2D Simulation of a Vertical-Axis Wind Turbine (VAWT) using Moving Reference Frame (MRF) Technique in OpenFOAM

A Hands-on Demo

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EuroCC 2 Project & TÜBİTAK ULAKBİM TRUBA

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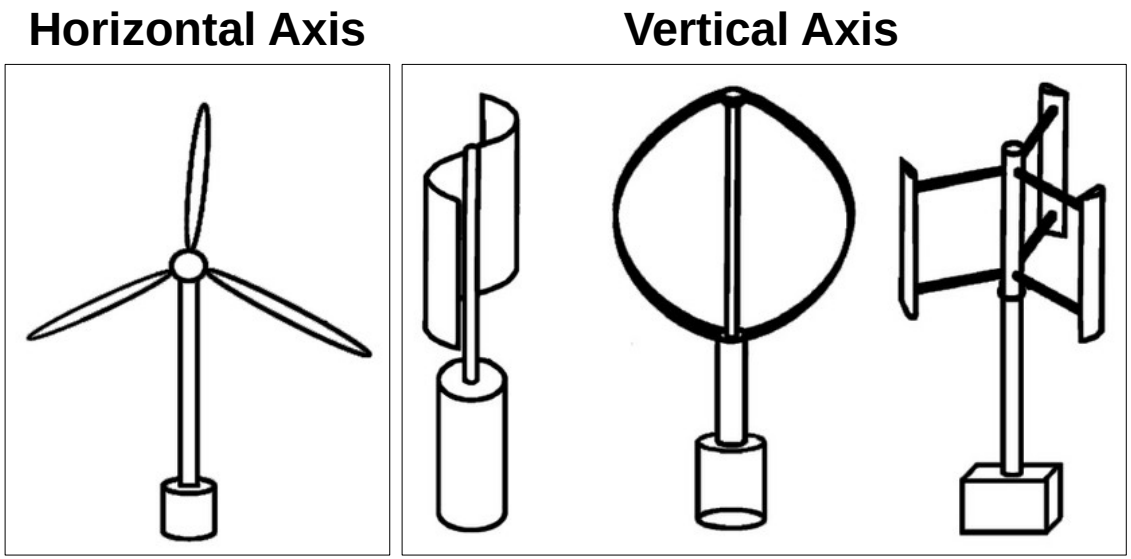
Overview

1. Introduction
   - Wind turbines: vertical vs. horizontal axis
   - Simulating rotating geometries in CFD
2. Method
   - OpenFOAM in brief
   - The *Moving Reference Frame* (MRF) technique
3. Demonstration
   - Accessing the TRUBA server
   - Details of the case study
   - OpenFOAM case structure
   - Simulation: running, residual tracking, post-processing
4. Discussion
   - Discussion of the results and conclusion

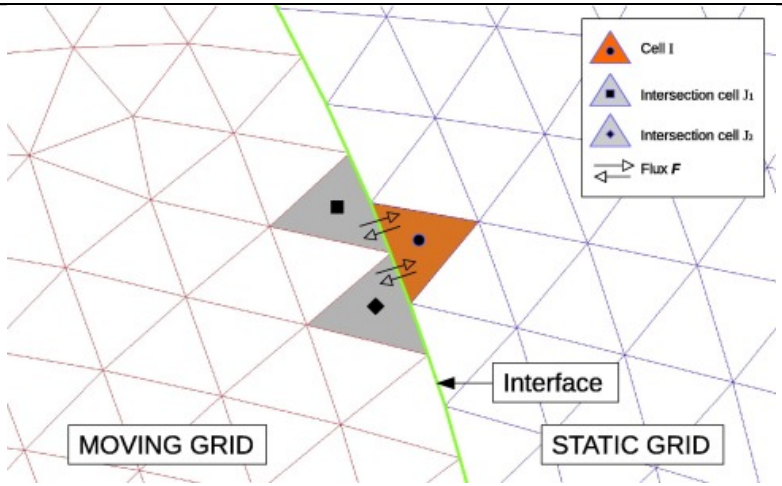
Wind turbines: vertical vs. horizontal axis



	HAWT	**VAWT**
Suitable applications	Commercial (large power plants)	Domestic, rooftop etc. (small scale)
Aerodynamic efficiency	●High	●Low
Investment cost (per MW)	●High	●Low
Manufacturing, operation, maintenance	●Complex (yaw control etc.)	●Simpler
Noise (per MW)	●Low	●High

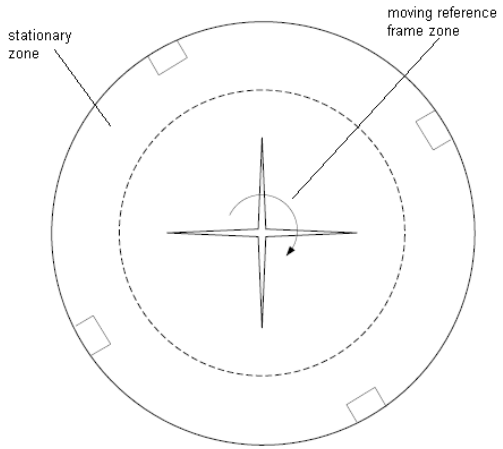
How to simulate rotating geometries in CFD?

