Wall-Modeled Large-Eddy Simulations of Airfoil Trailing Edge Noise

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Introduction

The present work seeks to validate a recently developed wall-modeling library (Mukha, 2019) for predicting airfoil trailing edge noise (TEN) of a NACA 0012 airfoil, with the long-term goal of developing a tool for industry level optimization of low noise wind turbine blades. TEN is a significant problem in the wind energy industry, as it is the dominant noise source on wind turbines. TEN puts an upper limit on the amount of power wind turbines can generate in order to maintain acceptable noise levels near communities. Prior studies have used Large-eddy simulations (LES) to simulate TEN (Wolf ,2011), however, simulating wind turbine flows of interest, with Reynolds numbers on the order of 1 million, require significant computational resources to resolve the boundary layer, thus making it an unfeasible tool for industry optimization. If validation of wall-modeled LES (WMLES) with benchmark data is successful, this tool can combine the fidelity of LES with the computational efficiency that wall-modeling provides, thus enabling a feasible path for industrial aeroacoustic optimization of wind turbine trailing edge designs. Previous studies have demonstrated the ability of WMLES to predicted trailing edge noise from airfoils at large Reynolds numbers (George, 2016). Demonstrating the WMLES capabilities of a publicly available OpenFOAM library in the present work will push the use of WMLES in industry and academic research, which is an immature but expanding topic.

Computational Methods

Wall-modeled LES (WMLES) fully resolves the turbulent eddies in the outer portion of the boundary layer, while modeling energetic eddies in the inner, viscous sublayer. Thus, the boundary layer grids used in WMLES can be significantly courser than that of wall-resolved LES. In the simulation framework, instantaneous velocity data from the LES is sampled at a height, h, above the wall and fed to the wall model, which uses this data along with a law of the wall model to compute the shear stress at each wall face. Thus, all of the inner layer dynamics are replaced with a single value of shear stress at the wall, so that the turbulent flow solution can be accurately calculated at the first off-the-wall cell.

The wall-model library is used in conjunction with OpenFOAM's existing LES framework. The present study uses the WALE model to compute subgrid scale viscosity, which was suggested by Mukha (2019) to perform well with the relatively coarse grids used near the wall. The PIMPLE (hybrid PISO/SIMPLE) algorithm is used for pressure-velocity coupling, which allows for a more feasible time step in the simulations. An equilibrium wall model is applied between each wall face and LES sample point, as was used by George (2016). Spalding's law is chosen as the law of the wall model, and is solved via a Newton nonlinear equation solver, which gives the shear stress at the wall faces.

Unsteady surface pressure is monitored for 12 chord flow through times, and spectral decomposition is done directly in python. The far-field acoustic data to be benchmarked will be calculated using the Ffowcs-Williams and Hawkings (FWH) equation. The input to the FWH equation is time dependent pressure data on the airfoil surface, obtained from the WMLES solution.

This work uses OpenFOAM v1906, since, when writing this abstract, it is the latest OpenFOAM version that the wall modeling library has been released for. To the best of our knowledge, this is the only industry level, multi-purpose CFD code with advanced wall modeling capabilities that are necessary to properly carry out a WMLES trailing edge noise study. Specifically, the library allows user control over the wall-model sample height, the choice of wall-modeling technique (i.e. equilibrium, non-equilibrium), and the choice of the law of the wall-model. This allows best practices from previous works such as Park (2014), Larson (2016), and

