MODELLING OF WIND SPEED AND TURBULENCE INTENSITY FOR A FORESTED SITE IN COMPLEX TERRAIN.

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ABSTRACT: With more and more onshore sites being developed in complex terrain and complex forestry environment, there is an increased need for accurate flow modelling. This contribution aims at quantifying the level of accuracy that can be achieved from CFD on complex sites. The site analysed is that of Harestanes, where the complexity arises as much from the forestry cover as it does from the terrain, and where data at masts was available at masts near hill tops and at a mast in a heavily forested valley. This work shows that simulations including the effect of free stream atmospheric stability deliver significant improvement in average wind speed cross predictions, particularly so at difficult mast locations where the maximum error in the predicted wind speed is reduced from 24% in a purely neutral case to 6.5% with stability. The inclusion of the free stream stability also helps improving the prediction of turbulence intensity ratios by direction compared to a purely neutral case. In the second part of the paper, the occurrence of flow separation predicted by the model in some circumstances is investigated. A comparison between the CFD results and Galion LIDAR data is undertaken, which shows that the behaviour in terms of flow separation predicted by the model is confirmed by the Galion data. It appears that the occurrence of massive flow separation on this site cannot be explained alone by slopes exceeding the critical slope for separation, even when accounting for the fact that the critical slope is reduced by the presence of forestry. It is suggested that the massive separation seen in some particular instances is triggered by a well defined forest edge with a direction more or less perpendicular to the flow travelling over it.

1. INTRODUCTION

With more and more onshore sites being developed in complex terrain and complex forestry environments, there is an increased risk for wind turbines to be exposed to adverse conditions, such as flow separation, negative shear exponent factors, and increased turbulence intensity. These all have implications for turbine longevity and energy output. On difficult sites, standard industry tools such as linearised models are typically used outside of the envelope where they are meant to operate \cite{1}. CFD models on the other hand are increasingly advocated as better suited for the task in complex conditions \cite{2}, thanks in particular to their ability to account for non-linear effects, turbulence, flow separation and also atmospheric stability. While some validation material on the use of CFD for wind resource assessment is emerging, there is still a need for model validation, particularly so when both complex forestry and orography occur on a given site.

The present contribution attempts such a validation, in the first part through a mast to mast cross prediction exercise, and in the second part through a comparison of model results with LIDAR data.

2. SITE DESCRIPTION

The investigation is carried out for the site of Harestanes (Figure 1), which is situated in the Scottish Borders, and is being developed by ScottishPower Renewables. Within a radius of 10 km around the site, the terrain elevation varies between 50 and 700 m above sea level. While the topography is complex, the slopes surrounding the site are by no means extreme, with few locations showing slopes that exceed the critical slope for flow separation (see Section 3.2). The complexity on the site arises more from the forestry cover, which comprises different coupes, each with its own size, shape, height and density, and which varies in time as the trees grow and the coupes are felled. The varying shades of green shown in Figure 1 represent the canopy height at the end of 2010 (representative for the forestry cover at the time of the LIDAR campaign).

The site was equipped with 4 masts, 3 of which are shown in Figure 1. These masts
had long term concurrent time series (from 29/10/2005 to 21/05/2009) that were used for the cross prediction exercise. The masts at Holehouse Hill and Hareshaw Rig are located near hill tops, while the mast at Bran Rig is located lower down in a valley in a region where tall forestry is located in the prevailing wind direction (west). All masts were equipped with cup anemometers at heights of 70 (2 instruments), 60, 40 and 30 m. At the three lower heights, the instruments are mounted such that winds blowing from the north-east (direction 45°) are affected by mast shadowing effects.

The wind regime around the site shows winds blowing predominantly from the north-west, west and south-west (Figure 2).

Figure 1. Details of forestry, mast locations and terrain elevation in the central part of the domain. Location of RHI plane scans shown by black lines. Forestry map for year 2010, representative of forestry cover at time of Galion measurements.

Figure 2. Wind rose at Holehouse Hill (70m).

More recently (November-December 2011), a measurement campaign using a Galion LIDAR was set up with the LIDAR located half way between Hareshaw Rig and Bran Rig (pink spot in Figure 1) and pointing towards the ‘Wee Queensberry’, over a series of forestry coupes with forestry edges more or less perpendicular to the LIDAR beam. The detail of the forestry coupes in the immediate proximity to the LIDAR location can see in the aerial view shown in Figure 3a, while the corresponding representation of the forestry coupes in the model is shown in Figure 3b. A comparison
of the two shows a good match between the model and actual layout everywhere except to the east of the site. From this good agreement, we expect the model forestry distribution to be suitable for cases with westerly wind directions, while some flow features may be missed by the model when the wind blow from the south east, where some forestry is missing in the model map.

