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Some limitations of built-in OpenFOAM ABL formulations for wind engineering applications

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SUMMARY: (10 pt)
One of the common difficulties in conducting Computational Wind Engineering (CWE) simulations is proper specification and propagation of the Atmospheric Boundary Layer (ABL) into the test area. As the use of computational studies in this discipline is relatively new and unregulated in comparison to the scale model testing, it is a common practice to compare the computational results against available wind tunnel data. Some of the biggest discrepancies in results can often be traced to differences in ABL profiles between tests.

Computational simulations of the ABL propagating into the urban areas are often performed using commercially available computational fluid dynamics codes. An important constraint of such simulations is that only the lower portion of the ABL can be represented in the model, since its well-established logarithmic specification of the velocity profile ensures good horizontal propagation through the domain by satisfying conservation and equilibrium equations. This ABL profile definition together with modified turbulent kinetic energy and dissipation profiles is implemented in the OpenFOAM ABL class. However, this implementation has limitations and can result in unconservative results.

Keywords: atmospheric boundary layer, computational fluid dynamics, OpenFOAM

1. VELOCITY PROFILE UNDERESTIMATION

Several approaches exist to model the ABL velocity profiles in wind engineering studies (Davenport, 1960; Richards and Hoxey, 1993; Deaves and Harris, 1978). All are based on the observation that the surface roughness length (z_0), understood as a cumulative statistical drag effect of many obstructions (Davenport, 1960), has predominant impact on the shape of this profile. Three main models used in the wind engineering studies and their significant features are described below.

1.1. Power-law model

The power-law model is an empirical model, applicable throughout the ABL, except very close to the ground (Cook, 1997) and takes form:

$$\frac{U(z)}{U_{ref}} = \left(\frac{z}{z_{ref}}\right)^{\propto} \tag{1}$$

where U_{ref} is the mean wind speed at reference height z_{ref} and α is the exponent of the power law. It is often used in wind modelling applications and is referred to by the ASCE 49-21 standard (ASCE, 2022), which guides the user on the model constant recommended values. This profile formulation is less frequently used in CWE studies, as the standard model equations based on it are not in equilibrium and the profiles are not maintained with downstream distance – the flow is not horizontally homogenous.

1.2. Logarithmic with parabolic defect model (Deaves and Harris (DH) model)

Davis and Harris model is more complex, depends on three scaling parameters and it is accurate in all ranges of ABL heights:

$$\frac{U(z)}{u_*} = \frac{1}{\kappa}\left(\ln\left(\frac{z}{z_0}\right) + a_1\zeta + a_2\zeta^2 + a_3\zeta^3 + a_4\zeta^4\right) \tag{2}$$

where u_* - friction velocity, κ – von Karman constant, $\zeta = z/z_g$, z_g – gradient height, $a_1=5.75$, $a_2=-1.87$, $a_3=-1.33$, $a_4=-0.25$.

Due to its complexity and the fact that it is a family of curves dependent on the wind speed for a given location, it is not practical to use it in the wind simulations. It is however used in tools like Engineering Sciences Data Unit (ESDU, 1993) which computes these profiles and provides estimates of topographic and variable roughness effects to determine design wind speeds or wind speed multipliers.

1.3. Log-law

Log-law model is applicable only to the lower part of the ABL (typically <200m):

$$\frac{U(z)}{u_*} = \frac{1}{\kappa}\ln\left(\frac{z+z_0}{z_0}\right) \tag{3}$$

Its formulation, together with appropriate equations for turbulent kinetic energy (TKE) and turbulent dissipation rate, can be made to satisfy the standard k-epsilon turbulence model equations with modified model constants, which is a necessary condition for horizontal homogeneity of the flow (Richards and Hoxey, 1993). This velocity profile is commonly chosen as an inlet profile in computational studies and is applicable to variety of turbulence models (Blocken et al., 2006). The necessary assumptions for this formulation to be mathematically consistent is that there is zero vertical velocity, constant pressure along vertical stream-wise direction and height of the computational domain is significantly lower than the ABL height (shear stress can be simplified by assuming it is constant with height). This velocity profile (along with profiles for other variables and boundary conditions) is implemented in the OpenFOAM ABL formulations referred to as *atmBoundaryLayer* class (OpenFOAM-2112).

1.4. Comparison

Figure 1 compares all three approaches with ±5% error bars for the log-law. For the DH model, as the velocity decreases, the values increase progressively below the log-law for $z/z_{ref} > 1$. The log-law velocities at $z/z_{ref} > 1$ are also underestimated in comparison to the ASCE 49-based power-law model and this error increases with increasing z/z_{ref}.