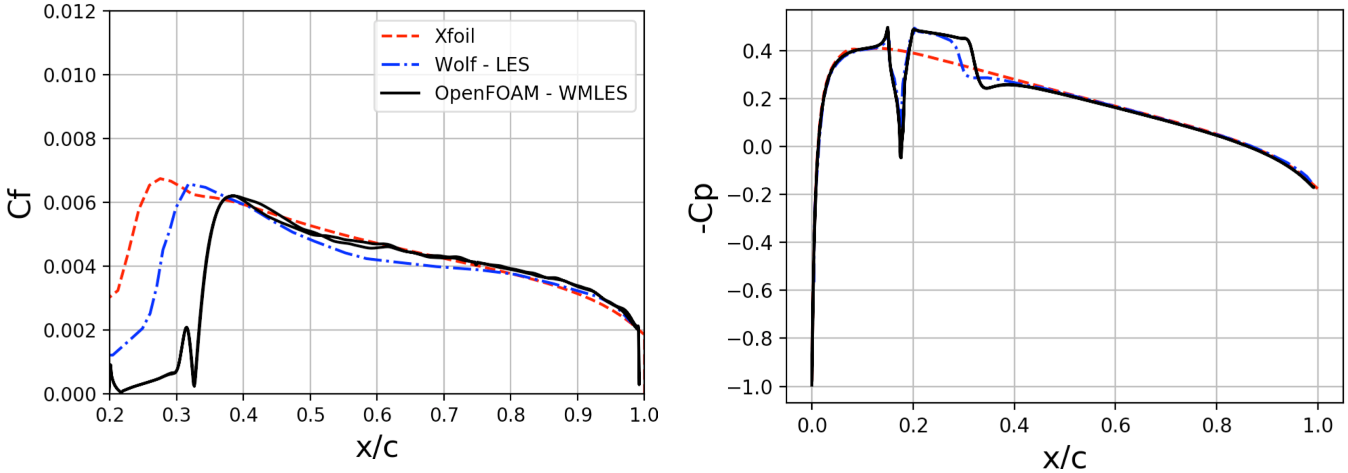
Mukha (2019), to be implemented. Primarily the practice of keeping the wall-model sampling height at a fixed distance from the wall, for a grid that is properly resolved, as this has been shown to mitigate log-law mismatch – a common error that arises in WMLES.

Meshing Strategy

For a WMLES simulation of a canonical boundary layer flow, the relevant length scale is the boundary layer thickness δ, which dictates the size of the energic eddies near the airfoil wall. The gridding practices have been adopted from previous studies, for instance (Larson, 2016) who suggested the criteria (Nx, Ny, Nz) = (12.5, 50, 20), which are the number of grid points per local boundary layer thickness in the stream-wise, wall-normal, and span-wise directions, respectively. Since a-priori boundary layer information is needed, a RANS precursor simulation is used to compute δ. In the present work, we have seen that proper grid resolution based on *local* boundary layer thickness is crucial to accurately calculating the wall shear stress. 3 grids have been tested and grid convergence was seen when the criterion of Larson (2016) was met. The grid is constructed by starting with a 2D hybrid grid with structured quadrilaterals near the airfoil, and unstructured quad/tris in the far-field, and then extruding this into a 3D mesh, all of which is done in ANSYS workbench.

Validation

Aerodynamic quantities are validated against LES data taken from Wolf (2011), and against the Xfoil panel code. The flow configuration used for initial validation is a Naca-0012 airfoil at $\mathrm{Re_c} = 4.08x10^5$ and 0-degree angle of attack. This configuration was chosen because there is sufficient published LES data of both the far-field noise and unsteady flow parameters (Wolf, 2011). Figure 1(a) WMLES prediction of the shear stress coefficient along the airfoil, which match the LES and Xfoil data very well in the fully turbulent regions (x/c > 0.4). The slight delay in the transition to turbulence is seen in the shear stress signatures, and is due to a slight difference in forced numerical transition between the 3 different data sets. Similarly, the pressure coefficient in figure 1(b) matches well with both benchmark data sets, aside from the slight deviation in the transition region.



(a) (b)

Figure 1: (a) Shear stress and (b) Pressure Coefficients of a Naca-0012 at $\mathbf{Re_c = 4.08x10^5}$ compared to Xfoil and LES data from Wolf (2011)

At the time of the conference, further aerodynamic quanties will be validated, such as the boundary layer displacement thickness, and Reynolds stress components, which are necessary to accuratley predict trailing edge noise. Power spectral density of the surface pressure, and far-field noise will also be validated against the benchmark data. Note that the increase in mesh size when scaling up to a Reynolds number of 10^6 is not a drastic change, as it is in fully wall-resolved LES. This is because the viscous sublayer is not resolved in WMLES, whereas in wall-resolved LES, the number of grid points in the viscous sublayer scales with $\sim \mathrm{Re_c^{2.16}}$. WMLES scales only with the outer layer, which scales roughly as $\sim \mathrm{Re_c^{0.5}}$ (Larson, 2016).

This project is in collaboration with Dr. Trevor Wood of GE Global Research. The direction of the work is informed by the extensive experience of our collaborators from GE, who have in the past performed wall resolved LES simulations for wind turbine airfoils at this scale, as a part of DOE's INCITE program.

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