System-Level Simulation of Floating Platform and Wind Turbine Using High-Fidelity and Engineering Models

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NAWEA 2015, 11th Jun 2015

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Overview

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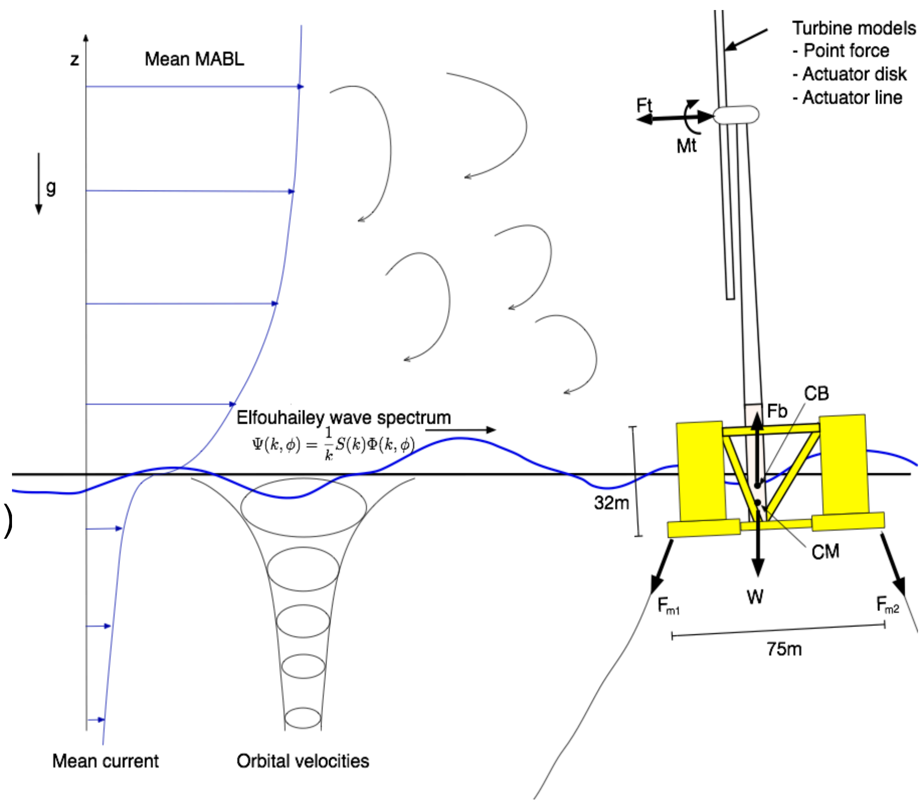
  - Review
- **Approach**
  - Computational methods
  - System geometry
  - Test cases and flow conditions
  - Computation resource
  - Analysis methods
- **Preliminary Results**
- **Conclusion and Future Work**

Objectives

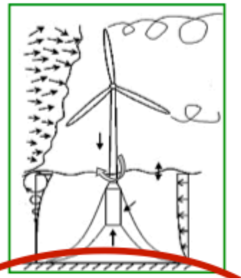
- Study the effect of mooring system on offshore wind turbine dynamics
  - Full-system simulations, including mooring-line and turbine aerodynamics
  - Based on OC3 configurations
- Study the interaction of wave field and wind-turbine platform dynamics
  - From linear waves to real wave fields
  - Quantify impact of platform motion and waves on turbine inflow
  - Validate against limited experimental data (OC3)
- Analyze turbine performance near Virginia coastline
  - Wave and meteorological data from statistics

Full hydrodynamic model



Review

Cyber Wind Facility



MESOSCALE, WEATHER

*ATMOSPHERIC BOUNDARY LAYER TURBULENT WINDS

WAKE TURBULENCE BLADE-WAKE-ATMOSPHERE

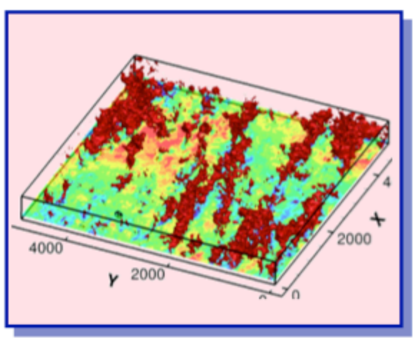
*PLATFORM-WAVE HYDRODYNAMICS and 6-DOF MOTIONS

*BLADETIME LOADINGS AERODYNAMICS, SPACE-

WAKE-TURBINE INTERACTIONS (wind plant)

*BLADE AND *TOWER ELASTIC DEFORMATION

*Shaft Torque, *Drivetrain Loadings



CYBER WIND FACILITY

- highly resolved 4-D cyber data
- coupled atmospheric turbulence-blade loadings-shaft torque data
- coupled wave structure – platform motion – turbine loadings data
- experiment design, test-bed, turbine design, controls concepts and testing
- advanced correlations for BEM and other design tools using look-up tables.

*sensors, controllers, diagnostics

Review

- **Turbine platform hydrodynamics by CFD**
  - Dunbar et al. (2013) – coupled solver
  - Calderer et al. (2014) – fluid structure interaction
- **Turbine and buoy**
  - Jonkman et al. (2009) - 5MW Turbine
  - Jonkman et al. (2010) – OC3 spar buoy
- **Mooring line modeling**
  - Faltinsen (1990) – catenary line
- **Actuator Line model(ALM)**
  - Sørensen and Shen (2002) – ALM theories
  - Churchfield et al. (2012) - SOWFA
  - Jha et al., 2014 - CWF
- **Waves**
  - Jacobsen et al.(2012) – waves2Foam
- **Offshore statistics**
  - National Buoy Data Center(DBDC)
- **Cyber Wind Facility(CWF)**
  - Vijayakumar et al. (2014) – blade aerodynamics module
  - Jha et al. (2013) – wake modulations module
  - Motta-Mena et al. (2013) – structural dynamics module
  - Dunbar et al. (2014) – hydrodynamic module

