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Published in:
Proceedings of The European Wind Energy Conference and Exhibition, EWEC 2007

Publication date:
2007

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Bechmann, A., Sørensen, N., & Johansen, J. (2007). Atmospheric Flow over Terrain using Hybrid RANS/LES. In *Proceedings of The European Wind Energy Conference and Exhibition, EWEC 2007* (pp. 64-67). The European Wind Energy Association. http://www.ewec2007.info/

Atmospheric Flow over Terrain using Hybrid RANS/LES

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Abstract

A hybrid RANS/LES model capable of simulating neutral atmospheric wind over natural terrain is presented. To reduce the computational cost of traditional LES the proposed method combines LES and a RANS wall model. Close to walls, where LES is computational expensive, the flow is treated with the RANS equations and this layer act as wall model for the outer flow handled by LES. The proposed model is based on the well-known two-equation $k-\epsilon$ RANS model and can either be run in LES-mode with wall modelling or in pure RANS mode. Calculations with RANS and the new LES model are presented for wind flow over the Askervein hill located in Scotland, and results are compared with measurements. Comparisons show that both RANS and the new LES model are able to capture the simple flow windward of the hill. In the complex wake region, however, only LES captures the high turbulence levels. The presented results are for a relative mild configuration of complex terrain, but the proposed method can also be used for highly complex terrain.

Keywords: CFD, terrain, large-eddy simulation

1 Introduction

For wind engineers to determine loads on wind turbines accurate wind information is important. With increased use of ever more complex sites for wind farms, local wind phenomena can be expected to greatly increase the structural loads on the wind turbines. When simulating wind over terrain using computational fluid dynamics (CFD) it is common to solve the incompressible RANS-equations (Reynolds-averaged Navier-Stokes) together with the $k-\epsilon$ turbulence model, using a finite-volume code. The solution of the RANS equations provides information on the mean wind and the mean level of turbulent kinetic energy at a site of interest. For many complex sites, however, the inherent unsteady features of the flow must be simulated in order to provide reliable predictions. To handle complex terrain, this paper proposes the use of large-eddy simulation (LES). LES resolves the turbulent structures larger than the finite-volumes and captures the flow unsteadiness.

The major downside of using LES compared to RANS is the increased computational cost. For high Reynolds number flows the amount of computational grid points required to resolve the near-wall turbulent structures using LES, are simply too large. Reducing computational cost of LES of wall-bounded flows is therefore a major challenge in CFD. Furthermore, to complicate things further the walls of atmospheric boundary layer flows are not smooth but consists of roughness elements. A computational mesh that resolves all the individual roughness elements is impossible. Ultimately, to alleviate the near-wall resolution requirement and solve the problem of the rough wall, approximate boundary conditions are necessary. We present a new LES model that is based on the high Reynolds number $k-\epsilon$ RANS model [5] found in most commercial CFD-solvers. To reduce computational cost and to be able to simulate flow over rough surfaces the proposed LES model solves the RANS equations close to the surface and switches to LES above. The near-wall RANS layer thereby act as wall model for the outer flow handled by LES. One advantage of this approach is that the wall-function, build into the $k-\epsilon$ RANS model, can be used directly to model the rough surface. The proposed model can be run as pure RANS or as LES with wall function dependent on the level of detail necessary.

In order to investigate the abilities of the new LES model for flow over terrain, we simulate the flow over the Askervein hill. The Askervein hill has been selected because of the experimental measurements available and because it has been extensively modelled by other researchers. During the Askervein hill project [14] both velocity and turbulence data was collected - we compare these measurements with simulation results of RANS and the new LES model. The goal of this paper is to demonstrate the possibility of using LES for wind over natural terrain.

