to wind turbines. For example, prescribed vortex wake models [13] have been developed for wind turbine applications [14]. Kinematic wake deficit models [10], based on self-similar velocity deficit profiles and global momentum conservation, are popular in the literature to predict a wind turbine's far wake, where flow convection and turbulent diffusion are the two main mechanisms that determine the downwind flow field.

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With increasing computer power, grid-based CFD simulations of wind turbines using the Navier–Stokes (NS) equations have become practical. Recently, full CFD methods [15, 16] were used to study the wake development and breakdown on a three-bladed rotor model of 4.5 m diameter. This rotor model was used in the MEXICO project [17], where blade surface pressure and wake velocity measurements with particle image velocimetry (PIV) were carried out in the DNW wind tunnel. The effects of wind shear, terrain and ambient turbulence were normally ignored. Therefore such results correspond to the strongest and most coherent wakes possible.

LIDAR sensors have thus far been used for characterization of aircraft wake vortices [18] and identification of aircraft wakes to alleviate wake impact [19]. However, published LIDAR measurements of wind turbine wakes are still rare and the data is highly dependent on local atmospheric conditions.

II.Wind turbine wake field measurement campaign

LIDAR measurements of wind turbine wakes were undertaken at the East Midlands airport in the UK, where two WTN250 wind turbines are installed. The WTN250 has a 3-bladed up-wind rotor with a diameter of 30 m and a rotor speed of 40 rpm. The wind turbines were installed on the south side of the runway at a distance about 22.5 rotor diameters (675 m) from the runway. The LIDAR was set-up by SgurrEnergy engineers to the north of the runway, about 868 m from the wind turbines (Fig. 1). The campaign started in Feb. 2014 and took two months to complete.

A. Galion LIDAR set-up and data processing

A Galion G4000 LIDAR, with a pulsed laser frequency of 20kz and a range of 4km was used. A gate overlapping technique was adopted to refine the measurement resolution. As shown in Fig. 1, the azimuth range of the scan was set from 180.694° to 186.454° at 0.24° intervals. The scan plane included 25 rays in the azimuth and covered an area from 478 m to 878 m in the radial direction with a 3 m overlap, producing 133 measurement points per-ray. A single scan took 35 sec to complete.

The LIDAR set-up fixed the scan plane in the downwind region and captured wind turbine wakes for southerly winds. The wind turbine cut-off wind speed was 4 m/s, hence a wind screening process was conducted using aerodrome weather data and the data from an anemometer located close to the LIDAR unit to identify meaningful scan data.

B. Results and discussion of the LIDAR campaign

The LIDAR captures the mean velocity deficits, and due to temporal variations in wind speed/direction, ten, thirty and sixty minute statistical measurements were used to represent the averaged mean velocity deficits.

Typical results for the WTN250 wind turbine wake are presented in Fig. 2, where two, ten-minute averaged line of sight velocity contours between 2 pm to 3 pm on 07/04/2014 are plotted. The wind direction changes during these one-hour measurements were between 190° to 210° and the wind speed changes were between 17 kt to 18 kt. The estimated location of the wind turbine rotor and the arcs between one and five rotor diameters from the hub are indicated in the figures. The one-hour statistical data reveal that the wake velocity deficit was recovered to approximately 10% of the free-stream wind speed at a downstream distance of 5D.

The LIDAR measurements were first compared with the full CFD results [16], indirectly, as the full CFD method was applied to the MEXICO rotor in a uniform inflow [16]. The CFD results revealed that wake instability started at a position of about 2.5D downstream of the rotor and the breakdown occurred further downstream between 3D and 4D. The mean velocity in the wake was about 63% of the free-stream wind speed at 5D downstream. As a reference, at a wind speed of 10 m/s, the WTN250 wind turbine tip speed ratio is 6.3, close to that of the CFD case.

The PARK [20] wake velocity deficit model was applied to the WTN250 wind turbine at a wind speed of 10 m/s. The PARK model predicted the mean velocity deficit recovered to 10% of the free-stream wind speed at about 4D. In this model, the effect of wind shear, terrain and ambient turbulence were not taken into account. These effects, however, would shorten the distances for wind recovery.

