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Wind flow simulations on idealized and real complex terrain using various turbulence models

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ABSTRACT

The effect of topographic features on wind speed and wake turbulence is evaluated by conducting Computational Fluid Dynamics (CFD) simulations using an in-house CFD program that features various turbulence models. The simulation results are assessed by computing Fractional Speed Up Ratio (FSUR) along longitudinal lines at different elevations. Such information is useful for evaluating wind loads on long span structures and micro-siting of wind turbines on complex terrain. Simulations are conducted on both idealized and real topographic features in both 2D and 3D domain. The turbulence structure behind hills is examined using several turbulence models such as the mixing-length, standard $k-\epsilon$, RNG $k-\epsilon$, realizable $k-\epsilon$ and Smagorinsky LES models. All turbulence models predicted FSUR values on upstream side of hills adequately; however, the performance of simple turbulence models, such as mixing length, is found to be insufficient for characterizing wakes behind hills. RANS turbulence models gave results close to one another; however, those models that incorporate modifications to account for adverse pressure gradient conditions performed better at wakes behind hills. LES conducted at full scale dimensions, and using wall functions, failed to give results that are comparable to the other turbulence models. Re-conducting the simulations at model scale dimensions, hence at relatively small Reynolds number, and without using wall functions gave results that are comparable to those found in the literature. Therefore, use of wall functions can degrade quality of results in LES of high Reynolds number flows of practical interest.

Introduction

Several building codes and standards incorporate the effect of topographic features on wind speed using idealized models of isolated and symmetrical orography [1]. On the other hand, real topography contain irregular three dimensional topographic features that are surrounded by other topographic features; thus, they are neither symmetrical nor isolated. Using such simplifications often leads to overly conservative design of structures located on complex terrain. The problem is pronounced for long span structures, such as transmission lines, that cross multiple zones with different speed-up and turbulence characteristics. Thus, mean wind speed and turbulence intensity information are required at several locations above the topography. Especially at crest of hills and escarpments, the Fractional Speed Up Ratio (FSUR) (Eq. (10)) can be high enough to cause major structural failures. Therefore, many national codes such as NBCC (Canadian standard), ASCE-7 (American standard), AS/NZS 1170.2 (Australian/New Zealand standard), and EUROCODE 1 (European standard), provide general guidelines to estimate topographical multiplication factors for wind speed over hills and escarpments. Experimental investigations, such as field observations and boundary layer wind tunnel tests, are recommended for complex terrain that are not covered well in national codes. This work focuses on Computational Fluid Dynamics (CFD) approach to asses the effect of topographic features on wind speed and turbulence.

A number of numerical studies over complex terrain have been conducted since Jackson and Hunt [2] first analyzed flow over isolated hills of low slope using linearized forms of fluid flow equations. Their approach is still in common use for large scale wind mapping, where a quick estimation of wind speed is required for turbine micro-siting or similar purposes. One such program developed at Ris ϕ-DTU is Wind Atlas Analysis and Application Program (WAsP) that includes a complex terrain flow model, and a separate wake model for accurate prediction of flow separation. Linear models are known to have problems in predicting flow separation behind high hills and mountains; thus, such models must not be used in alone. Some researchers [3,4] conclude that even non-linear steady-state numerical models have problems in

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recirculation regions, because orography can induce unsteadiness. The motivation for use of linear models in the past [2,5,1] is limitation of computational resources, but the problem is still present in case of large area wind flow simulations conducted for wind mapping. Therefore, choosing the most complex turbulence model, for simulation of wind flow on complex terrain, is not always appropriate in light of applicability issues. This work also investigates the simplest turbulence model, namely the mixing length model, to emphasize this view. Complex turbulence models, such as Reynolds Averaged Navier Stokes (RANS) and Large Eddy Simulation (LES), have been used by many researchers to get accurate information about the turbulence structure in wakes. LES has been used for various studies in wind engineering: pollutant dispersion [6], complex terrain [7–11], wind loading [12]. Many studies have been carried out using RANS as well: isolated hills [13,14], multiple hills in succession [15,6,16], real complex topography such as Askervein hill [17,18].

Overview of implemented turbulence models

The choice of turbulence model is important for simulation of separated flow behind hills. RANS models have the most appeal for industrial applications due to their relatively low cost of computation, while still reasonably matching field and experimental observations. Nowadays, Large Eddy Simulation (LES) is increasingly being used for simulating flows with moderately high Reynolds numbers. This is partly motivated by the fact that LES usually gives better results than RANS models in regions of flow separation. This has led to development of various RANS models aimed at curing their deficiency in separated flows. The different turbulence models and wall functions that are implemented in the in-house CFD program, and used for the current study, are briefly discussed in the following sections.