The Galion LIDAR can be operated in various modes providing data on RHI scans (varying beam elevation, with a constant beam azimuth), PPI scans (varying beam azimuth, with a constant elevation), and stare scan (beam azimuth and elevation constant)[3]. The scan geometry for the Galion campaign in Harestanes is illustrated in Figure 4, with details of the scan geometry given in Table 1.

![Figure 3](image1.png)

Figure 3. a) Aerial view of the forestry cover, b) forestry representation in model in the proximity of the Galion location.

![Figure 4](image2.png)

Figure 4. Terrain and forestry from the Galion location with illustration of the scan geometry.

<table>
<thead>
<tr>
<th>Scan Type</th>
<th>Azimuth</th>
<th>Elevation</th>
</tr>
</thead>
<tbody>
<tr>
<td>RHI 1</td>
<td>275°</td>
<td>2° - 7.5°</td>
</tr>
<tr>
<td>PPI 1</td>
<td>240° - 300°</td>
<td>4°</td>
</tr>
<tr>
<td>Stare 1</td>
<td>275°</td>
<td>4°</td>
</tr>
<tr>
<td>Stare 2</td>
<td>275°</td>
<td>5.2°</td>
</tr>
<tr>
<td>Stare 3</td>
<td>275°</td>
<td>5.6°</td>
</tr>
<tr>
<td>RHI 2</td>
<td>290°</td>
<td>2° - 9°</td>
</tr>
<tr>
<td>PPI 2</td>
<td>250° - 310°</td>
<td>8°</td>
</tr>
</tbody>
</table>

Table 1. Details of the scan geometry for the Galion deployment.

3. NUMERICAL SIMULATION

The flow conditions around the site have been simulated with WindModeller [4], using the ANSYS CFX solver, with a domain with a 10.5 km radius and a domain height of 4000 m. The horizontal resolution in the central part of the domain has been varied from 50 m (for the cross prediction exercise) down to 20 m (for the comparison with the Galion data). In the vertical, the first cell height was set to 0.5 m using a geometric expansion of the cells in the vertical with an average expansion factor of 1.12.

Turbulence closure is provided via a RANS model, using the SST two-equation model [5]. The effect of the forest canopy on the flow and turbulence field is modelled via a resistive approach, using the Lopes da Costa model [6] as used in [4], with a constant forestry loss coefficient of 0.05 m⁻¹. The forest height is derived from a map of aerodynamic roughness, using a background aerodynamic roughness of 0.05 m and switching on the forest canopy model in regions where the roughness exceeds the background value. The tree height is assumed to be 20 times the aerodynamic roughness. To account for the fact that the leaf area density is likely to be decreasing with height, the forest canopy height is reduced from the tree height (by a factor 2/3) similar to the recommendations given in e.g. [7], [8].

When including the effects of atmospheric stability, WindModeller uses an approach based on the solution of an additional equation for the potential temperature similar
to [9]. The effect of buoyancy in the momentum equation is explicitly modelled with an additional body force in the vertical, expressed as a function of the potential temperature. This term allows taking into account channelling and/or resonant mountain waves effects in the presence of significant topography. Additional buoyancy source terms are also included in the turbulence model, changing turbulence production/dissipation, based on the vertical gradients of the potential temperature, thereby affecting the level of mixing in the boundary layer.

3.1 Mast to mast cross predictions

A mast to mast cross prediction exercise was undertaken, comparing results obtained with two different sets of stability conditions. A first set of simulations was done with purely neutral flow conditions, altogether neglecting any effect of atmospheric stability. The second set assumed that a pre-existing stable atmosphere prevails in the free stream, with conditions typical of the standard atmosphere. This was set up by prescribing a potential temperature profile at the inlet with a constant vertical gradient of 3.3 K/km. At the surface, adiabatic conditions are used, leading to neutral stability conditions in the surface layer. Both sets of simulations used the same upstream boundary conditions for the velocity and turbulence quantities at the inlet, using equilibrium profiles for neutral conditions [10] in the boundary layer (with an assumed height of \(0.25u_*/f\)), and constant values above. The forestry map used for the simulations for the mast to mast transposition exercise used a tree height distribution representative of 2008 (not shown).

Using the wind speed ratios between the masts, the time series at a reference mast is transposed to the various mast locations on the site. The average wind speed from the transposed time series is then compared to the average wind speed from the measured concurrent time series at the prediction site, and the absolute relative error of the prediction is calculated as

\[
\% \text{err} = \frac{|V_{\text{meas}} - V_{\text{pred}}|}{V_{\text{meas}}} \times 100
\]

The resulting maximum relative error of the mast to mast cross prediction for each pair of masts is summarised in Table 2. The value given for one pair of masts is the maximum of the absolute error when going from one mast to the other or vice versa. For the columns on the left, only the cross predictions from 70 m above the ground to 70 m above the ground were considered, while on the right the cross prediction goes from 70 m above the ground to all anemometer heights. These errors show that while the purely neutral simulations are able to explain reasonably well the relationship between the Holehouse Hill and Hareshaw Rig masts (both near hill tops), it fails for pairs of masts involving the Bran Rig mast (located in the valley). Taking into account the effect of the free stream atmospheric stability, the model is then able to more consistently predict the wind conditions at all three masts, reducing the maximum error in the data transposition from 24% to 6.5%.