The LIDAR data indicate that the effects of the wind turbine rotor wake, in terms of velocity deficit, are limited within a downwind distance of 5D for this relatively small wind turbine (30 m diameter). This is in agreement with the CFD and the velocity deficit models.

III. Wind turbine wake encounter flight simulation

Piloted flight simulations were carried out using the HELIFLIGHT simulator [21] to investigate the severity of a wind turbine wake encounter. The wake encountering aircraft was a General Aviation (GA) training aircraft configured to be similar to a Grob Tutor. A flight dynamics model of this aircraft was developed using FLIGHTLAB. The wind turbine wake velocity fields, generated by the Kocurek model [13], were integrated into the aircraft dynamics model as interference effects on the aircraft's airframe and control surfaces using look-up tables.

During the simulations the aircraft state information was recorded, together with the pilot's control inputs, to provide a quantitative measure of the effect of the wake on the aircraft. After each set of runs, the pilot rated the hazard using the Wake Vortex Severity Rating Scale [22] to provide a subjective assessment of the level of wake encounter hazard. Two test pilots and two student pilots participated in the flight simulation trials.

A. Wake encounter scenarios

The wind turbine wake encounter scenario was designed for a light aircraft approaching an airport, where a WTN250 wind turbine was installed. The WTN250 wind turbine rotor hub was positioned at a height of 100 ft above the ground, and at several offsets from the centerline of the runway at orientation angles of 90° (crossing) and 45° (oblique). The pilots were asked to fly the aircraft at different altitudes along the runway to penetrate the wind turbine wake to simulate the crossing and oblique wake encounters (Fig.3). A wind speed of 10 m/s was used in the simulation for the wake generation.

B. Simulation results and discussion

The results of a typical wake encounter are shown in Fig. 4, where the aircraft dynamic responses are plotted during the approach. In this case, the pilot flew GA aircraft through the wind turbine wake at the same altitude as the height of the wind turbine rotor centre (100 ft) in the crossing encounter. A severity rating B (indicating minor aircraft state excursions which require minimal control corrections) was awarded by the pilot for this encounter which generated yaw disturbances of less than 10°.

The most significant disturbance caused by a wind turbine wake is in its axial direction and is manifested as a velocity deficit in the downwind region. The axial velocity gradients affected the aircraft's flight dynamics by exerting side-forces on the aircraft and caused yaw angle changes when it entered and left the wake region.

IV. Conclusion and future work

Wake field measurements using LIDAR were carried out on a WTN250 wind turbine located at the East Midlands airport in the UK. The measurements captured the wake flow patterns in terms of wake induced mean velocity deficit and indicated that for this particular wind turbine, the mean wake velocities recovered to the free-stream wind speed at a position about five rotor diameters downstream. The LIDAR measurements were compared with the results of a full CFD simulation, which was conducted on the MEXICO wind turbine with a similar tip speed ratio, and also compared with the wind turbine velocity deficit wake models. In general, reasonable agreement was shown.

The piloted flight simulation results suggest that the WTN250 wind turbine wake mainly generated yaw disturbances on the encountering aircraft of less than 10°. The wake encounter severity was regarded as minor.

The wake model and the LIDAR measurements can only generate the wake velocity deficit flow fields. The mean velocity deficits in wind turbine wakes normally decay faster than that of the wake turbulence [10, 11]. The wake turbulence persists further downstream. If the length scales of the wake turbulence are compatible with the size of aircraft lifting surfaces, it could cause unsteady upsets on the encountering aircraft. Methods of modelling and measuring wind turbine wake turbulence will be sought and be implemented in future wake encounter flight simulations.