Project Approach

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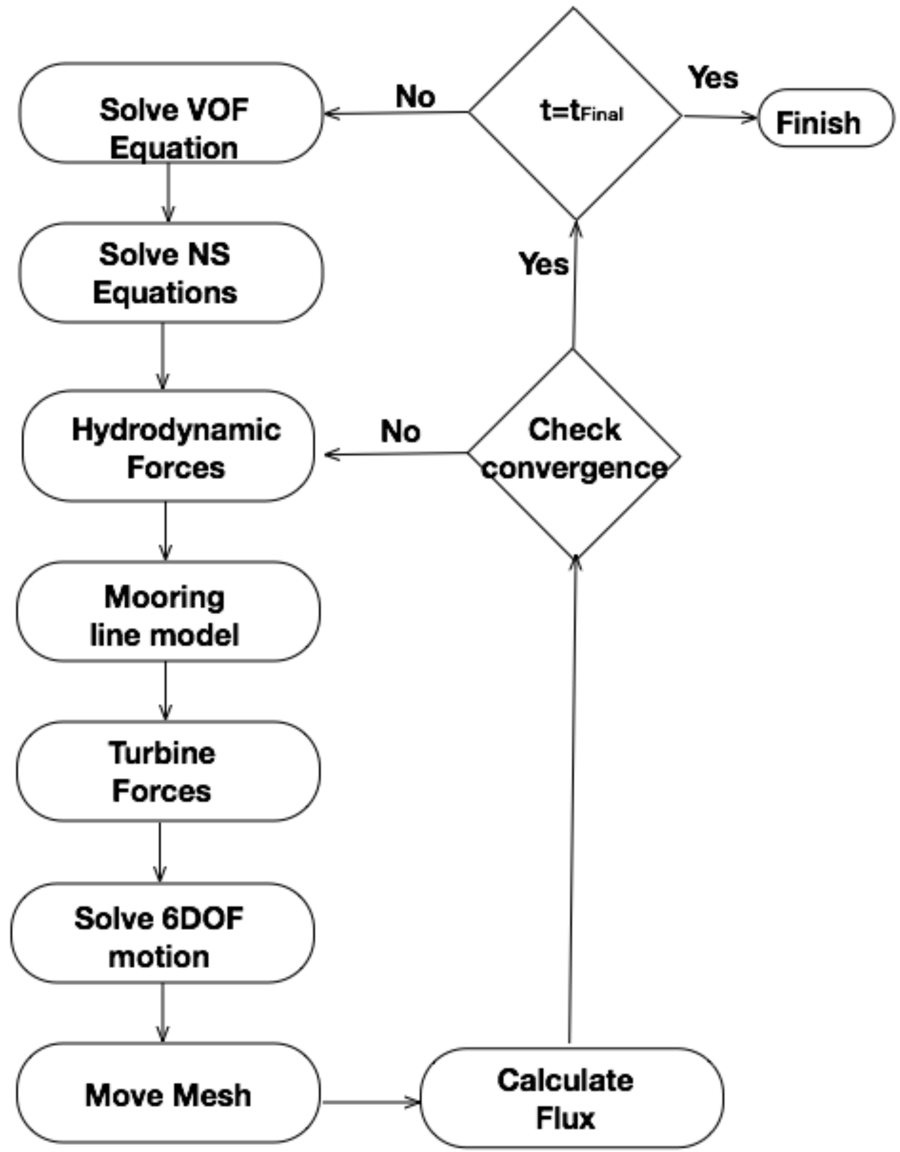
- **Implementation steps:**
  1) Generate surface wave with wave2Foam library and inspect the platform response: **Done**
  2) Implement mooring line model in CFD code: **Done**
  3) Integrate ALM with multi-phase solvers: **Done**
  4) Run simulations on the cases with OC3 configurations: **In-progress**
  5) Incorporate mooring line model and ALM with tightly-coupled 6DOF solver: **Under-development**

Multiphase CFD + 6DOF solver

- **CFD solver: interDyMFoam**
  - Two-phase incompressible solver
  - Interface tracking technique with Volume of Fluid (VOF) field alpha
  - Pressure Implicit with Splitting of Operator(PISO) algorithm solves the pressure-velocity coupled system
  - Coupled with 6DOF solver:
    - Extract force and moment from pressure and viscous effects
    - Calculate acceleration according to the mass of the object
    - Move center of mass
    - Rotate and translate patches
- **Tightly-coupled solver introduces inner loop for algorithm stability under large structure displacement (Dunbar et al. 2013)**