2 Simulation methodology

2.1 Askervein hill

A difficulty when validating models designed to predict the wind over terrain, is finding thoroughly documented experimental measurements of wind over natural terrain. Probably the best known and best documented field campaign is that performed in 1982 and 1983 over the Askervein hill located at the Hebrides in Scotland [14]. The Askervein hill's highest point is 116m above the surroundings and its planform is almost elliptic with major axis of about 1km and 2km (se fig.1). The Askervein hill is relatively isolated apart from some downstream hills and the surface roughness is homogeneous with a roughness length of about $z_0 = 0.03m$ (suggested value by Taylor and Teunissen [14]). Since the Askervein hill project provided turbulence measurements, it is a valuable test case for validating the performance of turbulence models.

The specific measurements that we use for validation were taken during a three hour period on October 3, 1983 and are designated TU-03B [13]. During the three hour period the atmosphere was approximately neutrally stratified and the mean wind speed at 10m above ground was $8.9ms^{-1}$. This wind speed was measured at a reference location (RS) located 3km upstream of the Askervein hill's highest point (HT). Nine measuring instruments was located along a line (line A) that intersected HT (see e.g. fig. 3 later). At these locations measurements of mean wind and turbulence were made at a height of 10m - these measurements are used to validate numerical results.

Figure 1: Photograph of Askervein hill taken at an upstream location

2.2 CFD solver

The CFD code Ellipsys3D developed by Michelsen [6, 7] and Sørensen [10] has been used in all calculations. It is a multiblock finite-volume discretisation of the incompressible Navier-Stokes (NS) equations. The multi-block facilities allow for large parallel computations and the exchange of information between processors is handled using Message Passing Interface.

The code is formulated in general curvilinear coordinates that can accurately describe the terrain and the code uses non-staggered grids with all variables stored in cell centers. In all simulations the PISO algorithm [3] has been used to solve the equation system and pressure/velocity decoupling is avoided by applying the Rhie/Chow interpolation technique [9]. The TDMA solver (Tri-Diagonal Matrix Algorithm) is used in altering directions to solve the transport equations and pressure solution is accelerated using a multigrid method. The solution is advanced in time using a second order iterative time-stepping method where the global time-step, Δt, is chosen to give a maximum CFL-number (Courant-Friedrich-Levy) of no more than 0.25 ($\Delta t = 0.3s$). The convective terms are solved using a fourth-order central differencing scheme, based on deferred correction [4].

2.3 Hybrid RANS/LES model

Since it is computationally too expensive to resolve the whole range of turbulent scales found in atmospheric flows, a set of flow equations that can be solved numerically are necessary. Two approaches are commonly used. The traditional RANS approach provides a time-averaged description of the flow, while the spatial filter applied for LES gives a time-dependent solution of the turbulent structures larger than the spacing of the computational mesh. Fig. 2 gives a visual impression of the two approaches by showing the instantaneous contours of wind speed at a plane through the Askervein hill for the new LES model and for the $k-\epsilon$ RANS model.

The RANS-equations are derived from the standard NS-equations by decomposing the variables into time averaged and fluctuating components followed by time-averaging. Even though time averaging is performed, the transient term of the NS-equations is retained, making RANS able to predict transient behaviors, when instationarities are on a large timescale compared to the averaging time. This is sometimes denoted URANS (Unsteady RANS) but is here just denoted RANS. The idea behind LES is to apply a spatial filter to the NS-equations thereby obtain-

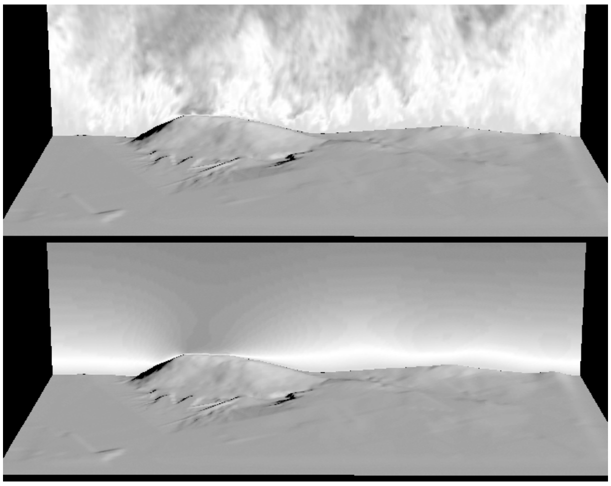

Figure 2: Cross sectional plane showing the instantaneous contours of wind speed for LES (top) and RANS (bottom) seen from an upstream location.