Arbitrary/Sliding Mesh Interface (**AMI**, **SMI**)



- Geometry is physically rotated
- Strictly unsteady, requires very small Δt
- Non-conforming cell interfaces require complex treatment
- Good for highly transient physics
- Difficult to set a good IC, requires many steps until convergence
- High fidelity, often used as the primary technique

Multiple/Moving Reference Frames (**MRF**)



- Governing equations are manipulated
- Can be run in steady-state
- Do not have such a numerical problem
- Handles them poorly
- Do not have such problem
- Mostly used to obtain an IC for AMI

OpenFOAM in brief

OpenFOAM

General

- More than a solver, it is a *CFD toolbox*:
  - Mesh tools (generation, manipulation, conversion, domain decomposition ...)
  - Many useful features and functions (force calculation, field probing etc.)
  - Many algorithms, schemes, turbulence models, boundary conditions etc. are readily available
  - Advanced features from cutting-edge research are quickly packed in new versions (dynamic mesh refinement, moving and morphing meshes, synthetic eddy models etc.)
  - ... many, many more!
- Open source, widely adopted, continuously enriched by the active community.
- A great environment to learn CFD: see the code → run → get result → modify → run → see alteration

Technical

- Finite volume-based
- Built upon incompressible algorithms (mainly SIMPLE and PISO): segregated in heart
- MPI-based parallel capability
- Two main branches:
  - Foundation (`openfoam.org` - OpenFOAM 11)
  - ESI OpenCFD (`openfoam.com` - OpenFOAM v2306)
- Downside: steep learning curve, no graphical interface, requires Linux knowledge, intimidating to new users

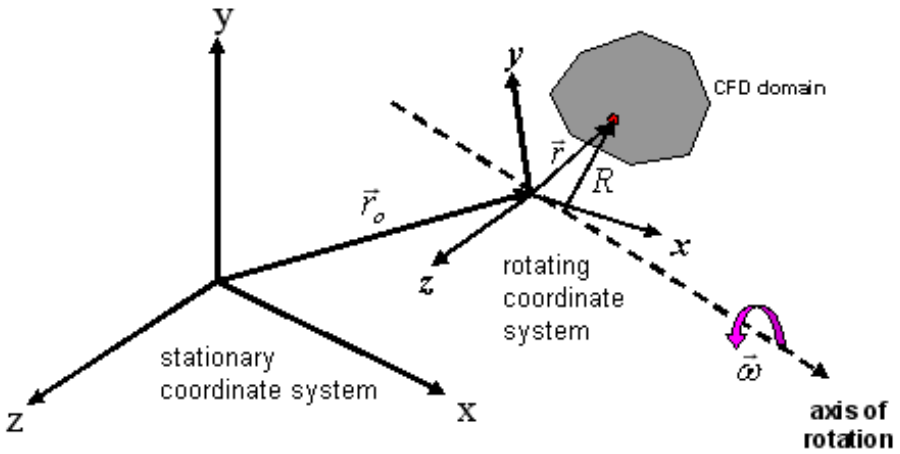
OpenFOAM in brief

- Code is intuitive and easy to modify
- An example: turbulent kinetic energy (k) equation

$$\frac{\partial k}{\partial t} + \nabla \cdot (uk) - \nabla \cdot [(\nu + \nu t)\nabla k] = \nu_t \left[\frac{1}{2}\left(\nabla u + \nabla u^T\right)\right]^2 - \frac{\epsilon_0}{k_0} k$$

```
solve (
    fvm::ddt(k)
  + fvm::div(phi, k)
  - fvm::laplacian(nu() + nut, k)
  ==
    nut*magSqr(symm(fvc::grad(U)))
  - fvm::Sp(epsilon/k, k)
)
```

The *Moving Reference Frame* (MRF) technique



1. Define: axis of rotation (**s**) and rotational speed (ω)
2. Define (for each cell in the MRF zone): distance vector ($\mathbf{r}_i$) of cell i from its center ($\mathbf{x}_i$) to **s**
3. Absolute velocity becomes: $\mathbf{u} = \mathbf{u}_r + \mathbf{\Omega} \times \mathbf{r}$
4. **u** is substituted into N-S equations $\rightarrow$ generates extra terms