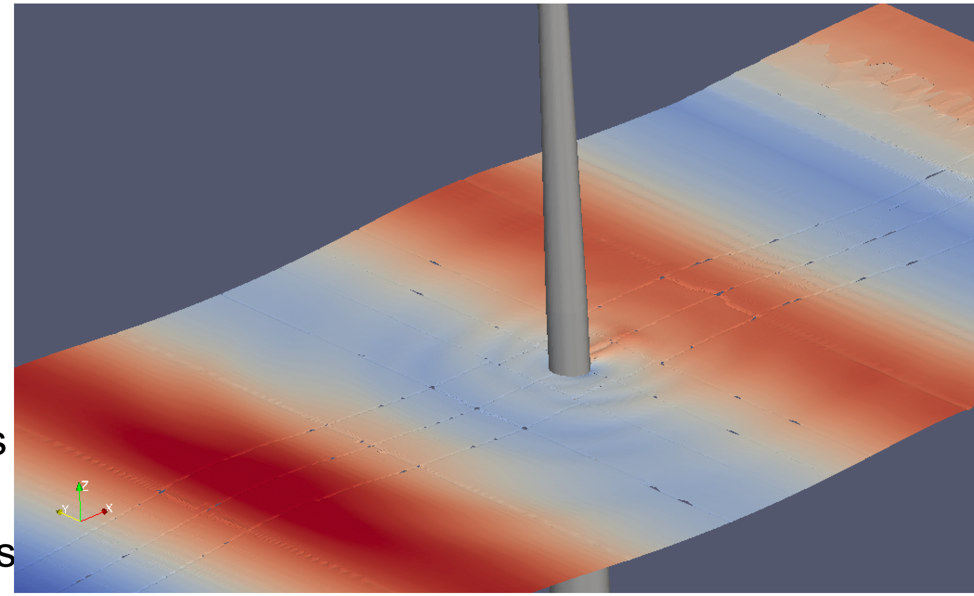


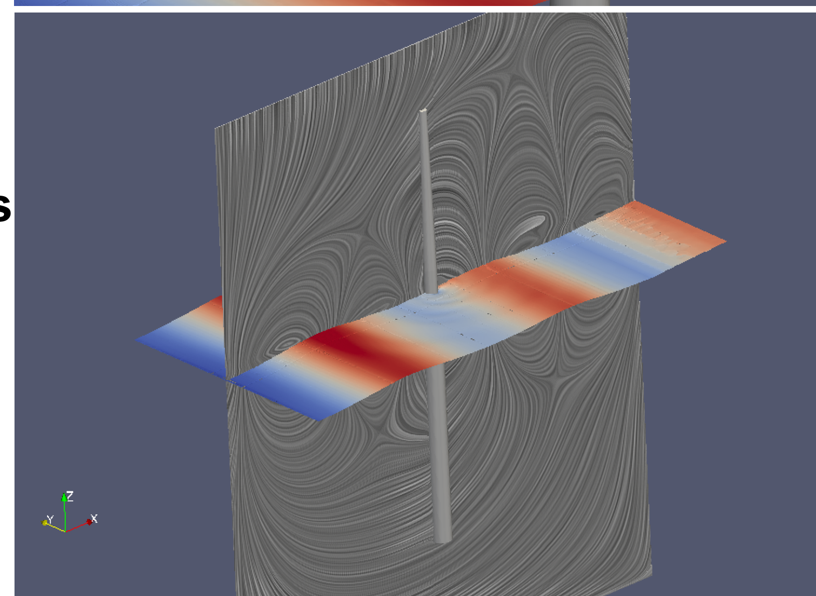
waves2Foam

- **Waves2Foam: wave generating toolbox**
  - Common wave theories
    - Potential current
    - Regular waves: Stokes wave
    - Solitary wave
    - Irregular waves
  - Boundary conditions apply wave theories to corresponding field
  - Relaxation zones control wave reflections on boundaries
  - Utilities that initialize wave field

- **Wave forces on OC3 spar buoy has been studies by direct CFD and Morison equation**
  - Morison equation is a pure empirical approach

Wave elevation on free surface (H=7m, L=90m)



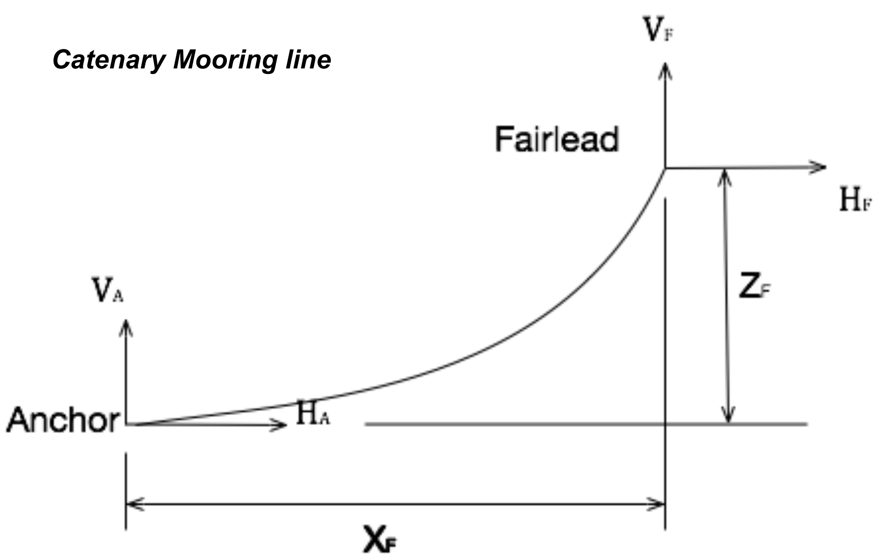


Wave elevation on free surface with wave-induced circulations in y–plane (H=7m, L=90m)

Mooring-line model

- **Quasi-static mooring line**
  - Based on catenary line equation
  - Mooring system dynamics are ignored
  - Mooring force is calculated at each time step according to current geometry

Catenary Mooring line



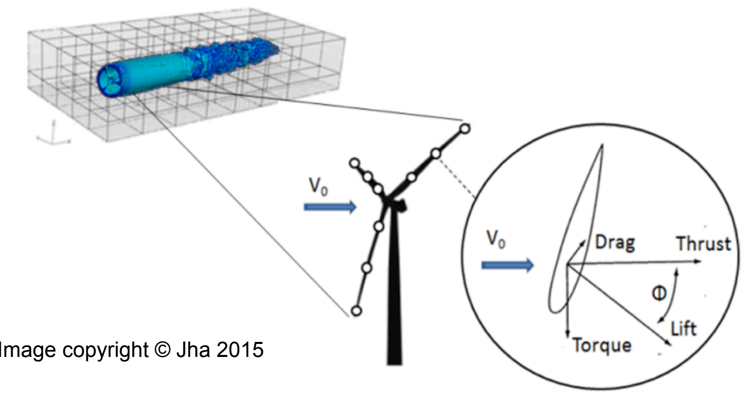
- **Pseudo code of mooring-line model implementation in OpenFOAM**

```
//test if the cable touches seabed
touch=testTouch(L,w,EA,CB,XF,ZF);

//initialize vertial and horizontal force
HF1=iniHF(w,XF,ZF,L);
VF1=iniVF(w,XF,ZF,L);

do {
    if touch{
        HF2=solveTouchHF(L,w,EA,CB,XF,ZF,HF1);
        VF2=solveTouchVF(L,w,EA,CB,XF,ZF,VF1);
    }else{
        HF2=solveUntouchHF(L,w,EA,CB,XF,ZF,HF1);
        VF2=solveUntouchVF(L,w,EA,CB,XF,ZF,VF1);
    }
    del_HF=abs(HF1-HF2);
    del_VF=abs(VF1-VF2);

    //set for next iteration
    HF1=HF2;
    VF1=VF2;
//test if converged
}while(del_HF>epi_HF & del_VF>epi_VF);
```

Actuator-Line Model

- **Actuator Line Model (ALM) – Pankaj / Churchfield**
  - Discretize each blade into sections, assume uniform blade configuration and flow condition for each section
  - Sectional force of each element is calculated according to local flow conditions and airfoil lookup table
  - Spread sectional force from each element by Gaussian distribution as additional body force at each cell