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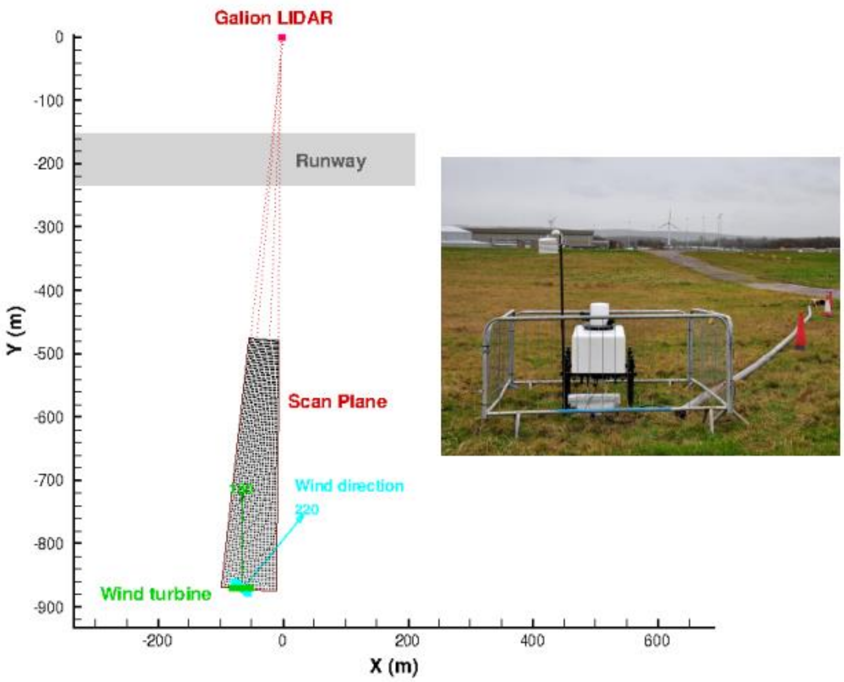
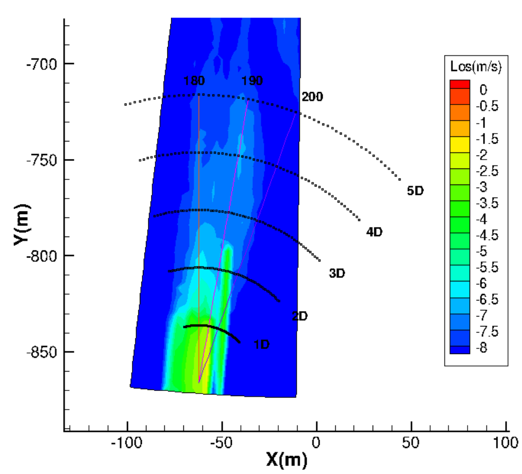


Fig. 1 Schematic of the LIDAR scan plane of wind turbine wake measurements.
On-site Galion LIDAR is shown by the insert picture.



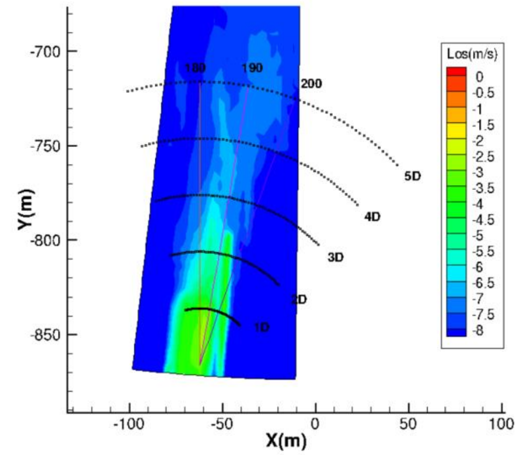


Fig. 2 Ten-minute averaged line of sight (Los) velocity, measured on 07-07-2014,

14:20 – 14:30 (left), 14:30 – 14:40 (right).