A *single* set of equations is solved, with rotational source terms *only* for the rotating zone cells:

$$\underbrace{\nabla \cdot (\mathbf{u}\mathbf{u}_r)}_{\text{Convection}} = -\nabla p + \nabla \cdot (\nu \nabla \mathbf{u}) - \underbrace{\Omega \times \mathbf{u}}_{\text{Source Term}}$$

- **u** and $\mathbf{u}_r$ under same div. operator: *treated with face flux correction* (for full derivation: `https://openfoamwiki.net/index.php/See_the_MRF_development`)
- Velocity at the boundaries within the rotating frame is corrected (solid body rotation)

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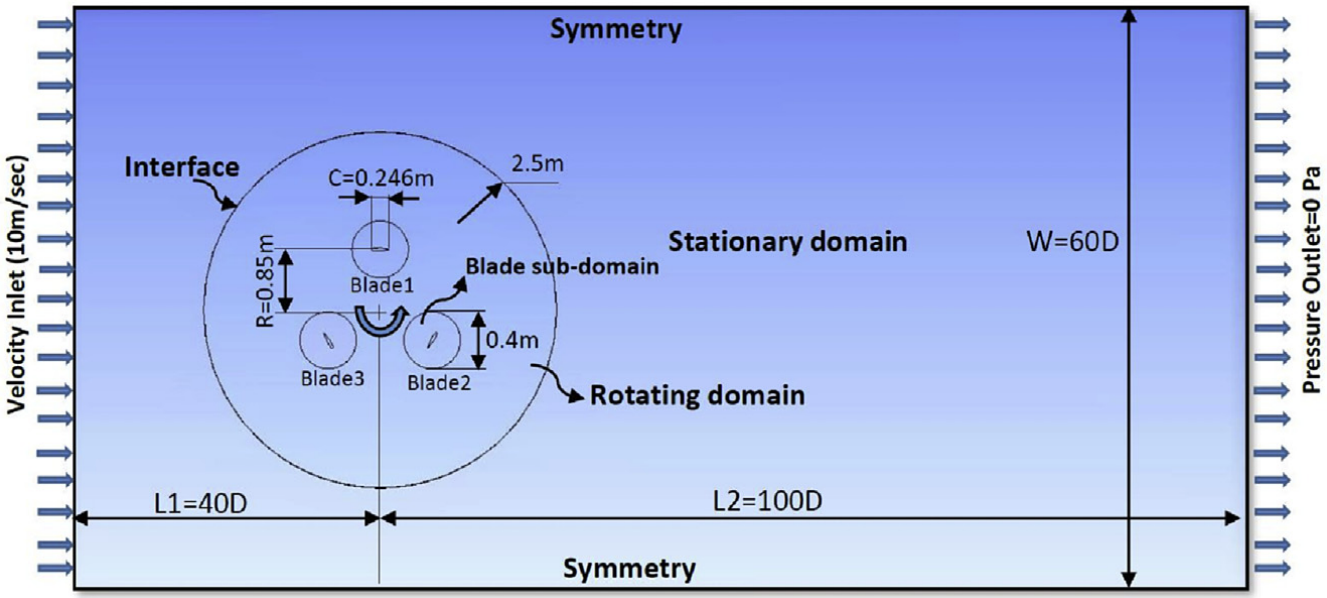
Accessing the TRUBA server

1. **[LOCAL]** Sign in:
   `ssh honel@levrek1.ulakbim.gov.tr`
2. **[LOCAL]** Mount your home directory:
   `sshfs honel@levrek1.ulakbim.gov.tr:'/truba/home/honel' $HOME/ae/truba`
3. **[TRUBA]** Locate pre-installed OpenFOAM libraries (we will use OpenFOAM-8)
   `cd /truba/sw/centos7.3/app/openfoam/OpenFOAM-8/`
4. **[TRUBA]** Get a sample *SLURM Workload Manager* script
   `/truba/sw/centos7.3/app/openfoam/OpenFOAM-8.sbatch`
5. **[TRUBA]** Load necessary modules and setting environment variables
   `$HOME/.bash_profile`
6. **[TRUBA]** Go to the OpenFOAM case directory
   `cd $HOME/OpenFOAM/honel-8/vawt_2d`

Solution grid and definition of zones[*]



