Study of Hydrokinetic Turbine Arrays with Large Eddy Simulation

"fastFlume" tutorial for SOWFA

Danny Clay Sale (dsale@uw.edu)

University of Washington, Seattle, WA, USA
Department of Mechanical Engineering
Northwest National Marine Renewable Energy Center

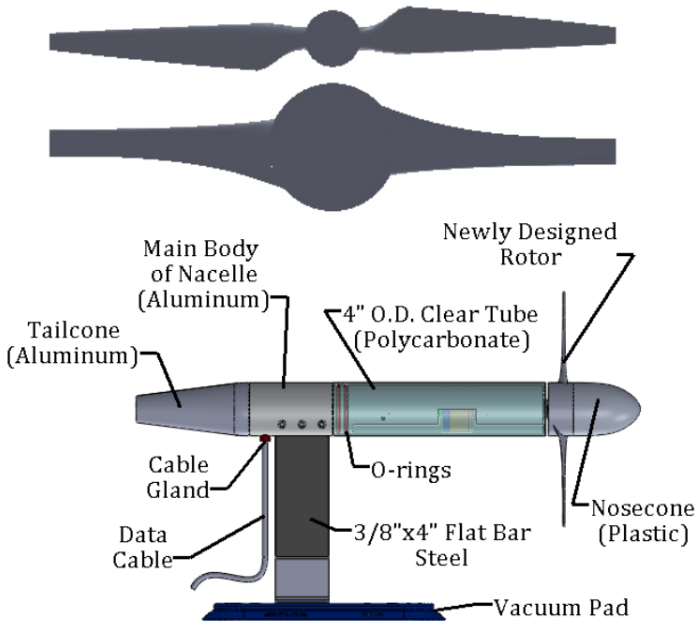
May 11, 2015

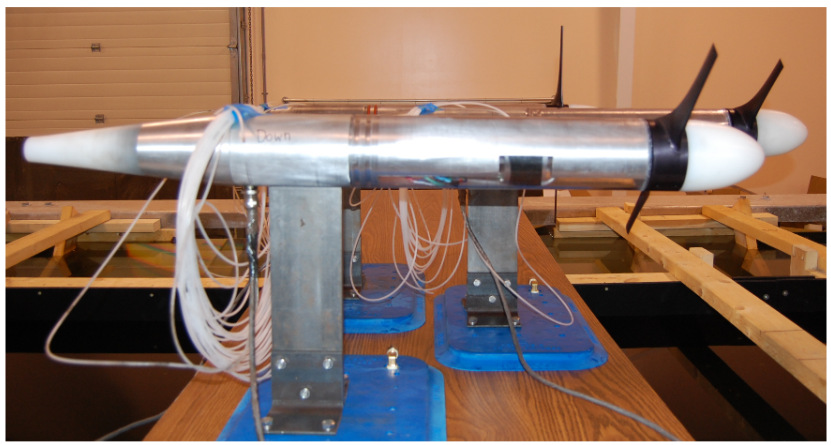
FOCUS

What is the potential power generation and environmental effects from marine hydro-kinetic (MHK) turbine farms?

- Areas to Investigate
  - fluctuations of power production and structural response due to turbulence
  - turbulence characteristics and wake evolution
  - near field pressure fluctuations in wake
- Comparison of Numerical Simulations and Experiment
  - physical testing of 3 turbines in water flume
  - large-eddy-simulation (LES) to replicate experiment

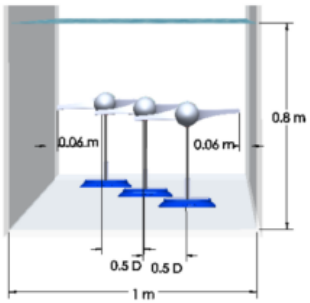
TIDAL TURBINE REFERENCE MODEL 1

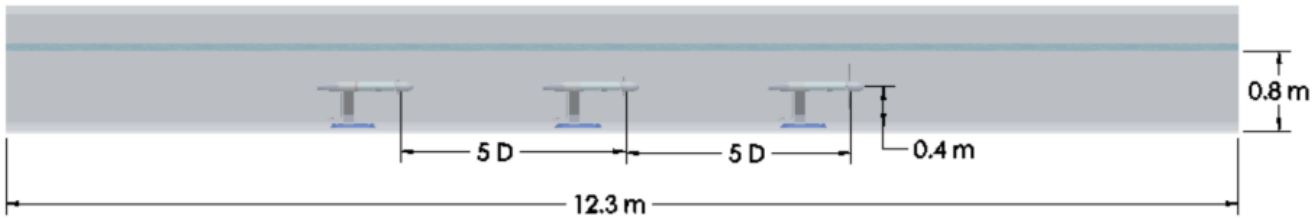


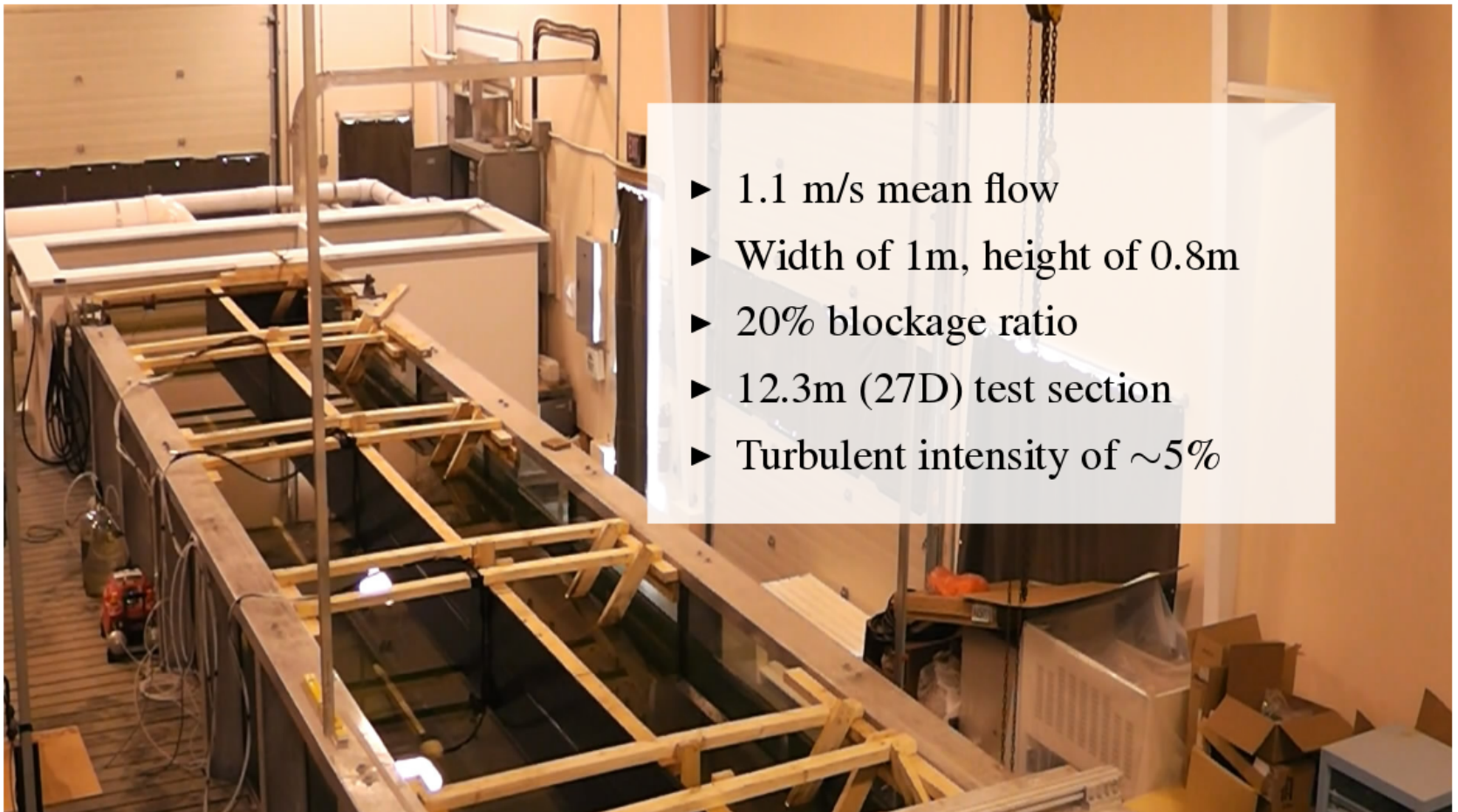


- horizontal-axis turbine, full-scale 550kW, diameter of 20-m
- created by US DOE to standardize experimental and numerical studies
- foils are NACA 4 and 6 series chosen for cavitation prevention and well known performance characteristics at low and high Reynolds
- laboratory turbine 45:1 scaling – diameter of 45-cm
- attempt to match power extraction and wake characteristics at lab-scale
- lab-scale rotor was re-designed to minimize Reynolds scaling effects