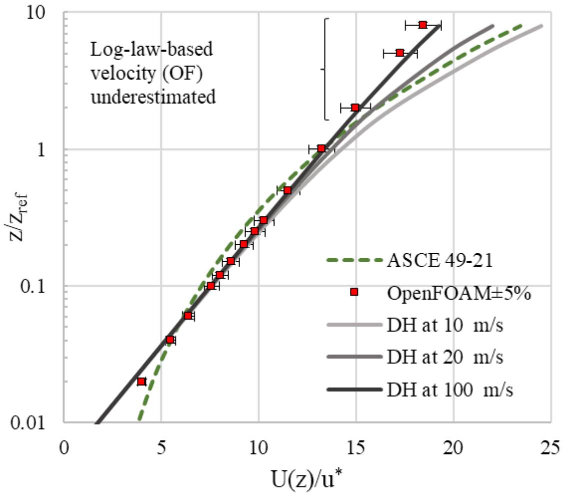

Figure 1. Normalized mean velocity profiles (z_0=0.5m, z_{ref}=100m, U_{ref}=10m/s, φ=37deg) b)

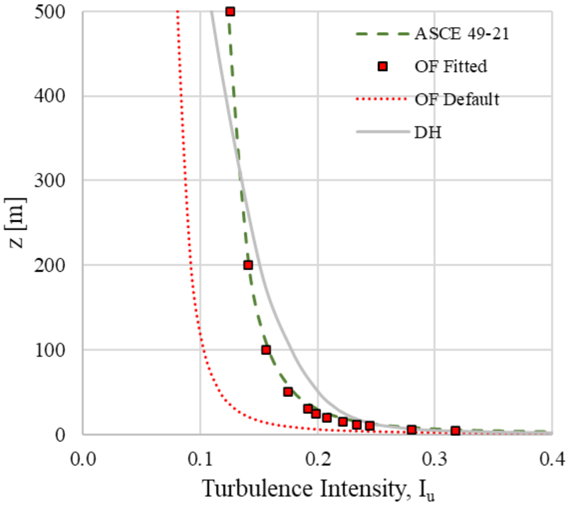

Figure 2. Turbulence intensity profiles (z_0=0.3m, z_{ref}=10m, U_{ref}=10m/s, φ=37deg) b)

This indicates that z_{ref} should be carefully chosen in the wind engineering CFD simulations with OpenFOAM *atmBoundaryLayer* class to ensure the results are conservative relative to the applicable code profiles. For example, if z_{ref} is chosen as a site building height and the site happens to be surrounded by much taller buildings, downwash from nearby towers could be underestimated for any building taller than the reference height, since there is a deficit of high-level wind speed.

2. ABL PROPAGATION ISSUES

Generally, the along-wind component of the turbulence intensity at height z can be represented as:

$$I_u(z) = \frac{\sigma_u(z)}{U(z)} = \frac{\sqrt{2/3k}}{U(z)} \qquad (4)$$

where σ_u is along wind speed fluctuations and k is the turbulent kinetic energy.

2.1. Turbulence Intensity profile

Typical empirical equations for turbulent intensity applicable to the entire height of ABL (ASCE 49-12; Deaves and Harris, 1978, respectively) are as follows:

$$I_u(z) = \frac{\sqrt{\beta(z_0)\exp\left(-1.5z/z_g\right)u_*}}{U(z)} \qquad (5)$$

$$I_u(z) = \frac{2.63u_*}{U(z)}\left(1-\frac{z}{z_g}\right)\left[0.538+0.090\ln\left(\frac{z}{z_0}\right)\right]^{\left(1-\frac{z}{z_g}\right)^{16}} \qquad (6)$$

where $\beta(z_0)$ is ASCE 49-21 estimated set of constants. Both expressions give similar results in the lower ABL heights (Fig.2).

In CFD models, the mathematically consistent assumption of turbulent kinetic energy constant with height (Richards and Hoxey, 1993; Hargreaves and Wright, 2006), which did not find support in experimental data, was revised by Yang et al., 2009:

$$k = \frac{(u_*)^2}{\sqrt{C_\mu}} \sqrt{C_1 \ln\left(\frac{z+z_0}{z_0}\right) + C_2} \tag{7}$$

where Cμ is an empirical model constant and C_1 and C_2 are fitting parameters. With C_1=0 and C_2=1 (OF Default in Fig. 2) this equation simplifies to constant TKE with height and significantly underestimates turbulence intensity relative to many code profiles.

2.2. Discussion

Equation 7 enables construction of a non-linear fit of the meteorological data or well-established empirical equations to determine more realistic turbulent intensity profile of the ABL (Fig.2 OF fitted). However, in order to satisfy the model's constant shear stress condition and transport equation for the turbulent dissipation rate, changes in the values of model constants C_μ and σ_ε were introduced (Yang et al., 2009). These values were optimized based on wind tunnel experiments and applicable to specific conditions. In simulations run with OpenFOAM's *atmBoundaryLayer* class we show that, implementing the new approach with non-default C_1 and C_2 values, chosen to fit turbulence intensity as in ASCE 49-21 (with other model constants unchanged) results in bad velocity and TKE profile propagation. Indeed, not only does the TKE profile fail to propagate, but the velocity profile's propagation is also significantly degraded. We show how use of *atmBoundaryLayer* could produce unconservative loads due to 1: turbulence levels are typically too low with default values for C_1 and C_2; and 2: providing C_1 and C_2 constants that better fit meteorological data or code profiles of turbulence can result in even worse outcomes.

Parente et al., 2011, found that this flexible definition of TKE requires for C_μ and σ_ε to vary with height and a source term for TKE transport equation needs to be added to the model. These changes are not a part of OpenFOAM *atmBoundaryLayer* class. We show that *atmBoundaryLayer* should only be used with these limitations in mind unless the required modifications are made to support variable C_1 and C_2 constants.

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