<table>
<thead>
<tr>
<th>Model</th>
<th>3 masts (70m only)</th>
<th>3 masts (all heights)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BRAN-HOL</td>
<td>BRAN-HAR</td>
</tr>
<tr>
<td>Neutral</td>
<td>11.8%</td>
<td>13.3%</td>
</tr>
<tr>
<td>Stable</td>
<td>0.4%</td>
<td>4.1%</td>
</tr>
</tbody>
</table>

Table 2. Maximum relative error in average wind speed cross-prediction for the three pairs of masts. Left: maximum taken over anemometers at 70m only, right: maximum taken over anemometers at all heights.
To better understand the differences in results between the neutral and stable configurations, the model predictions at the various anemometers were analysed on a direction by direction basis. Example comparisons are given in Figure 5 to Figure 7, where the purely neutral results are displayed with blue diamonds and results with stability with red triangles.

Looking at the wind speed ratio between Holehouse Hill 30 m and Holehouse Hill 70 m (Figure 5, left), both the neutral and stable configurations provide a very good agreement with the data, leading to an error of less than 1% for both cases when predicting the average wind speed at Holehouse Hill 30 m, from Holehouse Hill 70 m. For the ratio of the wind speed at Bran Rig 30 m and Holehouse Hill 70 m (Figure 5, right), the purely neutral case shows a reasonable variation of the wind speed ratios with change in direction, but with a generally positive bias (leading to an error of 24% in the average wind speed predicted at Bran Rig 30 m from Holehouse Hill 70 m). The bias is reduced when free stream stability is included and the error of prediction of average wind speed from Holehouse Hill 70 m to Bran Rig 30 m is less than 1%. The reduction in the bias when going from Holehouse Hill to Bran Rig is seen for all anemometer heights at Bran Rig (not shown). Rather than being caused by a significant difference in the prediction of the shear, the improvement in the prediction at Bran Rig seems to be associated with a change of the wind speed high up above the Bran Rig location.

The turbulence intensity (TI) ratios between Bran Rig 70 m and Holehouse Hill 70 m as well as between Hareshaw Rig 70 m and Holehouse Hill 70 m are shown in Figure 6 where they are compared to average data (grey symbols and error bars for standard deviation). When using a purely neutral setup (blue diamonds), the predicted TI ratios show relatively little variation with the direction, variation which clearly does not reproduce what is seen in the data. When free stream stability is included (red triangles), some variation of TI with the direction is captured and the predicted TI ratios generally agree better with the average data. The absolute values of the predicted TI (not shown) are reasonable at 70 m, but tend to be underpredicted at the lower heights.

For the shear exponent factor between 40 and 60 m (Figure 7), it is worth pointing out the extreme values seen at Bran Rig, with values exceeding 0.6 for the wind directions between 200 and 300. These observed values significantly exceed the typical design value of 0.2 taken according to IEC 61400-1 standard [11]. In general the model is able to capture the large difference in shear exponent factor between Holehouse Hill and Bran Rig. Including stable free stream conditions leads on average to slightly increased shear values. Except for the 280° sector at Bran Rig, the average shear exponent factor tends to be slightly better predicted when stability is included than when running purely neutral.

Figure 5. Wind speed ratio between anemometer and Holehouse Hill (70 m) by direction. Grey: average data and standard deviation. Red triangles: model results with stability, Blue diamonds: model results neutral. Left: Holehouse Hill 30 m, Right: Bran Rig 30 m.
3.2 Comparison with Galion data

The second part of the work looks at identifying flow features and comparing CFD results with data obtained during the Galion deployment. The simulations for this part were run with atmospheric stability, using a horizontal mesh resolution of 20 m in the central part of the domain. The forestry cover was as shown in Figure 1 and is representative of the forestry cover at the time of the Galion deployment. When comparing data with the Galion campaign, we focused on flow directions from the 250 to 310 sector, for which the flow direction is mainly along the line of sight (LOS) of the Galion beam. From the simulations we can identify regions of likely flow separation by looking for regions where the flow direction departs from the flow direction at the inlet by more than 90 degrees. These are shown with the yellow isosurface in Figure 8a. The simulations show that for wind directions from 250 to 300, some regions of flow separation are visible but on closer investigation, these are mostly occurring within the forest canopy. For the wind direction 310 however, a massively separated flow region appears (within the red circle in Figure 8a, r.h.s.) which happens to cross the RHI planes where the Galion scans are taken (identified with the black lines). From identifying regions where the slope along the flow direction exceeds the critical angle for separation (about 18 degrees in 2D [12]), shown in blue in Figure 8b, slope on its own can not explain the difference in the separation behaviour seen in the model between the wind directions 270 and 310. The presence of increased roughness is known to reduce the critical angle for separation [12]. Stuart et al [13] have proposed the following relationship between the critical angle for separation and the tree height:

\[ \alpha_{cr} = \alpha_0 - 0.25h \] (2)
Figure 8. a) Regions of likely flow separation (yellow isosurface) where the flow direction departs from the flow direction at the inlet by more than 90 degrees, b and c) regions where the slope along the flow direction exceeds the critical angle for separation (b: terrain only, c: terrain and forestry). Left: wind direction 270, right: wind direction 310.
Taking into account a variable critical angle vs. tree height as given in (2), we end up with a distribution of slopes along the flow direction exceeding the critical angle as shown in Figure 8c. While the extent of the regions where flow separation can be expected has increased when taking into account the effect of the forestry, these regions still do not explain why we get such a large difference in behaviour between the wind directions 270 and 310.

In order to assess whether the behaviour seen in the model is meaningful, a comparison with data obtained during the Galion campaign is undertaken.

The Galion LIDAR measures the line of sight (LOS) velocity along the laser beam. In order to have like with like comparisons, we plotted the same LOS velocity obtained from the CFD simulations. The comparison between LIDAR (top) and CFD (bottom) on the RHI 2 plane (plane pointing towards the azimuth 290) is shown in Figure 9 for the wind direction 270 and Figure 10 for the wind direction 310. Negative LOS velocities correspond to flow travelling towards the LIDAR, positive values corresponds to flow away from the LIDAR. The black isoline on the plots shows the location where the LOS velocity is 0, i.e. it delimitates regions with flow reversal. The reference wind speed in the CFD was adjusted in order to match the wind speed seen in the Galion data at high levels. The simulation to match the wind speed of the wind direction 270 case was set up with a reference wind speed of 10 m/s at 30m, while the simulation for the case with wind direction 310 used a reference wind speed of 18 m/s at 30m.

It is noticeable from the plots that the Galion data shows more flow structures than the CFD. This is because the Galion plots are produced by averaging 5 snapshots over 10 minutes and will therefore be seeing some of the turbulent structures present in the flow, while the CFD, based on a RANS approach, averages out the turbulent structures and represent these via turbulent quantities. This scale resolving issue aside, the agreement between the Galion plots and the CFD is quite remarkable. For the wind direction 270, both show no evidence of a well defined separation region down the slope, while for the wind direction 310 the massive separation seen in the CFD is very obvious in the Galion data. A good agreement is also seen on the RHI 1 plane (shown in the accompanying presentation).

As was shown here, the lack of strongly separated flow region for the wind direction 270 in the model is confirmed by the Galion data, and so is the presence of the massively separated region for the wind direction 310. At the moment a tentative explanation about the different behaviour between the two cases, is that the flow may separate off a well defined forestry edge, which in the 310 degree case is mostly perpendicular to the flow travelling over it.

Figure 9. Line of sight (LOS) velocity on RHI 2 plane for the wind direction 270. Top: Galion data, bottom: model results. Negative values: towards the LIDAR, positive: away from the LIDAR. Black isoline shows LOS Velocity of 0.
Variability to the extent and strength of the recirculation regions can be seen in the data, depending on the conditions (direction, reference wind speed) and such variability can also be seen in the CFD results. To illustrate this we show how the length of the recirculation region is increased in the CFD when the reference wind speed is reduced from 18 m/s (Figure 10) to 10 m/s (Figure 11) at 30 m.

4. CONCLUSIONS

This contribution aimed at quantifying the level of accuracy that can be achieved from CFD on complex sites. The site analysed was that of Harestanes, where the complexity arises as much from the forestry cover as it does from the terrain, and where data at masts was available at masts near hill tops and at a mast in a heavily forested valley. This work showed that simulations including the effect of free stream atmospheric stability delivered significant improvement in average wind speed cross predictions, particularly so at difficult mast locations where the maximum error in the predicted wind speed went from 24% in a purely neutral case to 6.5% with stability. The inclusion of the free stream stability also helped improve the prediction of turbulence intensity ratios by direction compared to a purely neutral case.

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5. Acknowledgements

The authors wish to acknowledge ScottishPower Renewables for access to the Harestanes site and data, as well as the Carbon Trust for part-funding the work under the project CT 0911-099.

6. References