- **Multiphase solver with ALM was tested**



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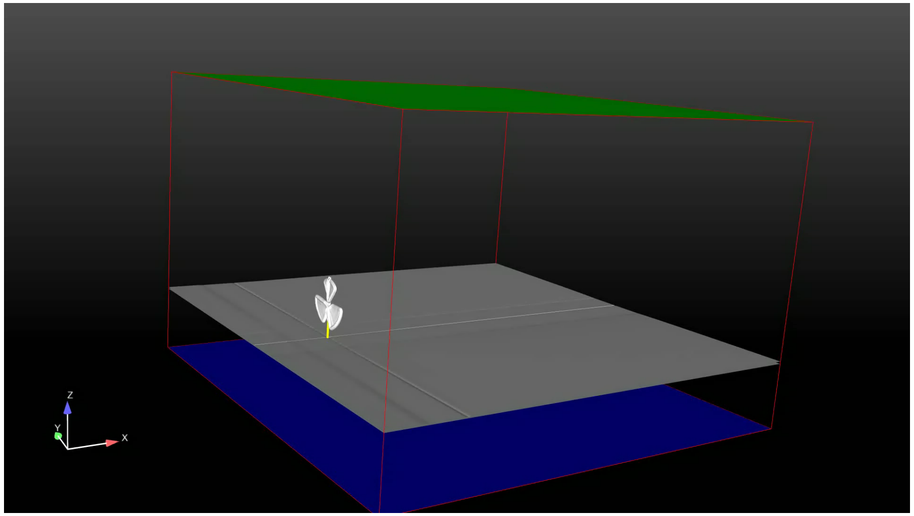

OC3 System Geometry

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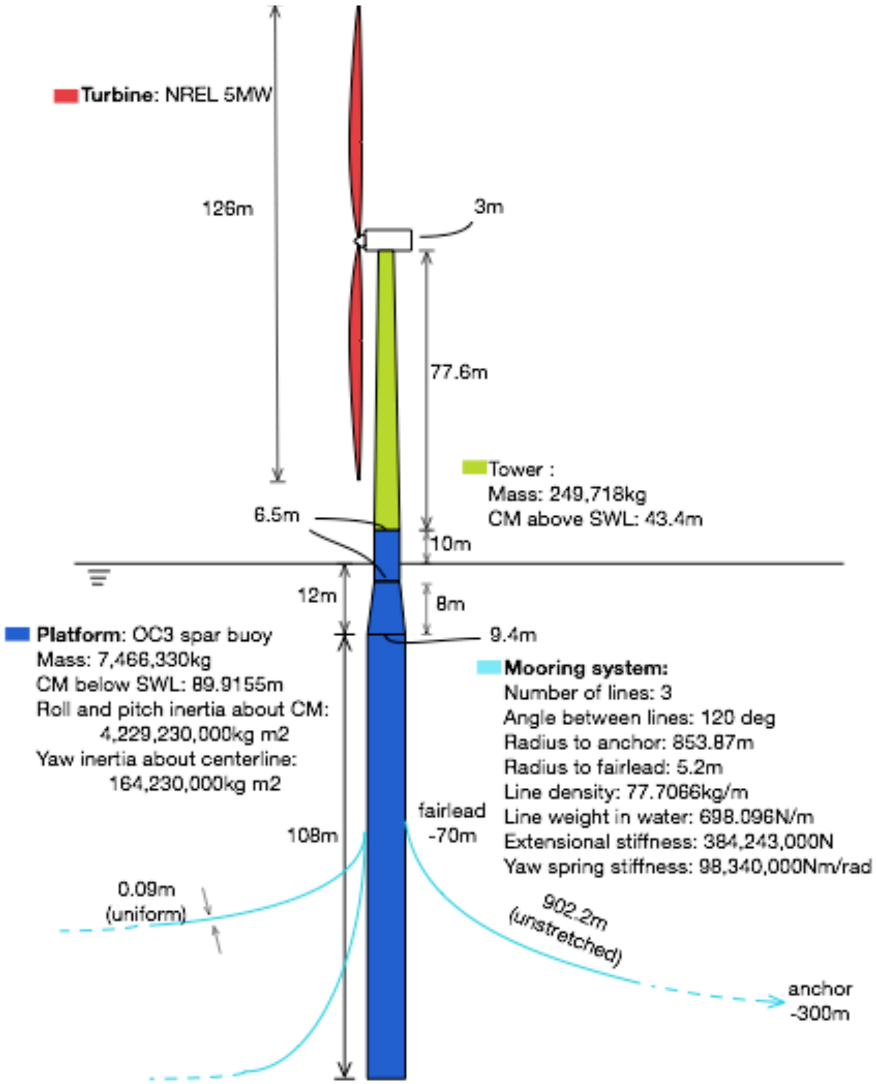
- **NREL 5MW turbine**
  - Diameter: 126m
- **OC3 spar buoy**
  - Total draft: 120m
  - Weight: 7,466,330kg
- **Uniform mooring cables**
  - Fairlead at 70m below Still Water Line(SWL)
  - Anchor point at 320m below SWL
  - 853.87m from buoy centerline to anchor
  - The vertical force on buoy is -1.66e6N



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Test Cases and Flow Conditions

- **In order to study the effect of free surface on turbine performance, 6 cases are tested:**

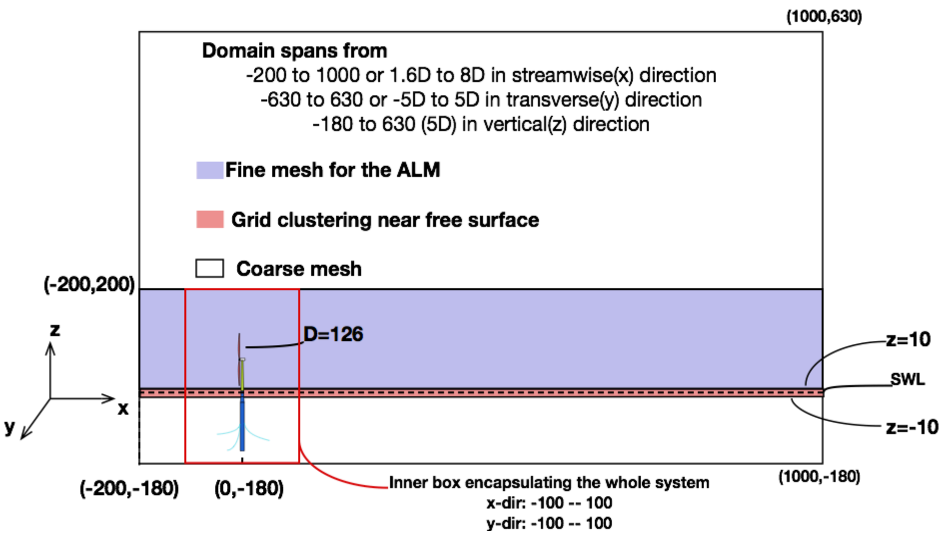
Free surface	LES	DES	RANS
Level ground	LES	DES	RANS