Rotor radius (R)	0.850 m
Num. of blades	3
Blade profile	NACA 0018
Chord (c)	0.246 m
Pitch angle	0^o
Tip speed ratio, TSR	2.5
Freestream velocity	10 m/s

$$U_\infty = 10 m/s$$

$$p_\infty = 0 Pa$$

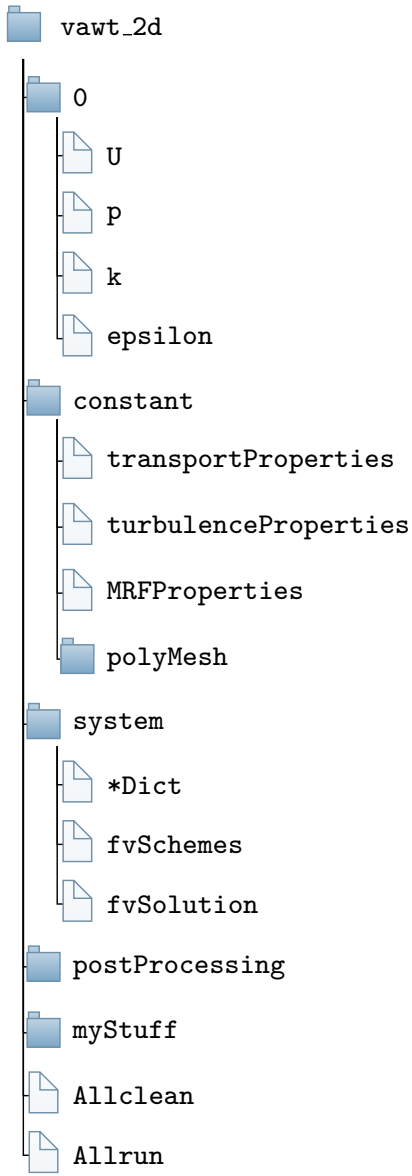
$$[TI = 10\%,\ \ell_{\text{ref}} = c = 0.246m,\ C_\mu = 0.09]$$

$$k_\infty = \frac{3}{2}(U_\infty TI)^2 = 1.500 m^2/s^2$$

$$\epsilon_\infty = \frac{C_\mu^{3/4} k_\infty^{3/2}}{\ell_{\text{ref}}} = 1.227 m^2/s^3$$

[*] Gebreel Abdalrahman, William Melek, and Fue Sang Lien (2017). "Pitch angle control for a small-scale Darrieus vertical axis wind turbine with straight blades (H-Type VAWT)". In: *Renewable Energy* 114, pp. 1353–1362. ISSN: 18790682. DOI: 10.1016/j.renene.2017.07.068.

Structure of the OpenFOAM case



Simulation: running, residual tracking, post-processing

Will be shown live...

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Results need further investigation!

TSR	Ref.[†]	Present	Rel.Err.
2	0.29	0.25	14%

- Does MRF *really* reflect the physics of the problem? It is worth checking the method's sensitivity to:
  - radius of the rotating zone
  - position of the VAWT
- How well do the $k-\epsilon$ model and its wall functions work? (y^+ should be checked)
- Is the mesh good enough? (grid convergence should be checked)
- We've only used 1^{st} order schemes, how accurate are they?

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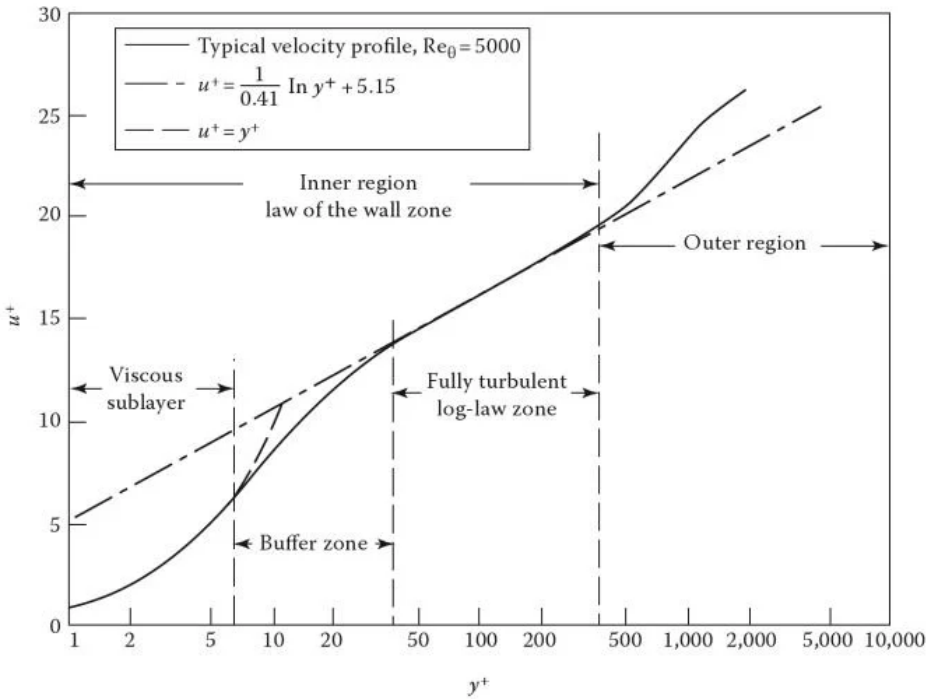