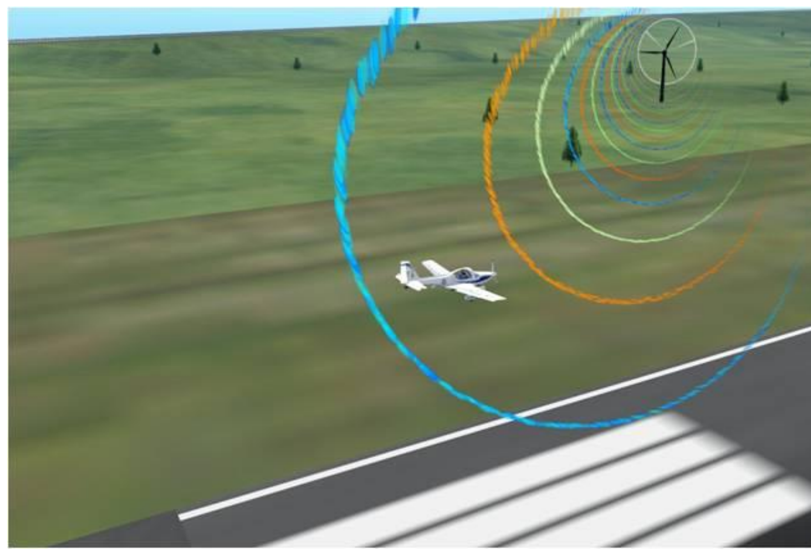


Fig. 3 Simulation scene of a light aircraft encountering wind turbine wakes.

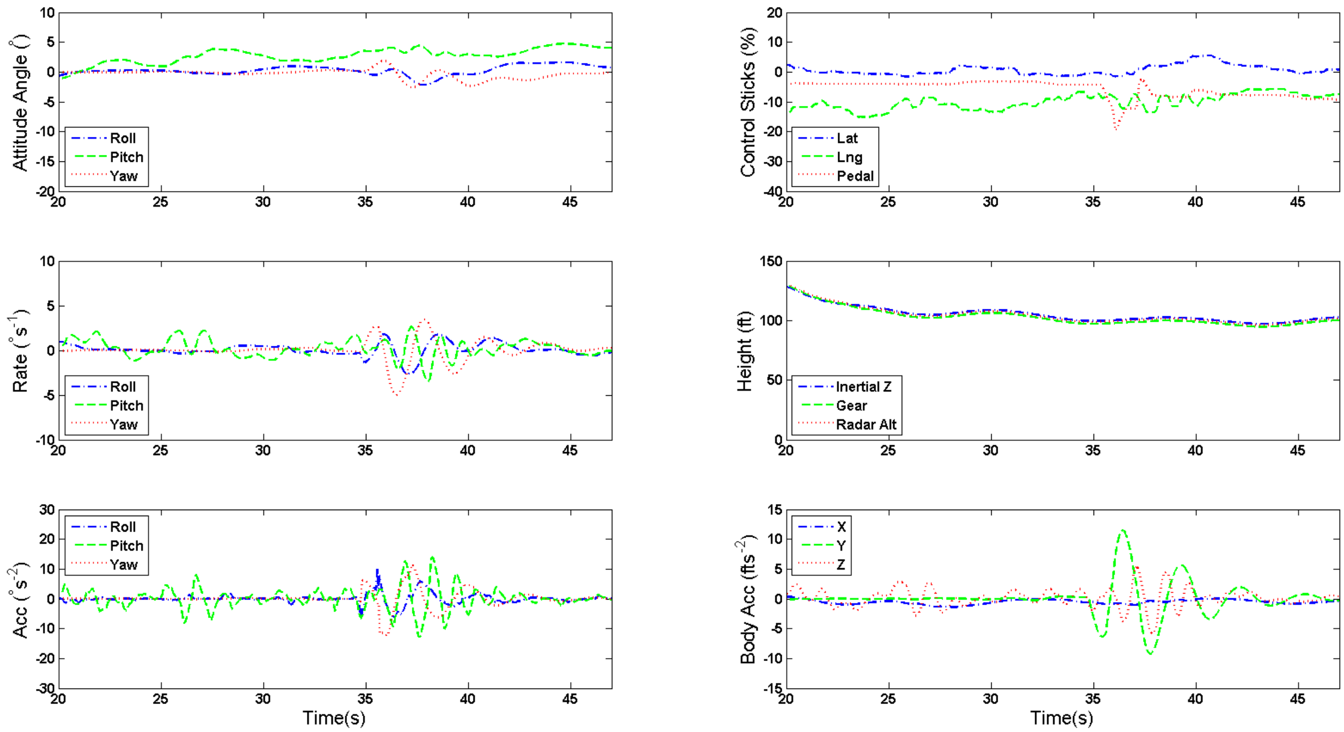


Fig. 4 Dynamic responses of GA aircraft and pilot's control activities during wake encounter, WTN250 wind turbine hub height 100 ft, wind speed 10 m/s, crossing encounter, offset 1.5 rotor diameters.