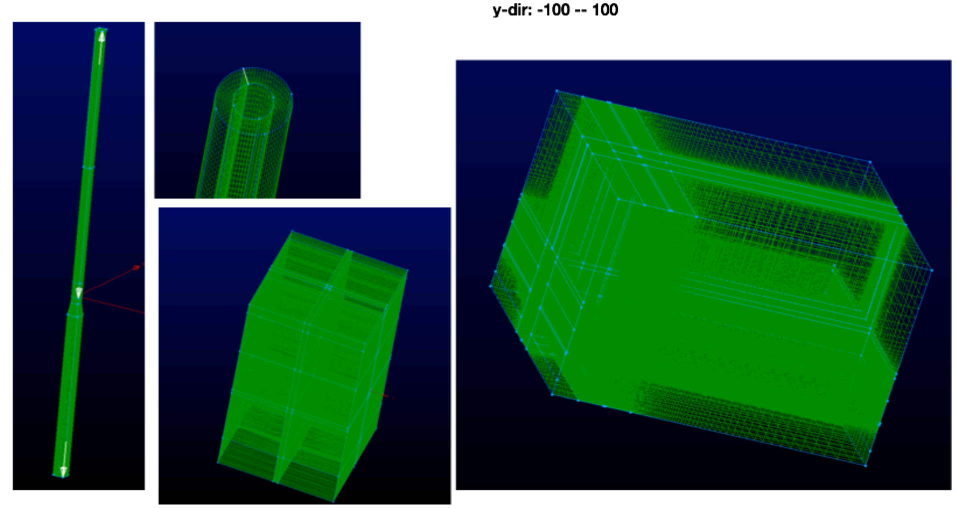
- LES: Smagorinsky
- DES: SpalartAllmarasDDES
- RANS: Standard SpalartAllmaras

- **Domain is cut at the SWL (z=0) for cases with solid surface**

- **Flow conditions:**
  - U=8m/s uniform in air
  - Water is kept still
  - Structure is fixed

Computational domain with free surface





Computational Resource

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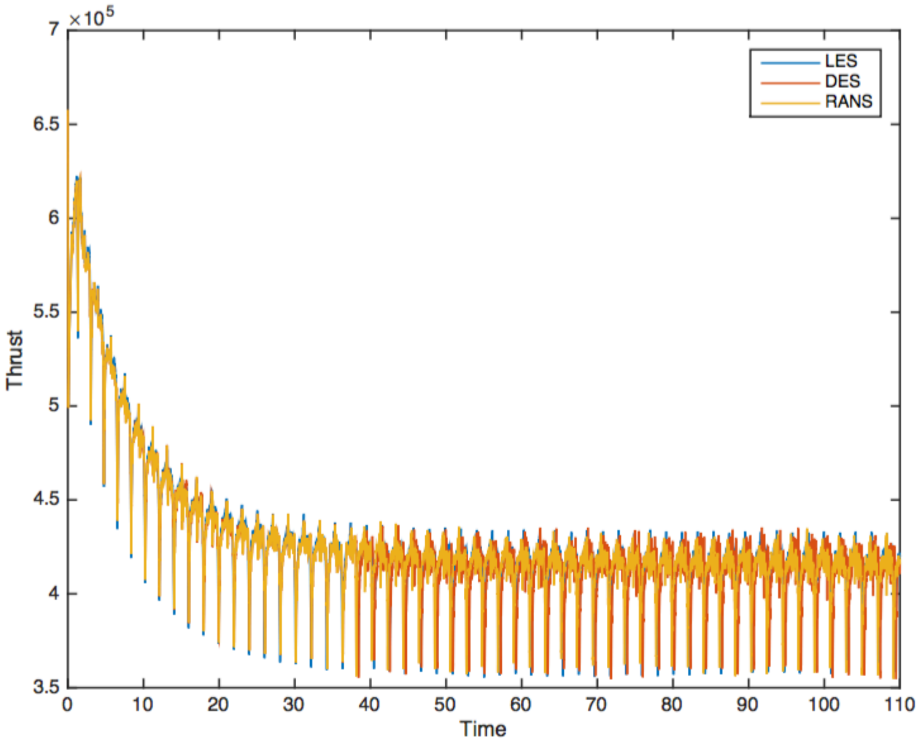
- **All simulations are supported by Advanced Research Computing(ARC) in VT**
  - Blueridge: 408-nodes Cray cs-300 cluster
    - Release in 2013
    - Two octa-core Intel Sandy Bridge CPUs per node
    - 64 GB of memory per node
  - Each case is ran on 64 cores
    - 7.2 millions cells for free surface cases
    - 1.12e5 cells/core
  - Simulation walltime is set to 72-hours
    - Initial turbine rotational speed ad 11rpm
    - Approximately 9.7rpm in steady state
    - Simulation runs until ≈120s
    - 0.6hour/revolution
  - Post-processing by Ensight
    - Parallel client-server using 4 cores