FLUME TESTING OF 3 TURBINES



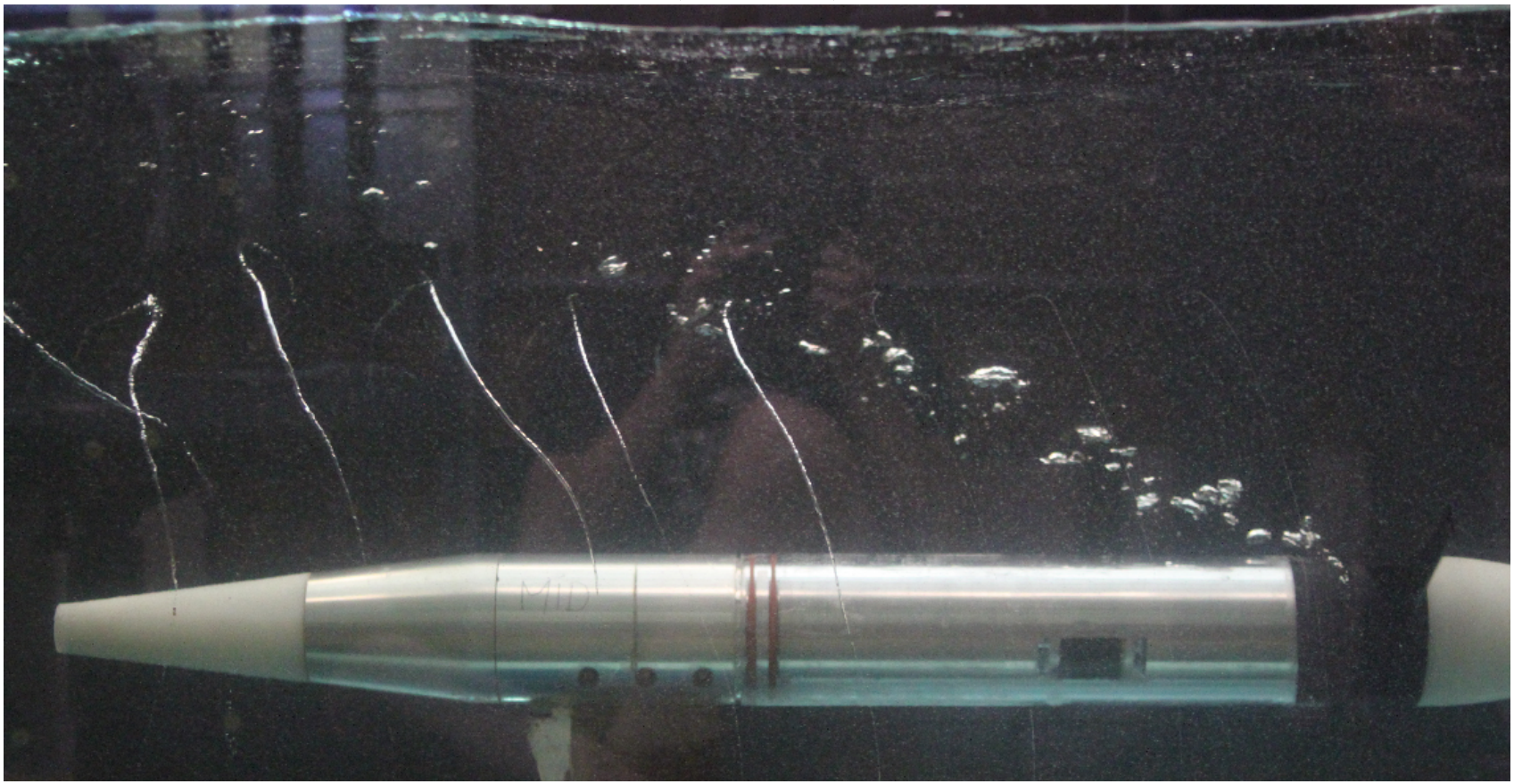




- 1.1 m/s mean flow
- Width of 1m, height of 0.8m
- 20% blockage ratio
- 12.3m (27D) test section
- Turbulent intensity of ∼5%

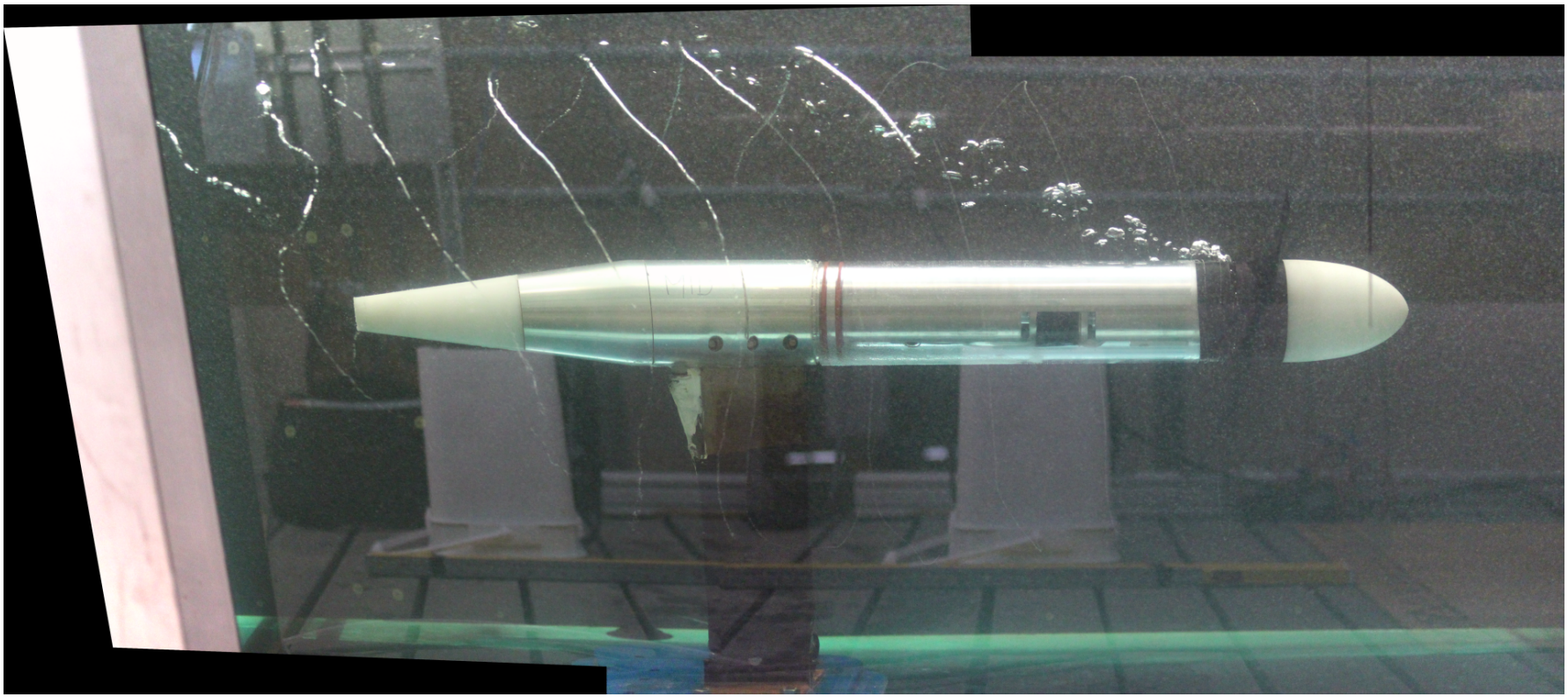
VISUALIZATION OF TIP VORTEX

bubbles are released from the nacelle to visualize tip vortex (movie)



