Multi-stage Large Eddy Simulation for Meso to Micro-scale Coupling for Wind Farm Applications

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Abstract
To bridge the mesoscale to microscale gap for wind characteristics study in wind farm applications, Large Eddy Simulation (LES) in multiple stages is performed and appeared as an economic alternative to the conventional LES approach. SOWFA, an incompressible flow solver based on OpenFOAM is utilized. In a brief investigation, the wind velocity and total stress profiles found to be consistent across the LES stages. An elaborate study will be performed to validate the multi-stage LES approach.

Keywords: LES*, Multi-stage, Meso-Micro Coupling, OpenFOAM, SOWFA*

Introduction

Understanding wind characteristic for wind farm applications is challenging on multiple fronts. The geostrophic wind at upper atmospheric boundary layer is continuously changing and characterized by large (meso) scale variations. And the near surface wind, where the wind turbines operate, interacts with the terrain which adds local, relatively small (micro) scale perturbations. The mesoscale motions can span multiple kilometers dictates the mean wind characteristics. On the other hand, topography induced micro scale motions are in order of meters, influences meso-micro scale interaction, turbine structural loads, and wake recovery. Thus capturing wind motions across multiple order of scales is essential for understanding inter scale as well as wind and turbine/farm interactions and their effect on wind farm performance.

The mesoscale motions can be modeled with regional weather forecast models (e.g. WRF) and wind data can be recorded in meteorological towers at high frequency to examine near surface micro scale motions. However, these two methods stand at the opposite ends of the huge scale-gap and neither is adequate for detailed wind farm study, especially in complex terrain siting. Large Eddy Simulation (LES), a numerical tool, can be used to computationally model the turbulent atmospheric layer, where turbulent flow scales in the order of terrain features or turbine structures can be resolved to bridge the scale gap.

The presence of such scale gap requires a very large domain to accommodate mesoscale motions (order of kilometers), yet demands mesh resolution fine enough to resolve microscale motions. Such constraints make the LES problem astronomical in size with prohibitive computational cost. On the contrary, the wind farm under consideration is often smaller than the mesoscale length scales and resolved microscale motions are required here only. So there is an opportunity to perform multiple LES in multiple stages, where domain size gets gradually smaller as the resolution gets higher, to keep the computational cost in check. The multi-stage LES research methodology and preliminary results are presented here.

Meso-Micro Scale Coupling

For comparative analysis, let us consider a LES of domain size $10x4x1\ km^3$, a reasonable extent to accommodate the mesoscale motions. For a homogeneous microscale resolution threshold of 4m, the domain contains $6.25x10^8$ cells. Since the timescale of the mesoscale motions is also very large and mesh resolution is small, the LES needs to run for a very long time along with small time. Executing such gigantic LES is infeasible in most practical applications.

The multi-stage LES starts with a large domain with coarse resolution, which intends to capture the relative large scales. In each subsequent stage, an additional domain with smaller size and finer resolution is considered. Flow field values from upstream coarse LES are fed into the inlet boundaries. After the flow transient is passed, the flow fields are recorded at outlet boundaries as input for downstream LES. At the final stage LES, the domain size becomes roughly at the size of the complex terrain or wind farm under investigation with desired resolution. In the table 1, a comparison between single LES and a three-stage LES approach is illustrated. To estimate the computational cost, number of solution variables are same in all simulation, hence does not included. Arbitrary minimum wind speed, $U_{min}=10\ m/s$ assumed.

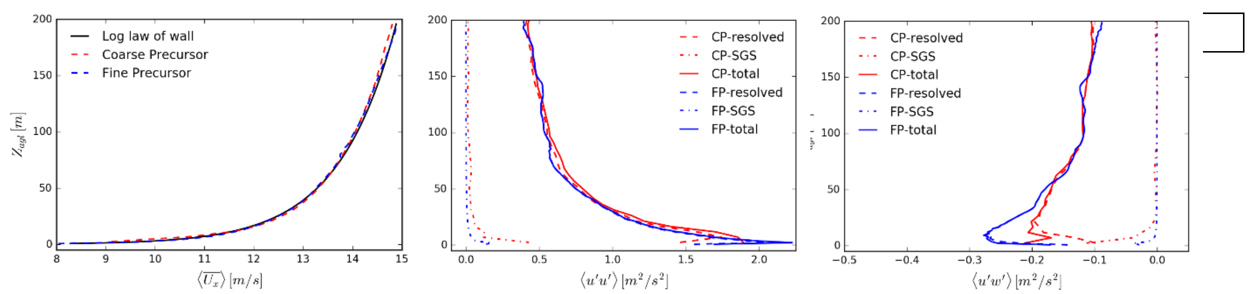
Stage	Domain size [km]			Resolution [m]	Cell count [x10^6]	Transient pass time [s]	Statistics collection time [s]	Number of LES run	Total runtime [s]	Computational cost [10^9]
0	*1*	*2*	*3*	*4*	*5 = (1*2*3)/4*	*6 = 1/U_{min}*	*7=$(6+7)_{upper}$*	*8*	*9 = 6+(7*8)*	*10=5*9*
N/A	10	4	1	4	625	1000	4000	1	5000	3125
3	2.5	1	0.25	4	10	250	600	4	3400	34
2	5	2	0.50	8	10	500	850	2	2700	27
1	10	4	1	16	10	1000	1350	1	2350	23.5
Multi-stage LES total: stage (3+2+1)					30	-	2800	-	-	67.5

Table 1: Computational cost comparison between single and multi-stage LES approach.

At the beginning of each LES, one flow through domain time is allowed for transients to pass and influence of initial condition to diminish. In the case of single stage LES, statistics are gathered for 4 flow through domain times to account for long term variations of mesoscale flow structures. On the other hand, in multi-stage LES, flow statistics are gathered at 4 spatiotemporally distant fields for 600s each, where the mesoscale motions can be assumed as uncorrelated. From, the table 1, it is evident that the multi-stage LES is approximately 45 times economic that the traditional LES approach. The challenges in multi-stage LES are flow field data storage and assignment at each stage and treatment of the open boundaries. A mixed inflow-outflow type boundary condition with spatial averaging filtration is applied in this work.

Multi-stage LES Approach Validation:

To validate the multi-stage approach, a neutrally stable atmospheric boundary layer and the wind velocity profile determined by the "Bolund Experiment" [1,2], a complex terrain field campaign is considered. The LES is performed is two stages. SOWFA [3], an OpenFOAM based incompressible flow solver library, is used as the LES model/solver. The coarse precursor domain is of size *3000x3000x1000* m^3 with *10m* resolution and fine precursor domain is of size *500x500x200*m^3 with *2m* resolution. The figure 1 shows that the wind velocity and total (resolved+ SGS) stress profiles agree very well across the LES stages. A detailed description and analysis will be presented in the conference.



a) Mean stream-wise velocity	b) Stream-wise stress	c) Shear stress

Figure 1: Comparison of wind velocity and stresses between coarse and find precursor LES.

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