Analysis

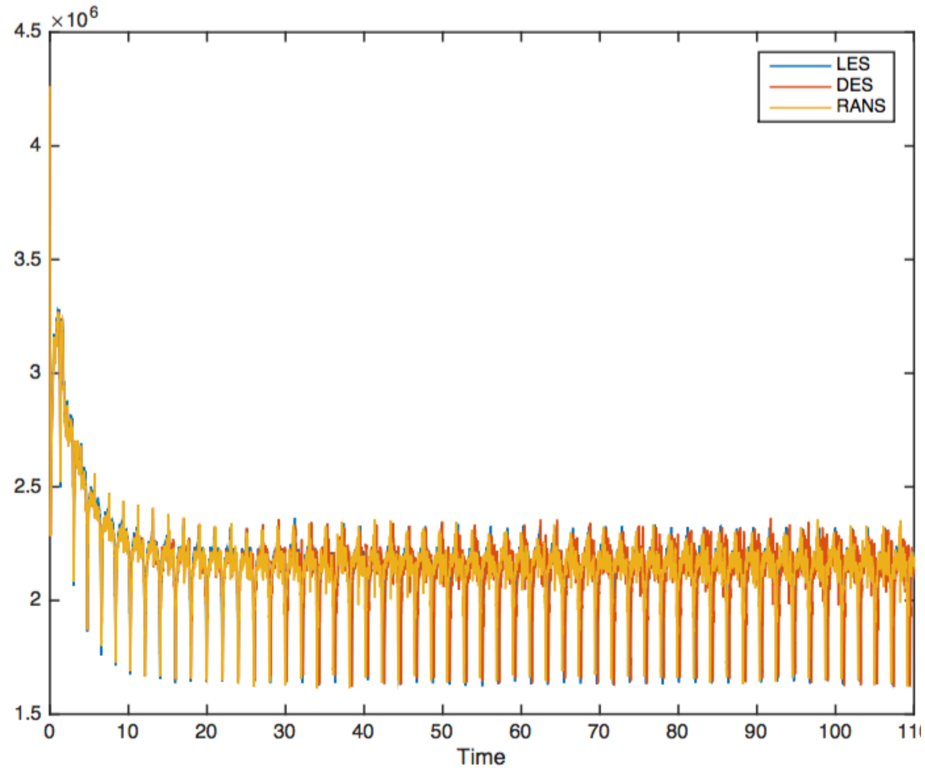
- The following fields will be analyzed:
  - Time history of thrust, torque on turbine blades
  - Diagnose angle-of-attack vs. radius over turbine rotation
  - Turbine wake at x/D = 0.5, 1.0, 2.0
    - Instantaneous U, TKE, vorticity
    - Mean U, TKE, vorticity
  - Surface shear stress and limiting streamlines on ground and water free surface
  - Wave field generated by turbine aerodynamics and platform hydrodynamics

Preliminary Results

Turbine Thrust of the cases with level ground surface



Turbine Torque of the cases with level ground surface



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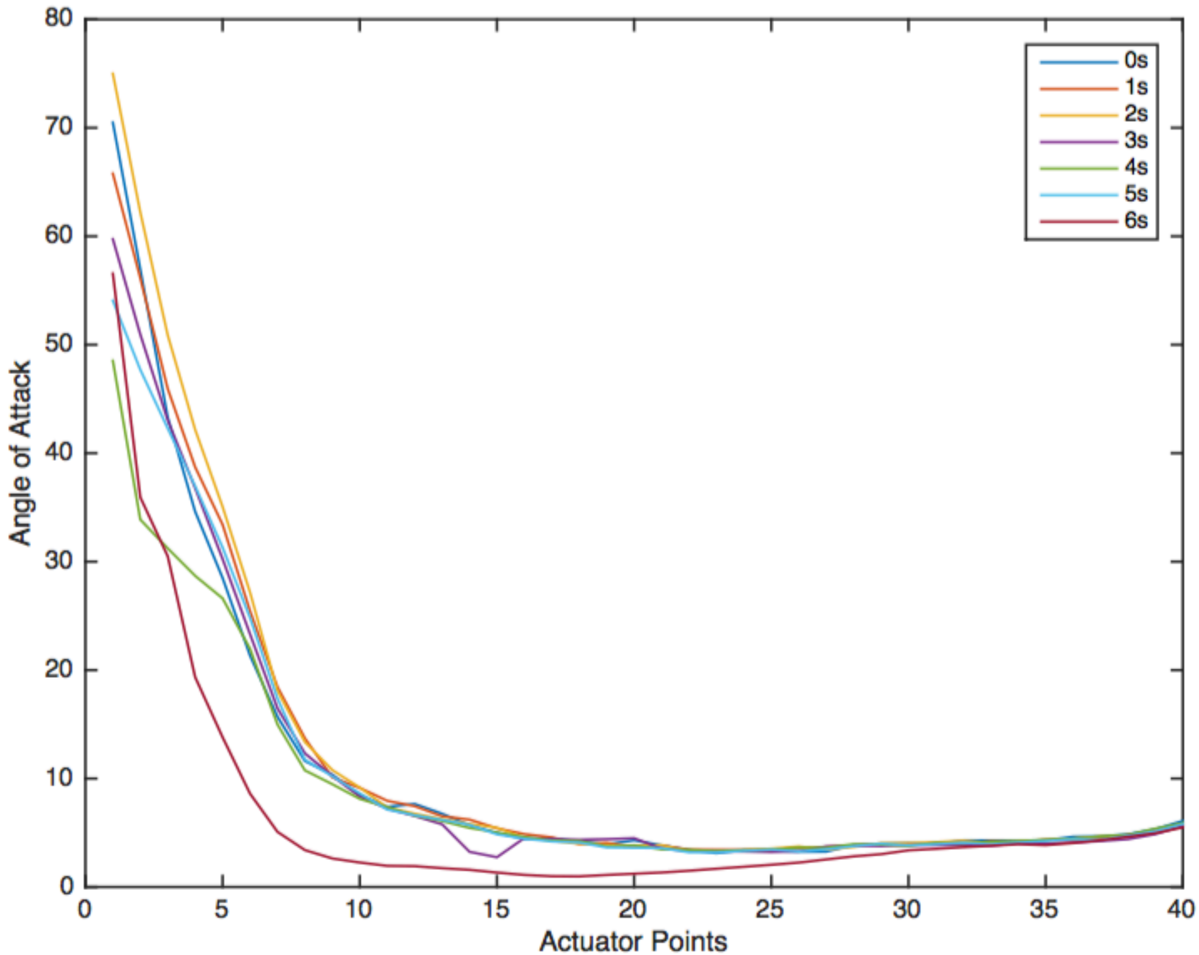
Preliminary Results