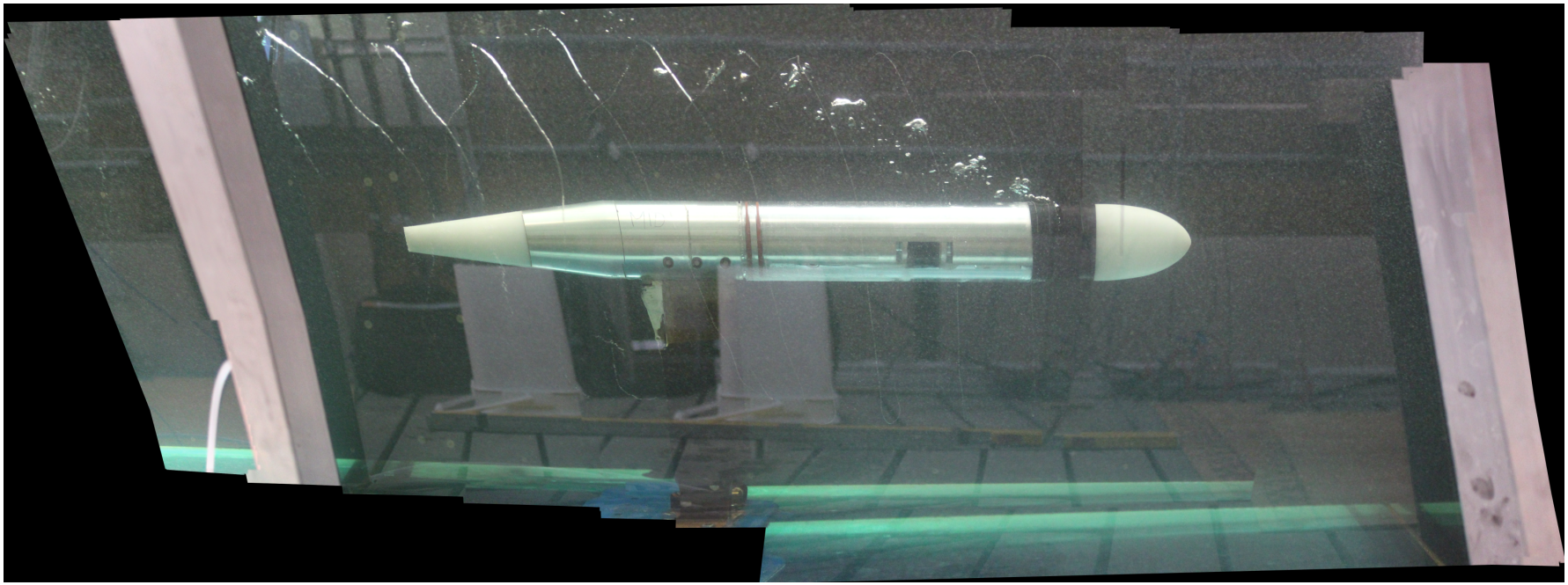
VISUALIZATION OF TIP VORTEX

bubbles are released from the nacelle to visualize tip vortex (panorama)

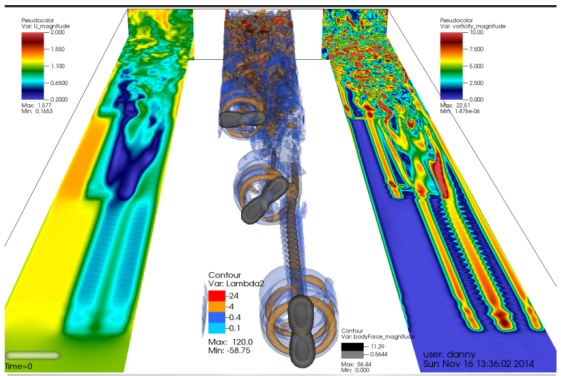


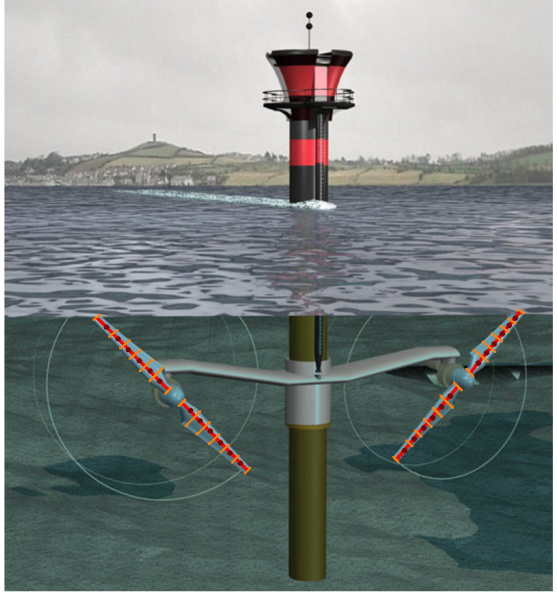
VISUALIZATION OF TIP VORTEX

bubbles are released from the nacelle to visualize tip vortex (panorama)



The turbine model uses the velocity field from the LES to compute the hydrodynamic forces imparted on the turbine blades, and then body forces are projected back onto flow field.[1]





- Large-Eddy-Simulation (LES)
  - code: OpenFOAM (Field Operation and Manipulation)
  - second-order accurate finite-volume (FV) formulation
  - filter is implicitly defined by the mesh and FV discretization
  - subgrid-stress (SGS) model is constant coefficient Smagorinsky
- Actuator-Line-Method (ALM)
  - code: FAST (Fatigue Aerodynamics Structures Turbulence)
  - creates turbulent wake and captures blade tip and root vortices
  - similar to blade element method discretize blades into spanwise sections
  - depends on airfoil lookup tables for lift, drag, moment, min. pressure coefficients
  - normalized forces projected onto flow field with equal and opposite direction

1.

TURBINES=3 TSR=6.2 MESH=(COARSE, MEDIUM)

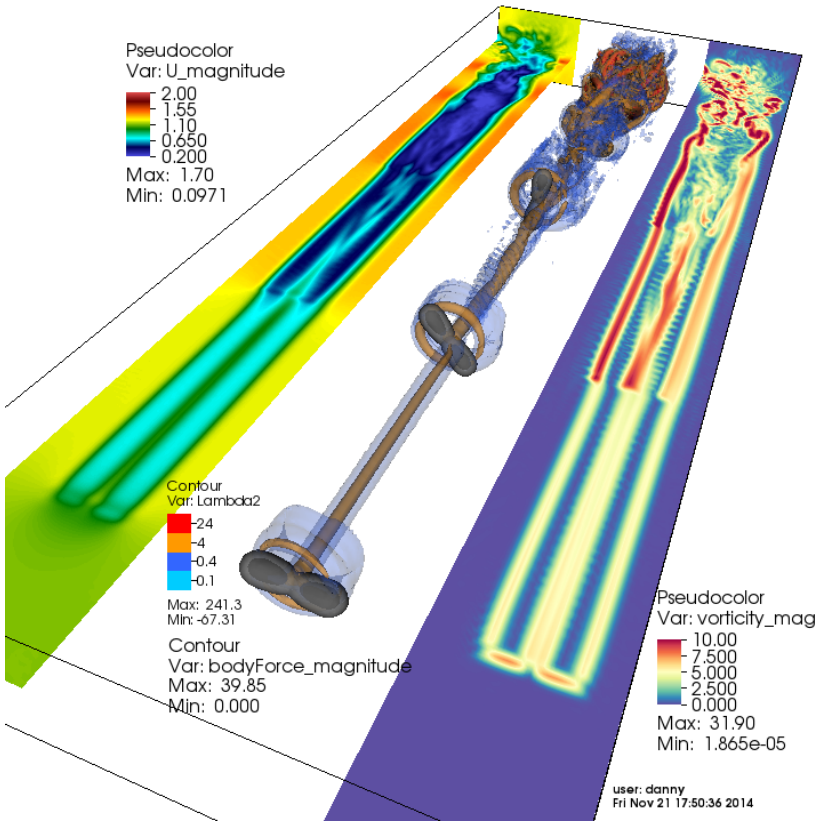


Figure : coarse mesh 465x50x40, dx = 0.020 m

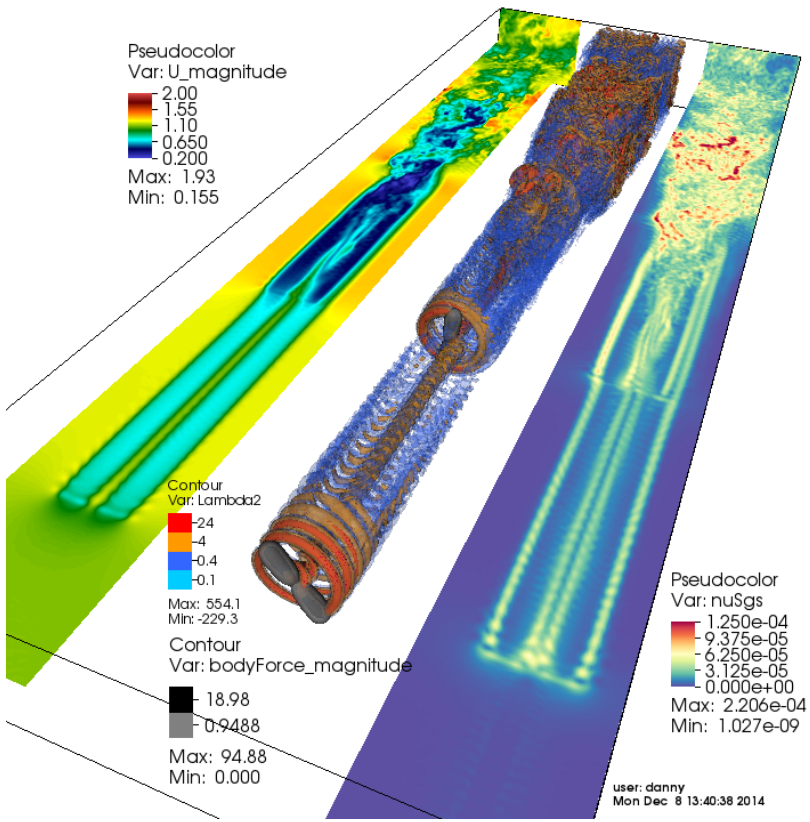


Figure : medium mesh 698x75x60, dx = 0.013 m

AT HIGHER RESOLUTION

care is needed to balance the body force spreading (epsilon parameter) with the radial spacing of actuator line points (same as blade discretization used for FAST) and the LES mesh spacing

