Development of OpenFOAM - WRF Coupling Methodology for Wind Power Production Estimations

Engin Leblebici & Ismail H. Tuncer

METUWIND - Ankara/TURKEY
Wind power predictions are currently based on:

- Linearized Models
  - WASP
- Statistical CFD based models
  - Meteodyn WT
  - WindSim
- Numerical Weather Prediction Models
  - WRF
  - NAM
  - ALADIN
Linearised Prediction Models

- Fast, linearised N-S solvers
- Assumes terrain, obstacles, surface roughness are small perturbations on a constant background wind field
- Derives regional wind climate based point measurement data
- Reverses the process to reconstruct the flowfield

Problems
- Assumes attached flow, cannot simulate flow separation, re-circulation...
- Not accurate in complex terrain
CFD based Prediction Models

- RANS solvers
- Assumes homogeneous, steady boundary conditions
- Starting from the zero degree, rotates inlet and outlet boundary conditions till 360 degrees in steps.

- Use fictitious flowfields and correlate whole domain with observation data
- Better than linearised models at capturing complex terrain effects

Both linear and CFD based Models:
- uses statistical averaging for wind speed and direction
- does not capture unsteady physics (no prediction!)
WRF is a numerical weather prediction software with many physical models including atmospheric boundary layers. It is a mesoscale model with a maximum resolution of 1 km and uses an \( \eta \) based coordinate system.

\[
\eta = \frac{p - \rho_{ht}}{\rho_{hs} - \rho_{ht}} \tag{1}
\]

WRF predictions are not accurate in complex terrains.
The Atmospheric Boundary Layer can be defined as the part of the atmosphere which is highly influenced by the earth’s surface and responds to forcing from surface within a time scale about an hour.

- 100 m to 3 km in height
- Changes diurnally
- Turbulent
- Unsteady
- 4 Sublayers
  - Roughness Layer
  - Surface Layer
  - Well-mixed Layer
  - Capping Inversion Layer
Objectives

- Coupling CFD solutions with a weather prediction model (Unsteady Physics)
- CFD based solutions on terrain fitted high resolution grids (Terrain Effects)
- Modelling real-time unsteady atmospheric flows (Prediction)
• Use unsteady WRF predictions (past/future) on low a resolution grid to provide unsteady BCs for high resolution terrain fitted CFD (OpenFOAM) solutions.
Coupled Solution Methodology

- WRF Solutions
- High Resolution Terrain Modelling and Grid Generation for CFD Sub-domain
- Unsteady OpenFOAM Solutions
  - Numerical Model
  - Challenges
    - (WRF) Mesh to (OpenFOAM) mesh interpolation of BCs for each WRF output time
    - Development of a Spatially and Time varying Inlet/Outlet BC
    - Parallel Implementation
- Alaiz Case Study and Comparison
  - Inflow/Outflow Profiles
  - Vertical/Horizontal Slices
  - Comparison with Met-Mast data MP5 at 118,102,90,78 and 40 meters above ground
  - Effects of Roughness
WRF Solutions

- **WRF inputs**
  - Terrain data from UCAR (University Corporation of Atmospheric Research)
  - Initial and Boundary Conditions (ERA-Interim) from ECMWF (European Centre of Medium Range Weather Forecast)

- **WRF solutions**
  - Horizontal Resolutions: 1km (Nest2), 3km (Nest1)
  - Vertical Resolution: 40m at ground level stretching rapidly
  - Time Resolution: 5 minutes
- ASTER GDEM data set: $\approx 30$ m terrain resolution
- Structured Stretching Grids
- Horizontal Resolution: 30 m
- Vertical Resolution: 2 m (at ground level)
Boundary Conditions
- Side and top surfaces as spatially varying Unsteady In/Outlet
- Ground as no-slip wall with rough wall functions

Incompressible
- No energy equation, Buoyancy neglected, Neutral Atmosphere

Solver → modified PimpleFOAM with $k-\epsilon$ turbulence
- Coriolis Acceleration
- 40 corrector loops with under-relaxation, Time Step: Cou <40
OpenFOAM Solutions - Numerical Model