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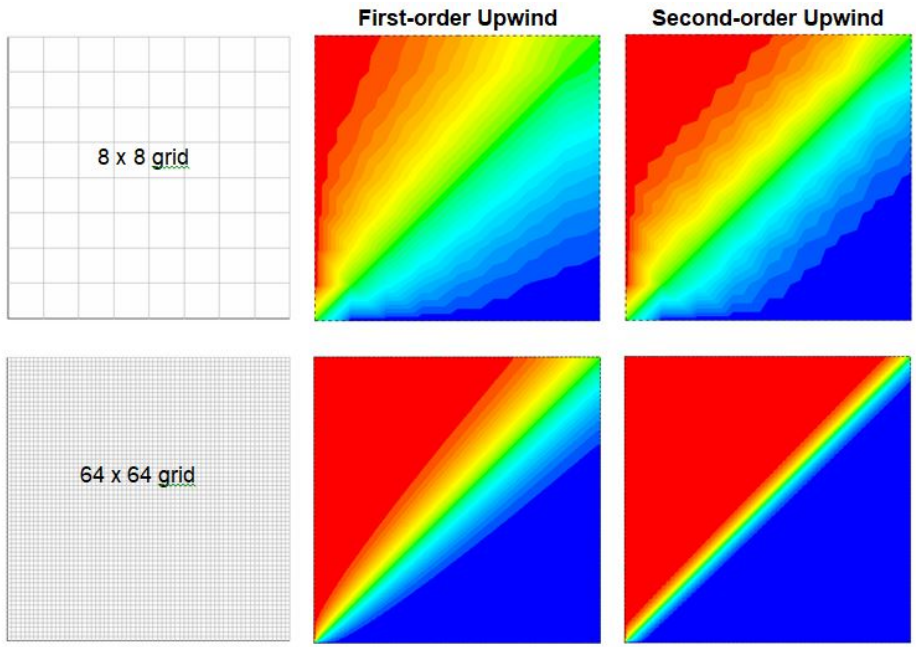

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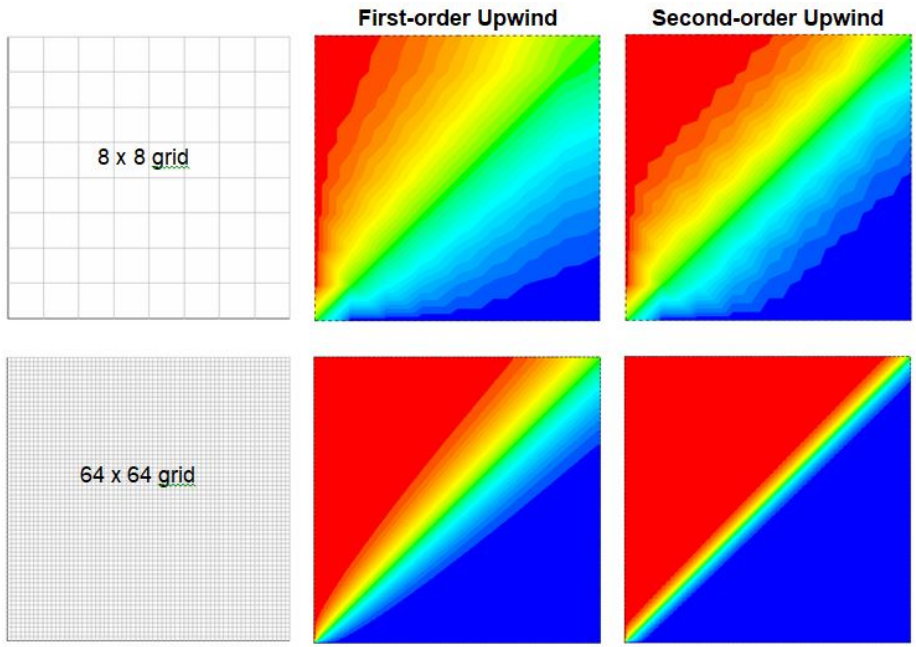

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Thank you,
hope you learned something new!