ing the LES-equations, which governs the turbulent structures larger than the filter-scale applied. Instead of explicitly applying a filter to the NS-equation, the finite-volume discretisation of the flow equations on a numerical mesh is interpreted as an implicit filter tied to the numerical resolution - only turbulent scales larger than the numerical mesh spacing are resolved. To be able to compare the wind fields from RANS simulations with the ones obtained from the highly unsteady LES, only ensemble averaged results are presented. These are obtained by time-averaging the statistically stationary RANS and LES wind fields over long time-periods.

As a result of time-averaging in RANS and filtering in LES a turbulent stress-term is produced, that needs to be modelled. The governing equations for RANS and LES are actually identical, but the turbulent stress-term needs to be modelled differently for the two approaches. The high Reynolds number $k - \epsilon$-model [5] is a widely used turbulence model for RANS. For this model the turbulent stress term is assumed to be the product of fluid strain and an eddy-viscosity. Based on dimensional grounds, the eddy-viscosity may be described as the product of a length scale and a velocity scale that should be characteristic for the turbulence that is modelled. For the $k - \epsilon$-model the two scales are constructed from values of turbulent kinetic energy, $\tilde{k}$, and dissipation of turbulent kinetic energy, $\tilde{\epsilon}$, determined by solving two transport equations. The high Reynolds number $k - \epsilon$ RANS model handles the rough surface of the earth by using a wall-function (the classical logarithmic wind profile) that relates the surface stress of the rough wall to the tangential near-wall velocity.

In order to develop a LES model for terrain simulations the $k - \epsilon$ RANS model is used as starting point. Since the LES model needs to handle flow over rough surfaces the wall-function used for RANS is also needed for LES. We adopt an approach where the near-wall flow is solved using RANS but blends to LES away from the wall. Thereby the wall-function build into the $k - \epsilon$ RANS model can be used directly and computational cost is reduced since a coarse computational mesh can be used in the RANS region. The approach is similar to DES (Detached-eddy simulation) [12], but can also be used for rough surface flows. More importantly, where DES is only designed to handle separated flow regions with LES, the idea behind the proposed turbulence model is to handle most of the flow using LES and only have a thin RANS layer near walls that act as a wall model for the outer flow. The switch between RANS and LES is performed by changing the characteristic length scale build into the eddy-viscosity. For RANS, the characteristic length scale represents all scales of the turbulent flow. For LES, the large turbulent structures are resolved, why the length scale represents the small unresolved structures that scale with the spacing of the computational mesh. Following Travin et al. [15] the dissipative term of the k-transport equation is modified to incorporate a new length scales, $\tilde{l}$,

$$\tilde{l} = \min\left(l_{RANS}, l_{LES}\right) = \min\left(\frac{\tilde{k}^{3/2}}{\tilde{\epsilon}}, C_\Delta \Delta\right) \qquad (1)$$

where Δ is the local maximum mesh spacing over the three directions and C_Δ is a model constant. The new length scale, $\tilde{l}$, automatically switches between RANS and LES. Near the wall l_{RANS} is smaller than l_{LES} and a RANS region is generated. Away from the wall l_{LES} is the smallest and the model switches to LES. Since turbulent structures from the LES region are mixed into the RANS region, the precise height of the switch is determined as part of the solution. For the presented simulation, however, the switch happens at a height of about 6m. Since this height is relative low compared to the hill height the presented RANS/LES model could be termed as LES with a wall model. It should be noted that the eddy-viscosity is still calculated using both $\tilde{k}$ and $\tilde{\epsilon}$ so the $k - \epsilon$-equations needs to be solved in the whole flow domain for both LES and RANS. A more detailed model description is found in [1] where C_Δ is determined by simulating decaying turbulence. A simple backscatter model that smoothen the RANS-LES transition region is also presented [1].