- Roughness and Turbulence Boundary Conditions
  - \( k-\epsilon \) constant, InletOutlet same as velocity BCs
    \[
    k = \frac{3}{2} (U_{ref})^2, \quad \epsilon = C_{\mu}^{3/4} \frac{k^{3/2}}{l}
    \]
    where \( I = 8\% \), \( U_{ref} = 14 \text{ m/s} \) and \( l = 0.4\delta_{ABL} \)
  - Roughness from Corine Roughness Data
  - Rough wall functions at the ground, \( y^+ = 800 \) at first level
• Latitude-Longitude(deg)-η (WRF) to North, East Direction and Altitude(m)(OF) coordinate conversion
• Ground level matching of WRF and OpenFOAM domain
• Trilinear interpolation of WRF variables to OF mesh at 5 minute intervals (289 BC set for 1 day)
A new boundary condition class is developed

- Boundary Conditions from WRF are imposed at the inflow boundaries
- Zero gradient condition is imposed at the outflow boundaries
- Inflow and Outflow boundaries are dynamically determined based on extracted WRF data
OpenFOAM Solutions - Development of a New BC Class

Get index and coordinates of the boundary faces

Interpolate WRF data at 5 min intervals on each face centre

Get Solution Time

Read (adjacent) interpolated BC profiles

Interpolate BCs at each boundary cell face in time

Solver calculates Phi (flux)

\[ \Phi = \overrightarrow{A_f} \cdot \overrightarrow{U} \]

phi > 0?

Yes (w=0)  No (w=1)

Call

mixedFvPatchField<Type>::updateCoeffs()

Next Iteration

SideNote: \[ x_p = wx_p + (1 - w) \left( x_c + \frac{\nabla \cdot x}{\Delta} \right) \]
decomposePar utility decomposes the domain into partitions in various ways. In this study manual decomposition is used:

- **manual**: user directly specifies the allocation of each cell to a particular processor
- All the cells where the developed BC is applied, should belong to the same processor
  → Face indexes should not change
- Give all of the timeVaryingMixed boundary to a single processor! *(while maintaining parallel efficiency!)*
- Use METIS while defining all timeVaryingMixed cells as one cell and use manual decomposition
• Domain decompositions

8 processors

16 processors
- Location: Navarra region, North-East of Spain
- Complex Terrain, steep slopes
- Interaction between mountain and upstream to the North
- Interaction between terrain and forest canopy
- Date: 01.01.2015
OpenFOAM Solutions - Inflow Boundary

Time: 604.221000

U Magnitude
OpenFOAM Solutions - MP5 Met-Mast Location

Time: 604.221000
OpenFOAM Solutions - Turbulent Kinetic Energy

Time: 604.221000
OpenFOAM Solutions - Velocity Magnitude

Time: 604.221000
OpenFOAM Solutions - 102 m above ground

**Graph 1:**
- **Corl 102m**
- **Foam 102m**
- **WRF 102m**
- **Mast 102m**

**Graph 2:**
- **Wind Direction (° degree)**

**Time (hh:mm):**
- 00:00:00 to 24:00:00

**Velocity/Magnitude (m/s):**
- Range from 0 to 18
OpenFOAM Solutions - 90 m above ground

![Graph showing velocity magnitude (m/s) over time, and wind direction (°) over time.](image-url)
OpenFOAM Solutions - 78 m above ground

Graph 1: Velocity Magnitude (m/s)
- Cori 78m
- Foam 78m
- WRF 78m
- Mast 78m

Graph 2: Wind Direction (° degree)

Time (hh:mm)

00:00:00 04:00:00 08:00:00 12:00:00 16:00:00 20:00:00 00:00:00
OpenFOAM Solutions - Effects of Roughness

![Graph showing velocity magnitude over time with data points for different conditions. The graph compares Cori 40m, Mast 40m, and smooth40 conditions with time on the x-axis and velocity magnitude on the y-axis.]
Concluding Remarks

- OpenFOAM was coupled with WRF via using low resolution WRF data on high resolution OpenFOAM grid as unsteady spatially varying boundary conditions (timeVaryingMixed).
- Unsteady Turbulent flow solutions are done for 24 hour period using k-ε Turbulence Model with rough wall functions in ALAIZ, Spain.
- Parallel implementation of the timeVaryingMixed boundary condition is successfully done. Accurate daily runs in high resolution can be completed within 4 hours on with 16 cores (2.3Ghz).
- Results are compared with experimental data from MP5 Met-Mast, and seems promising especially in vicinity of the ground.
- Studies to use TKE profiles from WRF instead of constant ones is ongoing.
- Trials for different atmospheric stability conditions are ongoing.
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Engin Leblebici
engin.leblebici@ae.metu.edu.tr