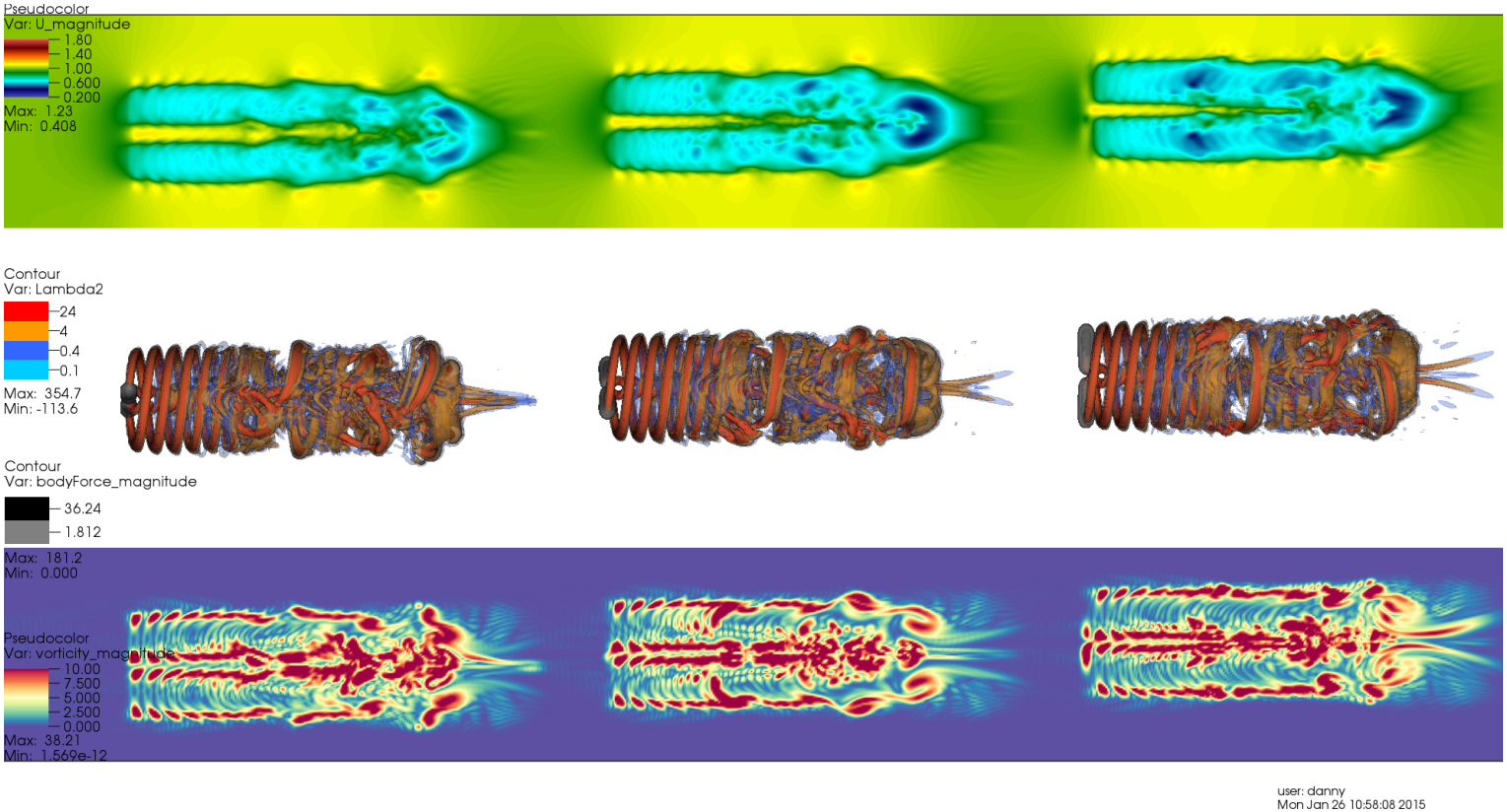


Figure : finer mesh 1047x113x90, dx = 0.00885 m

AT HIGHER RESOLUTION

care is needed to balance the body force spreading (epsilon parameter) with the radial spacing of actuator line points (same as blade discretization used for FAST) and the LES mesh spacing

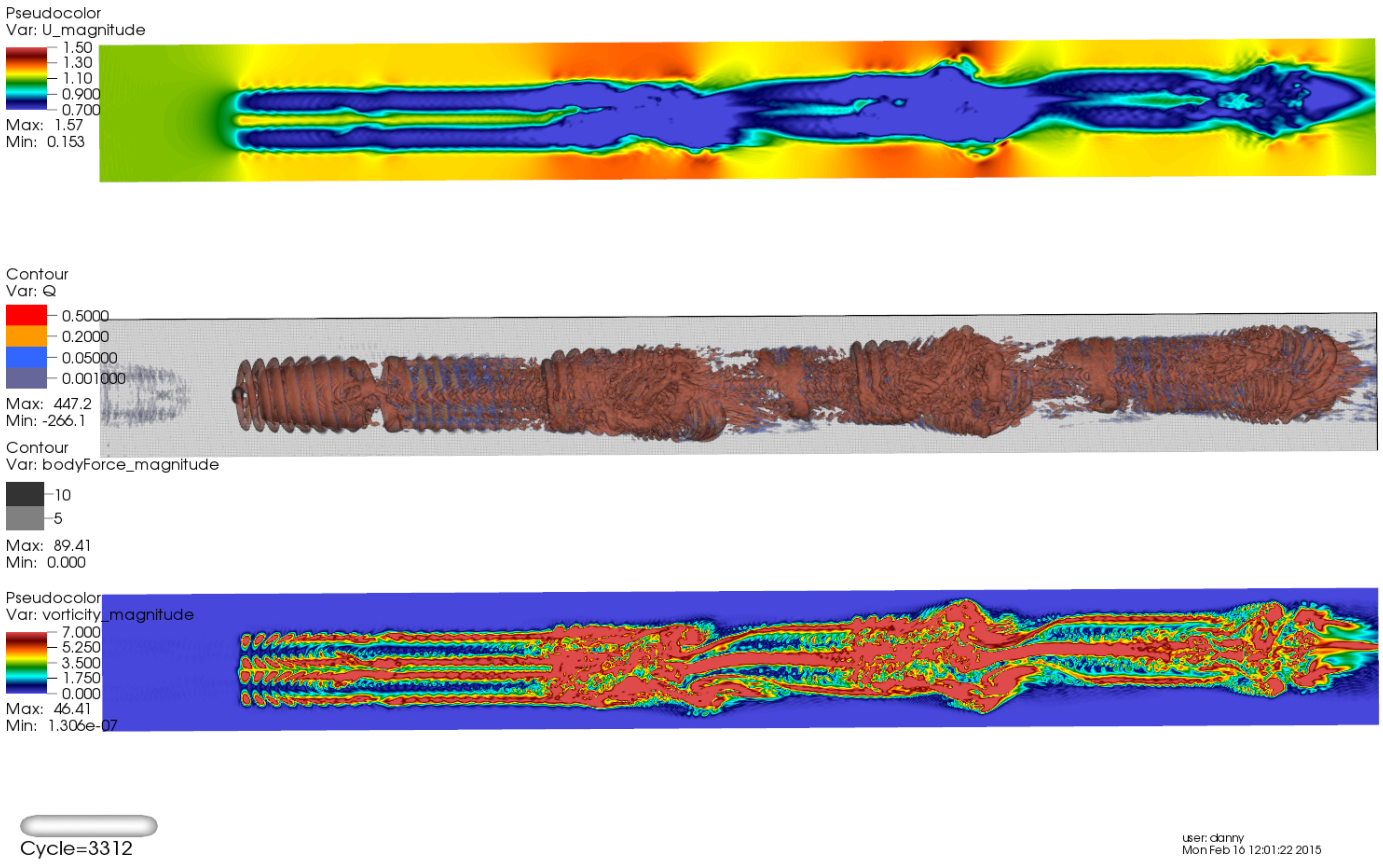


Figure : finer mesh 930x100x80 (7.4 Million), dx = 0.01 m, dt = 0.00125 s

AT HIGHER RESOLUTION

care is needed to balance the body force spreading (epsilon parameter) with the radial spacing of actuator line points (same as blade discretization used for FAST) and the LES mesh spacing