The $k-\epsilon$ model constants are adjusted to ensure the same level of turbulent kinetic energy at the reference location as found in the measurements. The turbulence intensity ($I=\sqrt{k}/u$) 10m above ground at RS was measured to 0.12. This turbulence level should be reproduced for both the pure RANS simulation and for the near-surface RANS layer of the LES. Using equation 4 (see later) it is found that $C_\mu = 0.11$. Additionally, other $k-\epsilon$ constants need to be modified from their standard value using,

$$C_{\epsilon 1} = C_{\epsilon 2} - \frac{\kappa^2}{C_\mu^{\frac{1}{2}} \sigma_\epsilon}, \tag{2}$$

$$C_\Delta = C_s C_\mu^{-3/4} \frac{C_{\epsilon 1}}{C_{\epsilon 2}} \tag{3}$$

where $\kappa = 0.4$ is the von Karman constant, $C_{\epsilon 2} = 1.92$, $\sigma_\epsilon = 1.30$ and $C_s = 0.144$ (see [1]). The model constants used are summarized in table 1.

Table 1: $k-\epsilon$ model constants for RANS and LES

C_μ	$C_{\epsilon 1}$	$C_{\epsilon 2}$	σ_k	σ_ϵ	C_Δ	κ
0.11	1.55	1.92	1.00	1.30	0.61	0.40

2.4 Computational mesh

Since the Ellipsys3D code uses terrain-following coordinates it is possible for the lower boundary of the computational mesh to follow the Askervein topography. To generate the mesh, contour lines of the Askervein hill and the surrounding area has been digitized. Two contour maps have been used - a high resolution map of the Askervein hill only, and a coarser map that includes the neighboring hills. The elevations of these maps are interpolated to a horizontal resolution of 23.3m using 240×240 grid points that covers an area of 5.6×5.6km. To provide a buffer zone between the Askervein hill and the computational outlet, the domain length is increased to 8.8km by additional 48 grid points. The height of the first near-wall grid cell is equal to the roughness length, $z_0 = 0.03m$. From this height the mesh is stretched in the vertical, using a 3D hyperbolic mesh generator based on [11], to a height ($z \approx 150m$) from where near-cubic grid cells are achieved ($\Delta = 23.3m$). 40 cells are used for the first 150m in order to capture the large near-surface velocity gradients. The total height of the computational domain is H=1500m and (288×240×96) grid cells are used (se fig. 3).

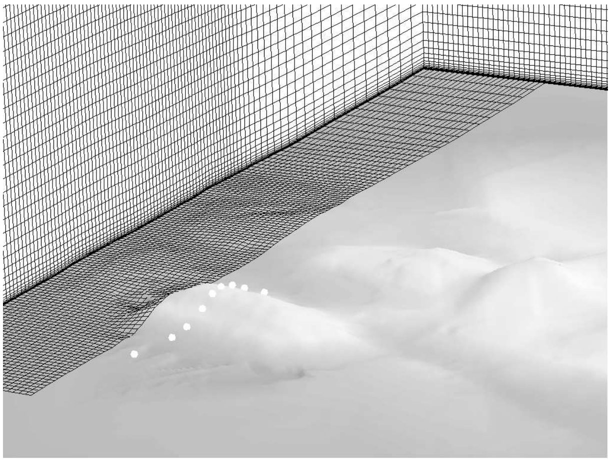

Figure 3: The Computational mesh. Only every second grid point is shown. The white dots denote the measuring stations located along line A.

At the top of the computational domain a symmetry boundary condition (friction free wall) is used ($\partial u/\partial z = \partial v/\partial z = 0, w = 0$). The symmetry condition's effect on the flow is to inhibit the turbulent normal motions while tangential motions are enhanced - the symmetry condition therefore resembles an inversion layer (a layer where temperature increase with height at the top of the atmospheric boundary layer). The transverse horizontal boundaries are specified as periodic and the Neumann boundary condition (zero normal gradient) is used at the outlet.