Angle of attack at each actuator point of turbine blade over one rotation



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Preliminary Results

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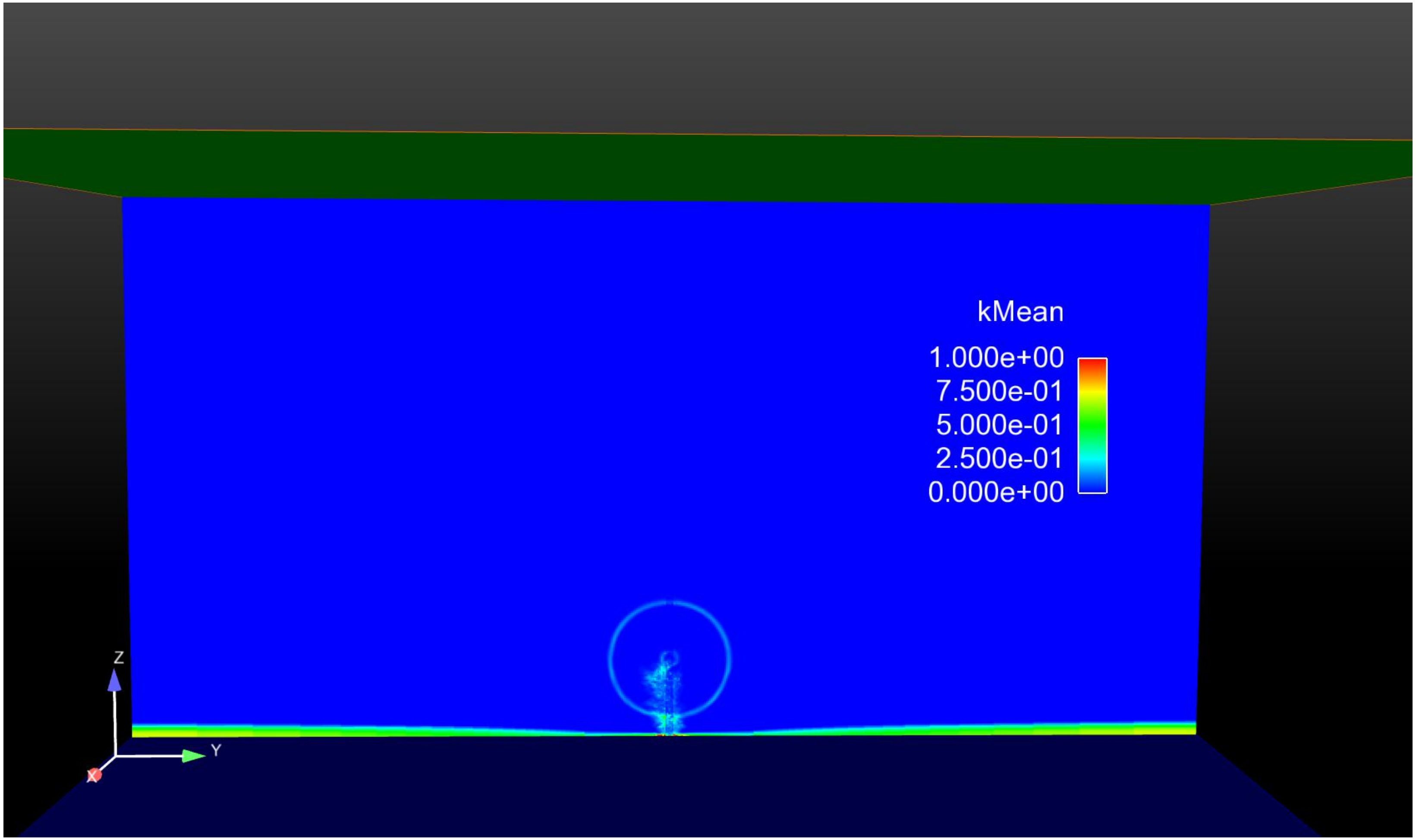
Mean turbulence kinetic energy 0.5D downstream



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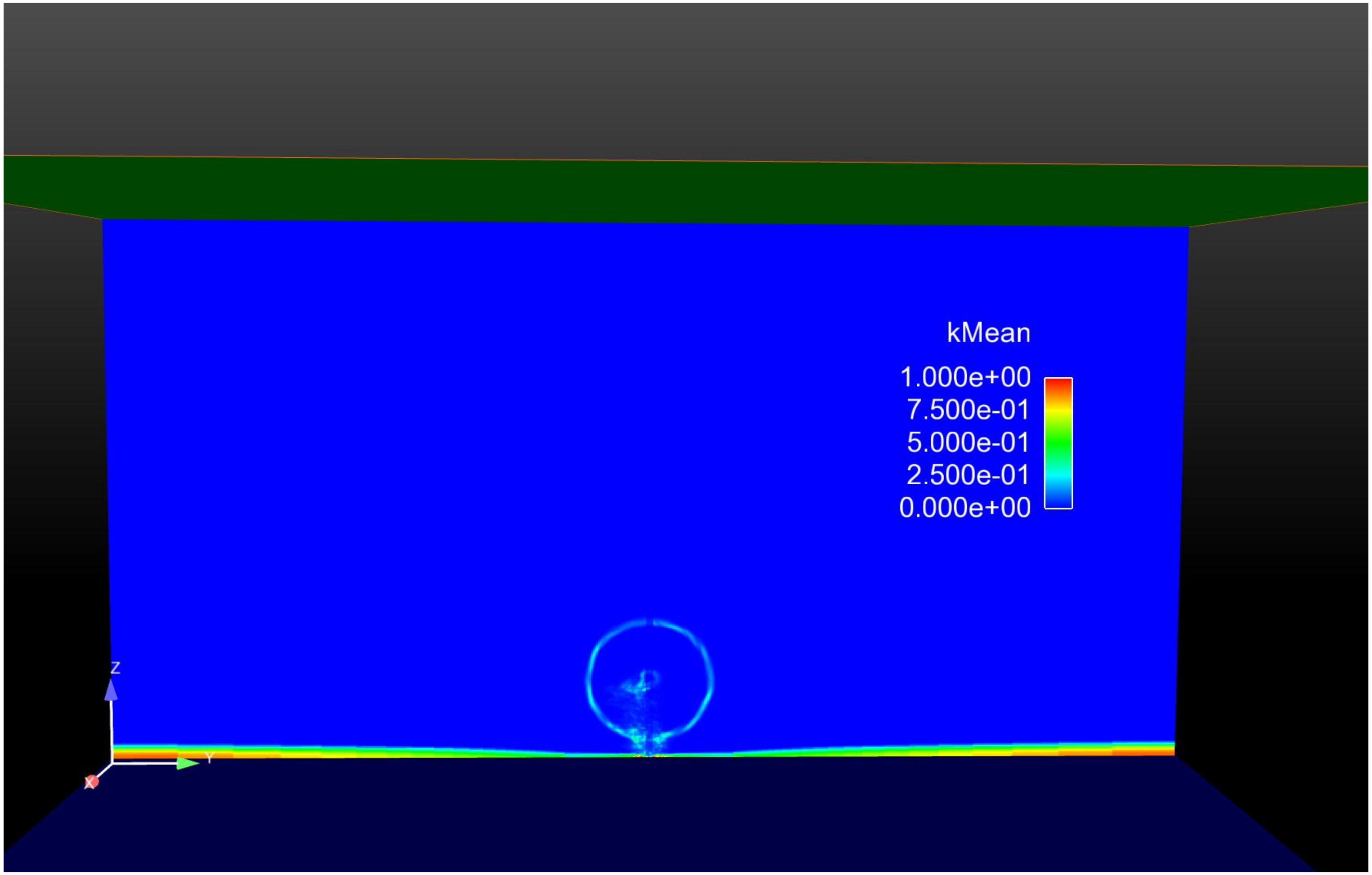
Preliminary Results