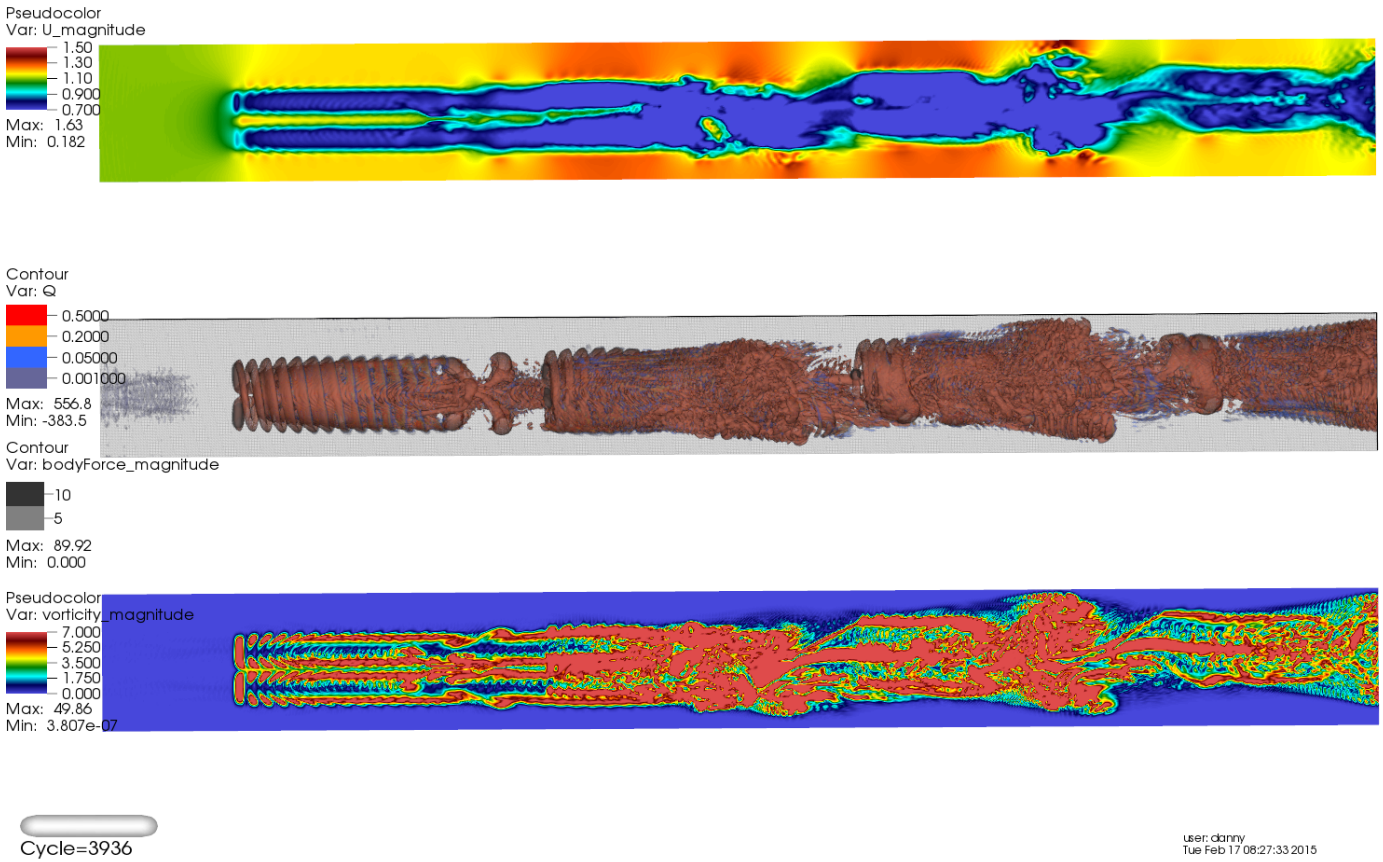
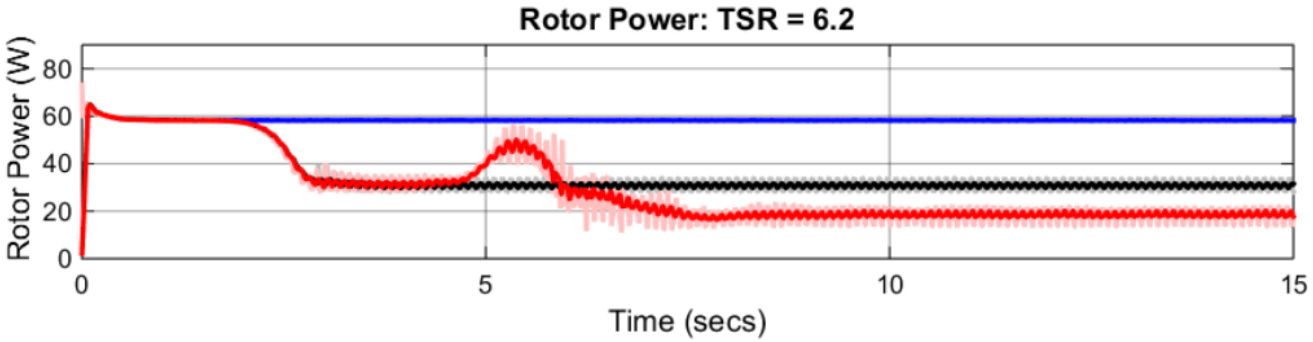
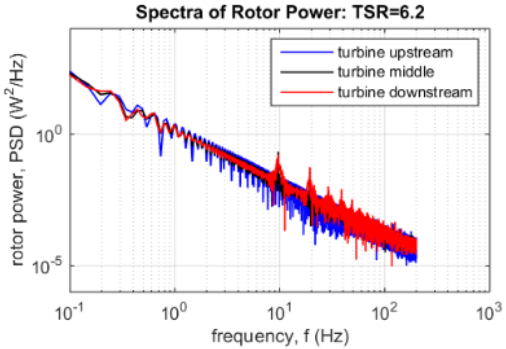
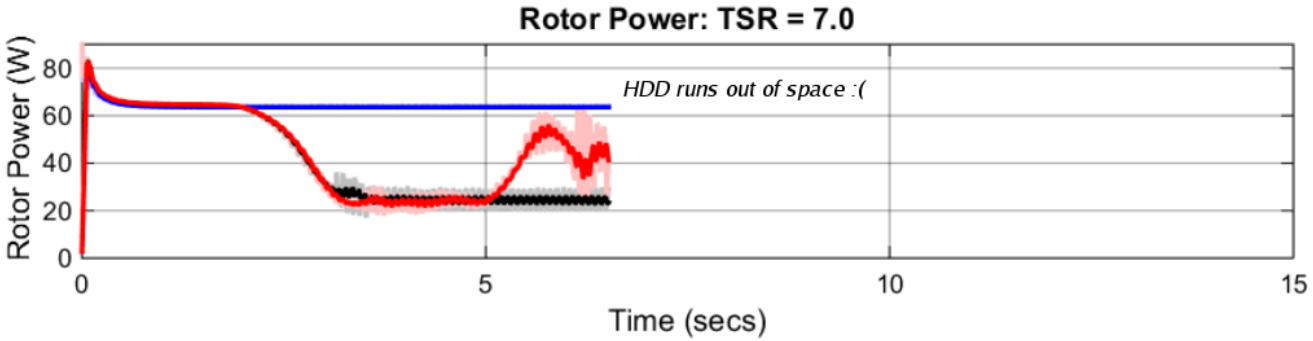


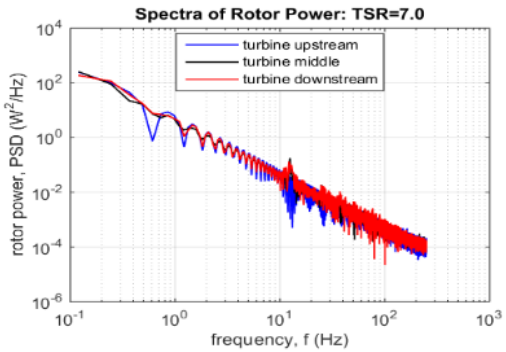
Figure : finer mesh 930x100x80 (7.4 Million), dx = 0.01 m, dt = 0.00125 s