In order to simulate the wind over the Askervein hill, the "undisturbed" wind profile measured at RS is used as input to simulations. For RANS simulations, mean values of velocity $\langle u \rangle$, turbulent kinetic energy $\langle \tilde{k} \rangle$ and dissipation of turbulent kinetic energy $\langle \tilde{\epsilon} \rangle$ are specified at the inlet boundary by,

$$\langle u \rangle = \frac{u_*}{\kappa} \ln \frac{z}{z_0}, \quad \langle \tilde{k} \rangle = \frac{u_*^2}{C_\mu^{1/2}}, \quad \langle \tilde{\epsilon} \rangle = \frac{u_*^3}{\kappa z} \tag{4}$$

where $u_* = 0.618ms^{-1}$ is used. To provide a realistic turbulent inflow for LES, a separate simulation, a precursor, with streamwise periodic boundary conditions and flat terrain is performed. Coriolis forces are included ($f_c = 10^{-4}s^{-1}$) and the flow is driven by a constant pressure gradient of $0.0017Nm^{-3}$. Data from the precursor simulation is extracted from a transverse slice at every time step and is used as inflow for the Askervein simulation. To avoid spatial interpolation, the inflow boundary of the Askervein mesh exactly matches the precursor slice. Figure 4 shows the onset wind profile for LES and the logarithmic profile used for RANS compared to the measurements taken at the Askervein hill's reference location. As seen, the measured wind agree well with the wind profiles used for simulations. The turbulence intensity ($\sqrt{k}/u_{10m}$) for RANS is specified to 0.12 - equal the experimental value. For LES the simulated value is about 0.16 i.e. a bit higher than the experiment.

3 Results

80 minutes of turbulence from the precursor was saved and used as inflow for the LES simulation. The LES simulation was allowed 40 minutes of simulation time before results were sampled and averaged (over the final 40 minutes). Figure 5 gives an impression of the LES resolution before averaging. It shows five minute time series of the streamwise and vertical velocity fluctuation taken at the hill top 10m above ground level.

3.1 Mean velocity

The time-averaged velocity fields for RANS and LES are first compared with measurements. To allow comparisons the fractional wind speed-up ratio is defined,

$$\Delta S = \frac{\langle u(z')\rangle - \langle u_{ref}(z')\rangle}{\langle u_{ref}(z')\rangle} \tag{5}$$

where z' is the local height over terrain and $\langle u_{ref}(z')\rangle$ is the reference velocity. The reference velocity is taken at RS for the measurements and at the computational inlet for simulations (see figure 4).

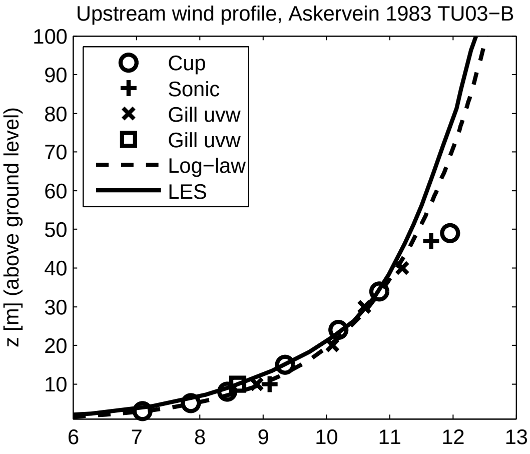

Figure 4: Comparison of the inflow wind speed profiles to the observed values at the reference site. The logarithmic profile used for RANS simulations with $u_* = 0.618 ms^{-1}$ and $z_0 = 0.03m$ is also shown