Mixing length model

The mixing length model is the simplest turbulence model that is known to give good results for simple two dimensional flows such as wakes, jets, mixing layers and boundary layers [19,20]. Its limitation is that the length scale (l_*), and also the velocity scale (u_*), depend on the nature of flow, therefore different values may need to be specified in different regions. For boundary layer type flows with high Reynolds numbers, Prandtl's mixing length formula $l_m = \kappa y$ is commonly used. However, the formula is not accurate in regions with adverse pressure gradient, such as the one behind hills.

$$l_* = l_m; \quad u_* = l_m|S| \tag{1}$$

where S is the mean strain tensor. Calculating the wall distance y for irregular three dimensional topography is a non-trivial task. A partial differential equation (Eq. (2)) first proposed by Spalding [21] should be solved to get y.

$$\nabla \cdot \nabla\phi = -V; \quad y = \sqrt{\nabla\phi \cdot \nabla\phi + 2\phi} - |\nabla\phi| \tag{2}$$

where V is the volume of a cell. The boundary conditions for ϕ are Dirichlet at ground surface and Neumann elsewhere. This partial differential equation is solved only once at start up; hence, it is not as costly as solving an additional set of turbulence equations at each time step.

RANS models

The first improvement to the mixing length model is to calculate the velocity scale u_* from the turbulent kinetic energy k using Eq. (3). One-equation turbulence models solve an energy transport equation for k from which velocity scale is determined [19,22,20].

$$u_* = ck^{1/2}l_m \tag{3}$$

For a complete model, i.e. one that does not require any flow-dependent specification, the length scale has to be calculated from the flow as well. Two-equation turbulence models such as k–ϵ and k–ω solve one additional transport equation for turbulence dissipation or similar quantity to determine time/length scales, thereby completing the model. However the standard k–ϵ model can overestimate turbulence production in separated flow regions. To address this problem many modifications have been proposed, of which the simplest is probably an ad hoc modification [23] that incorporates vorticity term $\bar{\omega}$ in Reynolds stress formula as follows.

$$R = \nu_t\sqrt{2\bar{S}_{ij}\bar{\omega}_{ij}} \tag{4}$$

More formal approaches to the problem have lead to different RANS models with moderate degrees of success. RNG k–ϵ and Realizable k–ϵ models are implemented and used in the current study to analyze the wake flow behind hills.

LES models

In LES, the effect of the larger eddies is explicitly solved while that of smaller scales is modeled using an eddy-viscosity approach, similar to that used in RANS models [19,20]. The major difference with RANS is that LES models the smallest scales that are below a certain filter width (Δ), and thus is a low-pass filter. The grid itself is commonly used as a filter, in which case explicit filtering operations are not necessary. The simplest sub-grid scale stress model (SGS) is that of Smagorinsky [19], which is first developed for meteorological applications. This model is similar to a mixing length model where the length scale is replaced by a new dimension calculated from cell volume ($V = dxdydz$).

$$l_m = C_s\Delta; \quad \Delta = \sqrt[3]{V} \tag{5}$$

Smagorinsky's coefficient C_S is determined experimentally to be usually between 0.1 and 0.2. The length scale at walls should be zero but the formula gives non-zero values. This problem led to use of damping functions to reduce the length scale at walls to zero. This can be achieved, for instance, by integrating Prandtl's mixing length as follows

$$l_m = min(C_s\Delta, \kappa y) \tag{6}$$

LES with near-wall resolution is very costly for high Reynolds number flows. The number of cells required is estimated to be about $Re^{1.76}$ [19]. Instead of resolving all near-wall flow, wall models can be used to reduce the associated cost significantly. Unlike wall damping functions, which are applied to all control volumes, wall functions are applied only to the cells nearest to the wall. With the use of wall models, the length scale becomes in order of the flow length scale. As a result, the number of cells required becomes independent of the Reynolds number, just like the cases of high Reynolds number RANS models.

Wall models

High Reynolds number flows have thin viscous layers that necessitate use of very fine grids to resolve all near-wall flow behavior. Universal wall models, such as the log-law equation, are commonly used near walls to reduce cost of computation. In the standard wall function approach [24], the first cell close to the wall is placed in the logarithmic region ($y^+ \geqslant 30$). Then, the friction velocity u_* is calculated iteratively from the log law equation using U_p and y_p of the first cell. Then, the wall shear stress