COARSE MESH

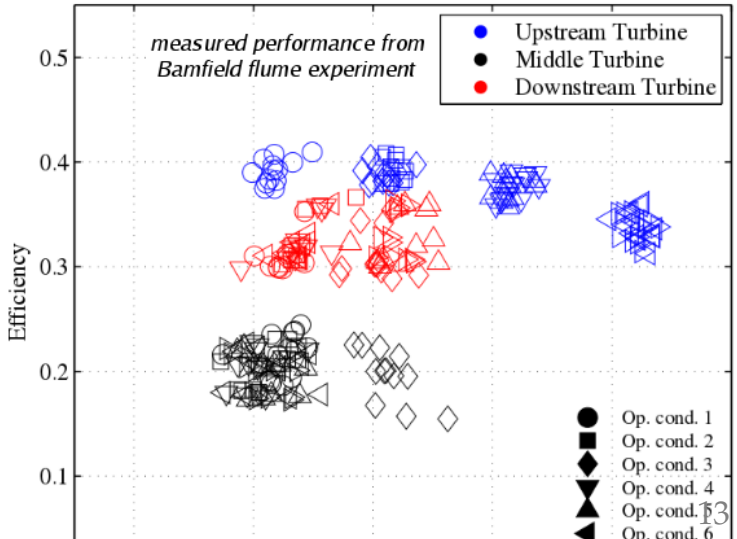




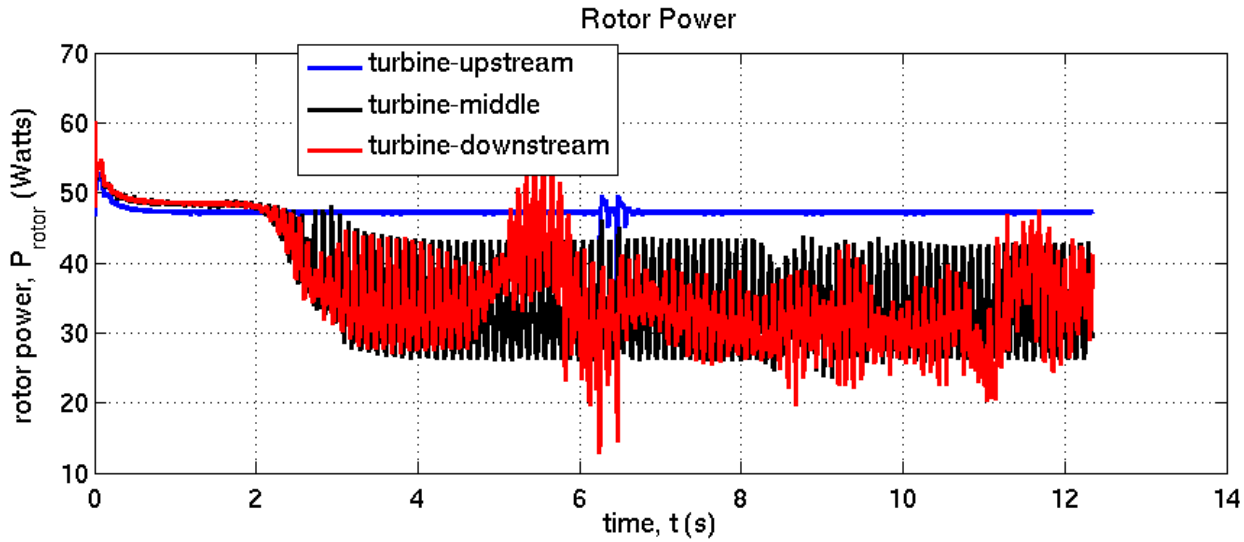


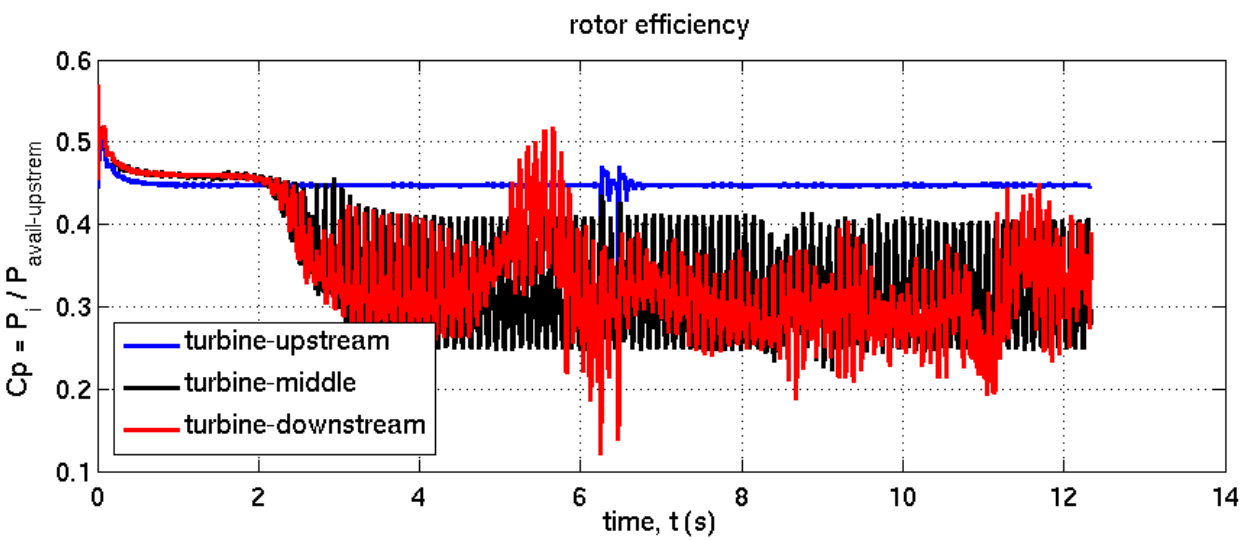


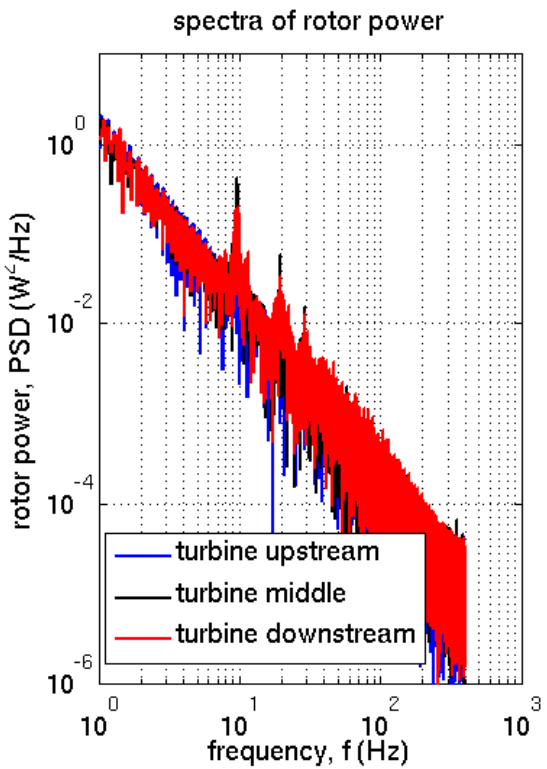
- can observe moments when wakes impact rotors
- passage of rotor blades apparent in FFT, higher freqs. due to turbulence
- LES still too coarse for quantitative comparison yet
- care is needed to compute efficiency of individual turbines in farms



FINER MESH


Rotor Power
turbine-upstream
turbine-middle
turbine-downstream
rotor power, P rotor (Watts)
time, t (s)


rotor efficiency
turbine-upstream
turbine-middle
turbine-downstream
Cp = P i / P avail-upstrem
time, t (s)


spectra of rotor power
turbine upstream
turbine middle
turbine downstream
rotor power, PSD (W²/Hz)
frequency, f (Hz)

DOE REFERENCE MODEL 1 TIDAL TURBINE

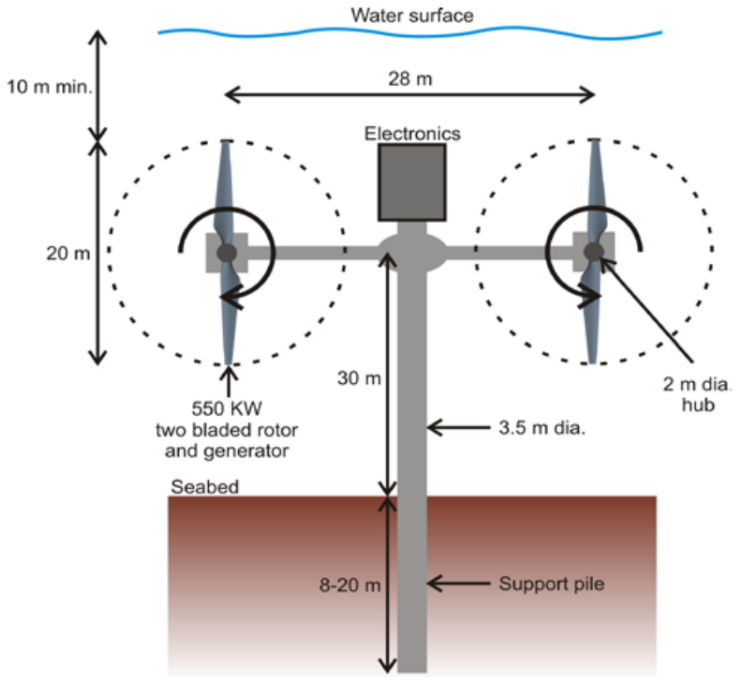


FIGURE 2A. SCHEMATIC OF THE MONOPOLE-SUPPORTED TIDAL CURRENT TURBINE. THE MONOPOLE IS DUG INTO THE SEABED AND THE TWIN ROTOR ASSEMBLY CAN SLIDE UP AND DOWN THE VERTICAL SHAFT.