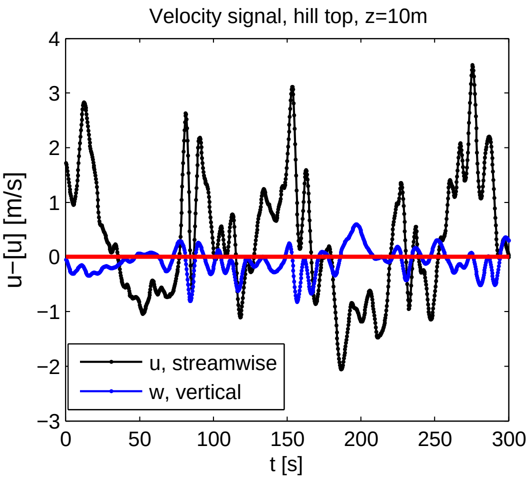

Figure 5: Time series of streamwise and vertical velocity fluctuation from the LES simulation. The time series are taken at the hill top (10m agl).

Figure 6 shows the observed and simulated speed-up at 10m above ground along line A. On the windward side of the hill RANS and LES produce similar results. The hill top speed-up is well captured by LES and slightly underestimated by RANS. The main difference in calculated speed-up is observed on the lee side of the hill. Here RANS slightly overestimates speed-up while LES underestimates. The reason for this discrepancy is related to the complex flow on the lee side. Several authors describe the flow

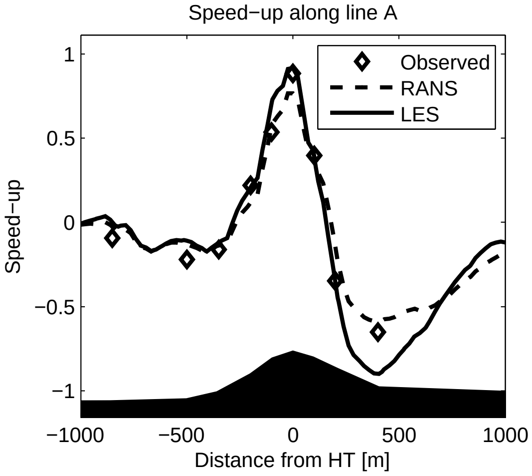

Figure 6: Comparison of observed velocity speed-up along line A to LES and RANS simulations. The dashed line shows the RANS result while the full line is for LES. Measurements are marked with diamonds.

as being on the verge of forming a separation zone or as having intermittent separation [2, 8]. RANS overestimates speed-up because it completely lacks separation while LES underestimates because the separation zone is overestimated. The mean region of reverse flow for LES is shown on figure 7. Here it is seen, that the final measuring point is located inside the recirculation region. The reason for the exaggerated separation zone may be related to the chosen value of surface roughness [2], however, the measured value of turbulence intensity (see later) suggest that separation should be present - at least intermittent. The hill top speed-up is shown on figure 8 and is seen to be well predicted. The LES speed-up is slightly overestimated at about 40m. This may be related to the reference velocity (figure 4), which is lower than the measured at this height.

3.2 Turbulence intensity

Figure 9 compares the computed and observed TKE along line A. For LES the TKE is resolved while it is modelled for RANS. As seen, the LES prediction is clearly superior to RANS. Upstream of the hill the RANS model captures the TKE well but underestimates on the lee side. For LES the level of TKE for the inflow turbulence was higher than for the measurements, therefore the overall level of TKE along line A is also slightly too high. It is, however, seen that LES predicts the TKE increase on the lee side.

Figure 10 shows the three components of turbulence (the velocity variances) for LES compared with measurements. These quantities are also seen to follow measurements very well. The RANS model does not resolve turbulence anisotropy and is not shown.

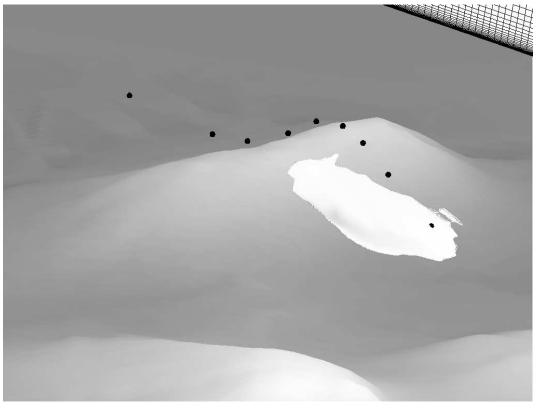

Figure 7: Region of reverse flow on the lee side. Contour of zero u-velocity (the inflow-direction) is shown.