Mean turbulence kinetic energy 1D downstream



Preliminary Results

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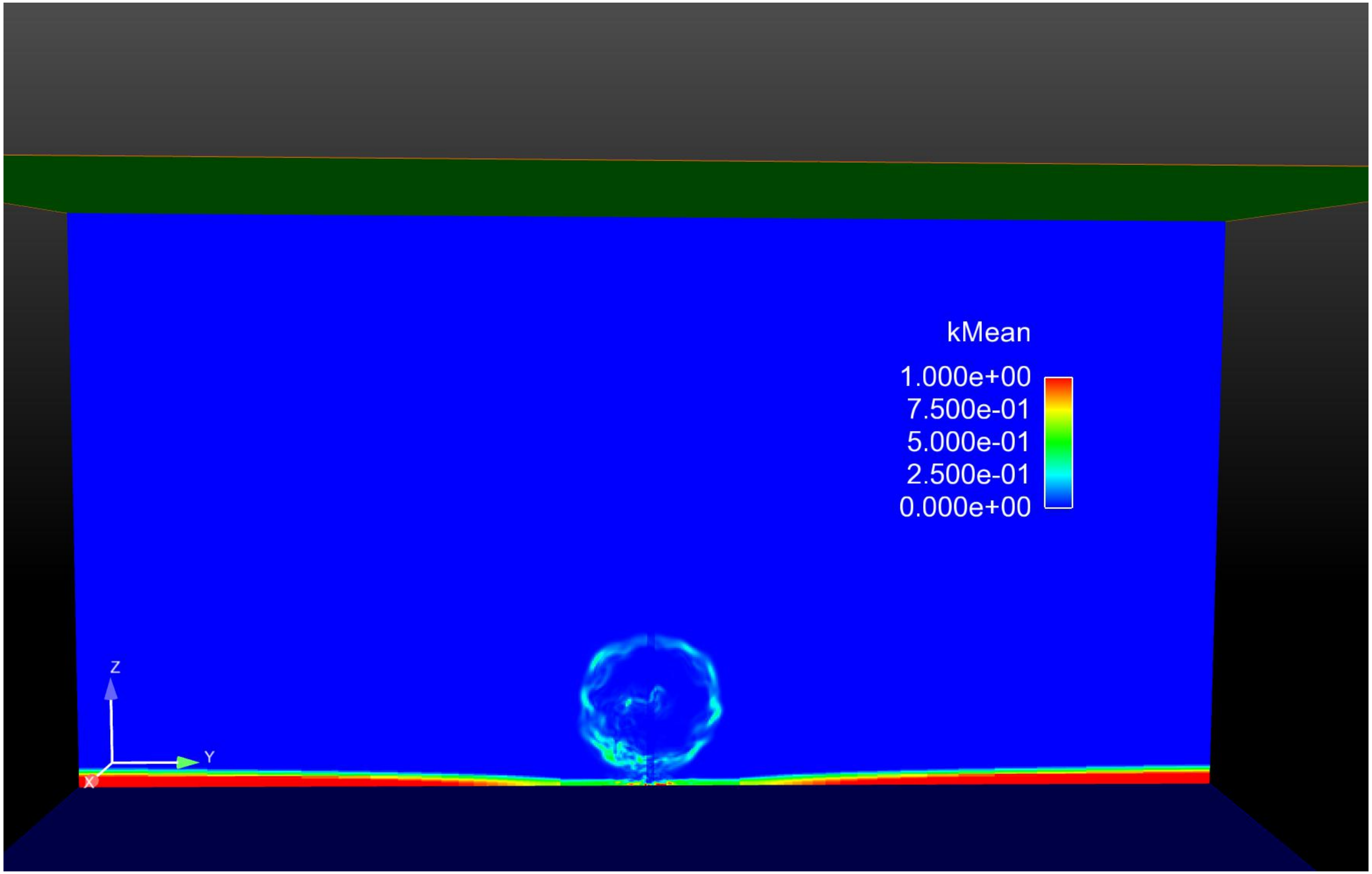
Mean turbulence kinetic energy 2D downstream



Conclusion and Future Work

- The implementation of mooring-line model in OpenFOAM provides restoring force for the platform, further validation is needed(NREL's HydroDyN).
- Actuator Line Models works with multiphase solver, studies on turbine-wave interactions can be conducted bases on it.
- Use of robust HPC resources at VT-ARC gives good turn-around.
- Current multiphase solver was proven to be unstable under large structure displacement, tightly-coupled solver will be adopted in future work.
- waves2Foam supports various long-crest wave theories, in order to model statistical conditions, it needs to be extended for directional spectrum and short-crested wave model.

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