Figure : Reference Model 1 Tidal Turbine

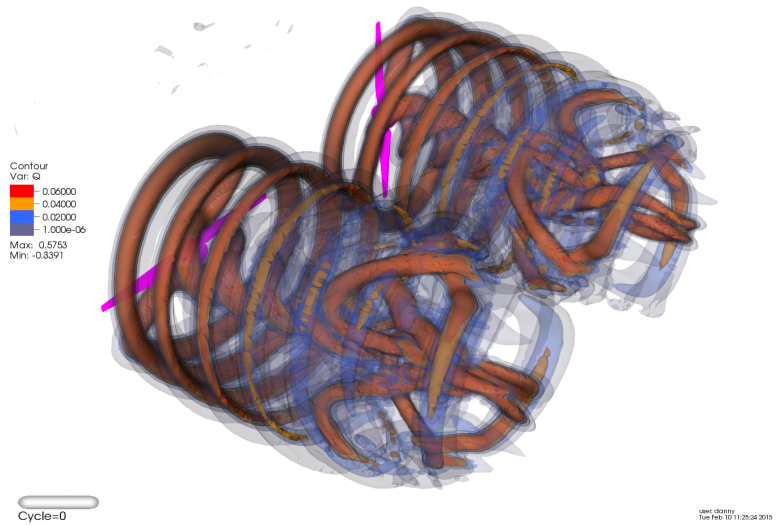
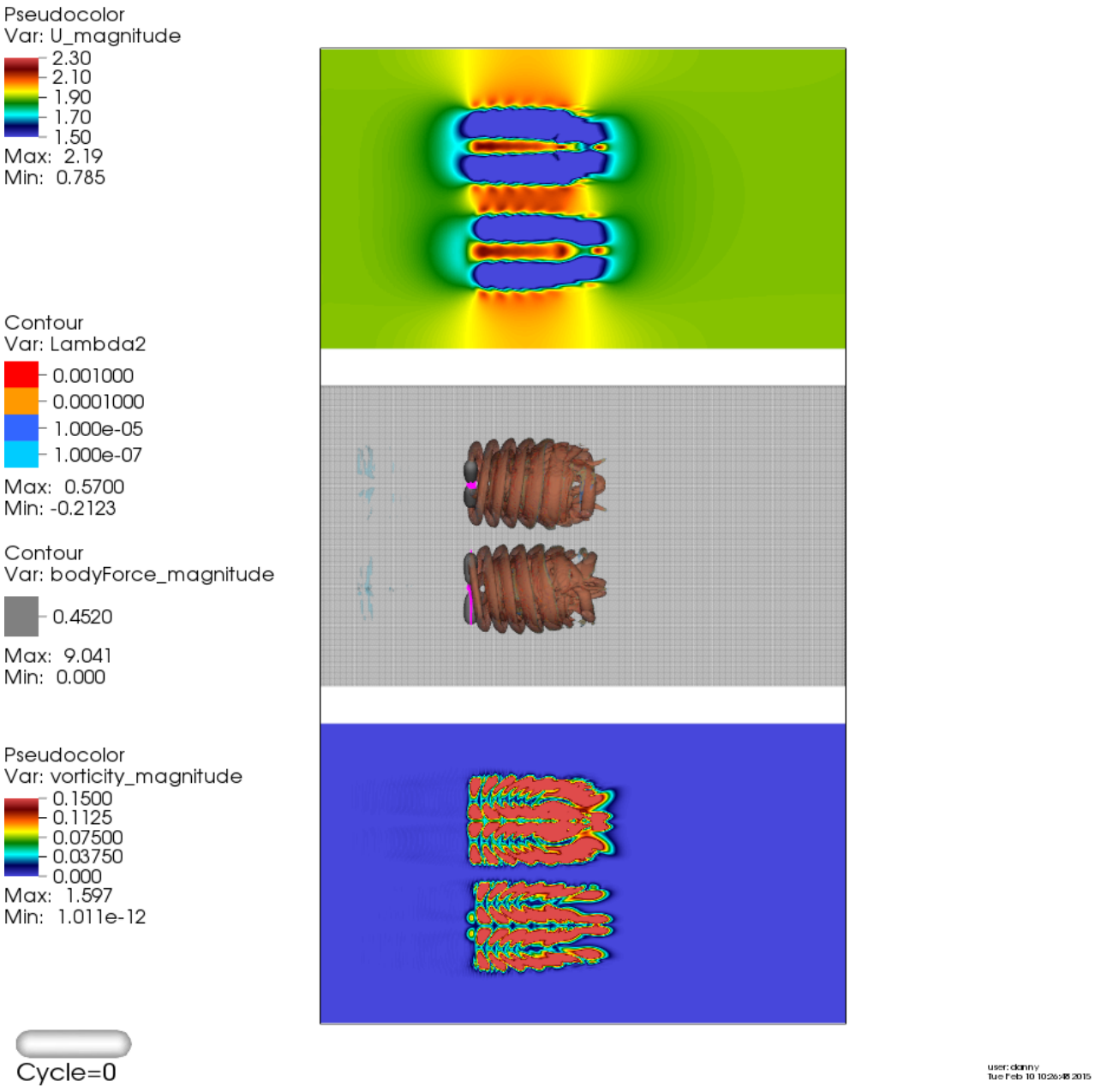
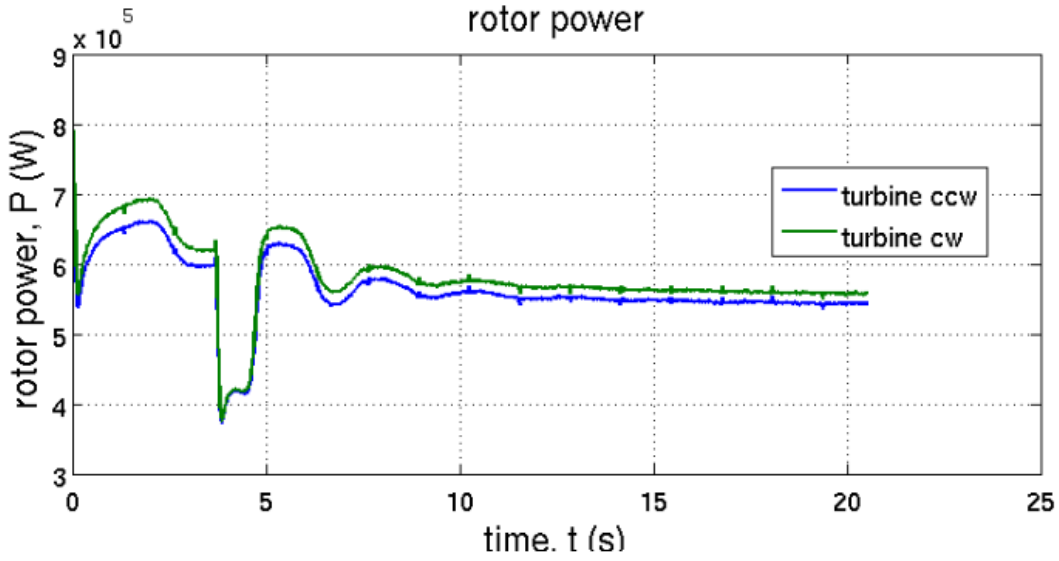
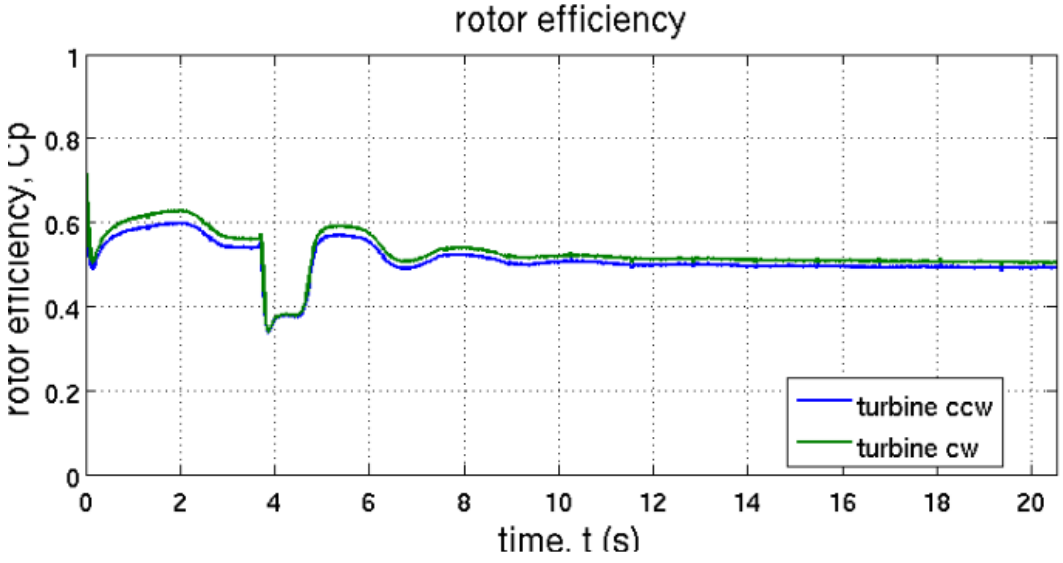
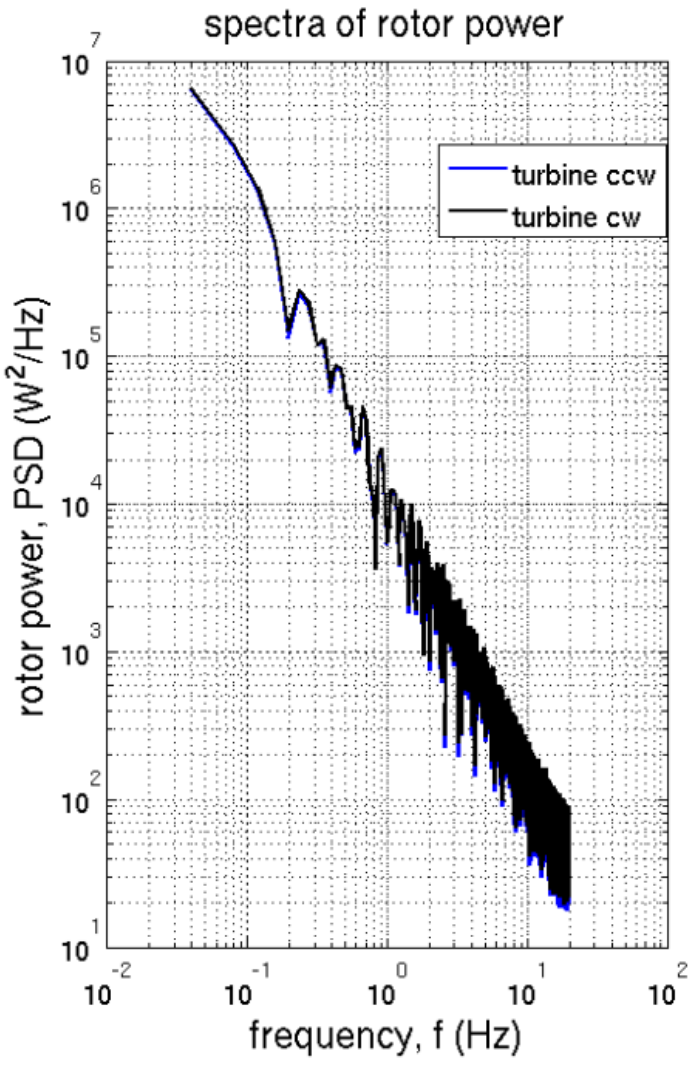