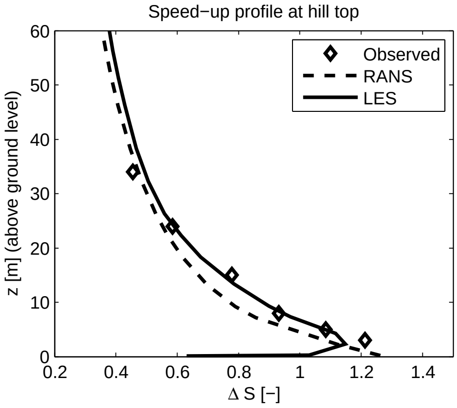

Figure 8: Velocity speed-up at the hill top.

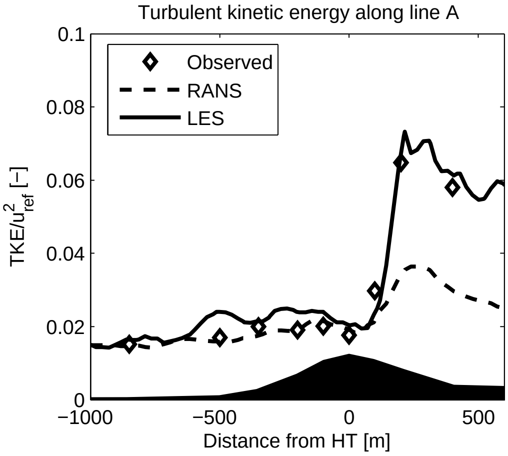

Figure 9: Turbulent kinetic energy along line A.

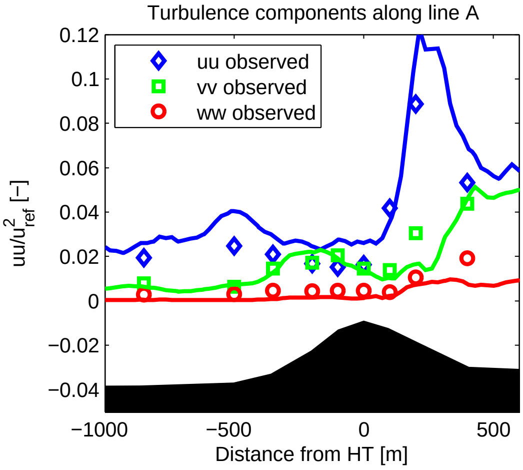

Figure 10: LES turbulence components along line A.

4 Conclusion

This paper presented a method by which LES can be used to simulate the wind over natural terrain. Since the LES method is computational expensive (even with proposed wall model) it should primarily be used for complex terrain where inherent unsteady features that dominate the flow need to be captured accurately. The presented model is based on the standard high Reynolds number $k - \epsilon$ RANS model [5] found in most commercial CFD-solvers. By changing the turbulent length scale build into the RANS model a LES model is created. The new turbulence model can be run in either RANS or LES mode dependent on the level of detail necessary.

The LES model was tested by simulating the flow over the Askervein hill. Since the Askervein hill project [14] provide turbulence measurements it is a good test case for validating turbulence models. Simulation results showed that the turbulence intensity and mean velocity was well captured on the wind ward side for both RANS and LES. The lee side flow, however, was more difficult to capture. The flow in this region consist of intermittent separation [2, 8], which results in high turbulence levels. Generally, RANS models are unable to capture this flow separation resulting in too low velocity and turbulence predictions - this result was reproduced with the $k-\epsilon$ RANS model. The new LES model was able to capture flow separation, though not intermittent as measurements suggests. As a result, the velocity speed-up was underpredicted but turbulence intensity was well predicted.

The use of LES to simulate wind in natural terrain has been shown possible. Even though good results have been achieved, more test cases are needed to further validate the method.

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