Figure : mesh 350x200x125, dx = 0.4 m


Pseudocolor
Var: U_magnitude
2.30
2.10
1.90
1.70
1.50
Max: 2.19
Min: 0.785
Contour
Var: Lambda2
0.001000
0.0001000
1.000e-05
1.000e-07
Max: 0.5700
Min: -0.2123
Contour
Var: bodyForce_magnitude
0.4520
Max: 9.041
Min: 0.000
Pseudocolor
Var: vorticity_magnitude
0.1500
0.1125
0.07500
0.03750
0.000
Max: 1.597
Min: 1.011e-12
Cycle=0


rotor power
x 10^5
rotor power, P (W)
time. t (s)
turbine ccw
turbine cw


rotor efficiency
rotor efficiency, Cp
time. t (s)
turbine ccw
turbine cw


spectra of rotor power
rotor power, PSD (W²/Hz)
frequency, f (Hz)
turbine ccw
turbine cw

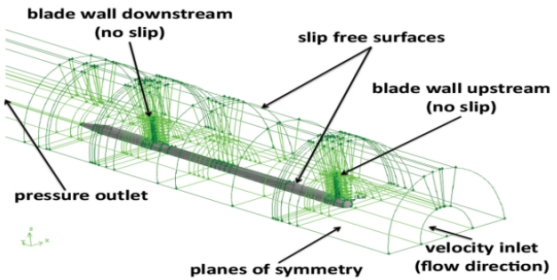
FUTURE WORK

- Code and Computers
  - prototype simulations for running on more powerful hardware
  - shared memory, distributed memory, co-processors
  - want to understand resolution required to resolve wakes and turbine performance accurately
  - based upon free and opensource software
- Ambient Turbulence
  - turbulent structures within ambient flow can cause loading events with significance comparable to when turbines operate in upstream wakes
  - boundary data on inlet planes generated from either precursor LES or synthetic turbulence methods (e.g. pyTurbSim)
- Control Strategies
  - dynamical model of rotor drivertrain to allow variable TSR as response to fluctuations in rotor torque
  - rotor speed and pitch control for ”in-water” dynamometer testing

Simulations were performed with Reynolds Averaged Navier-Stokes (RANS) methods to resolve geometry of blades and nacelle. Turbine wakes measured using particle image velocimetry (PIV) and acoustic Doppler velocimetry (ADV), and efficiency derived from torque and rotational speed measurements.[2][3][4]

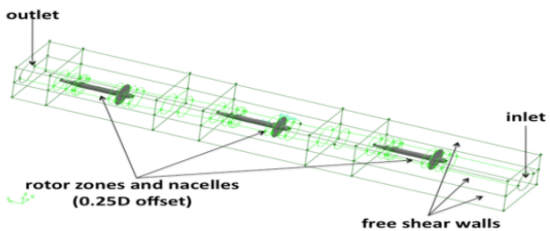
Rotating Reference Frame (RRF)

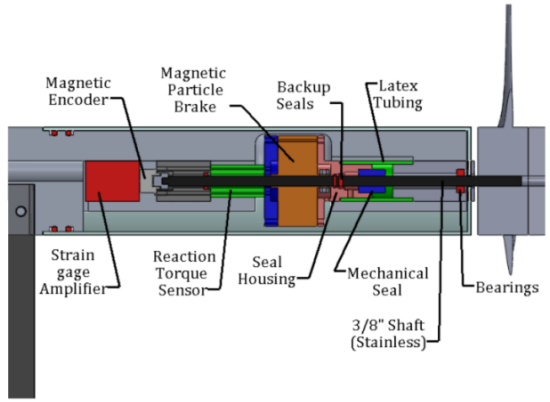
- Renders an unsteady problem in the fixed reference frame into a steady problem in the rotating reference frame.
- Solves the RANS equations in the rotating reference frame.
- Flow field around the actual geometry of the blade is resolved



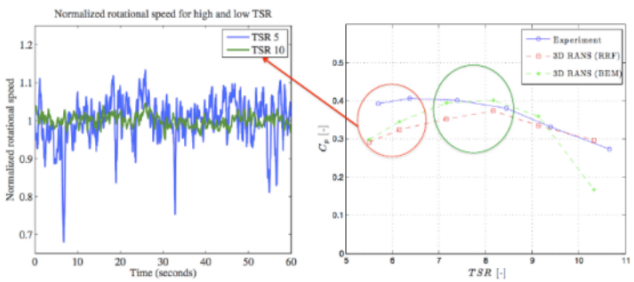
Blade Element Model (BEM)

- Models the turbine effect based to the Blade Element Theory.
- Simulate the blades rotation through body forces (lift and drag)

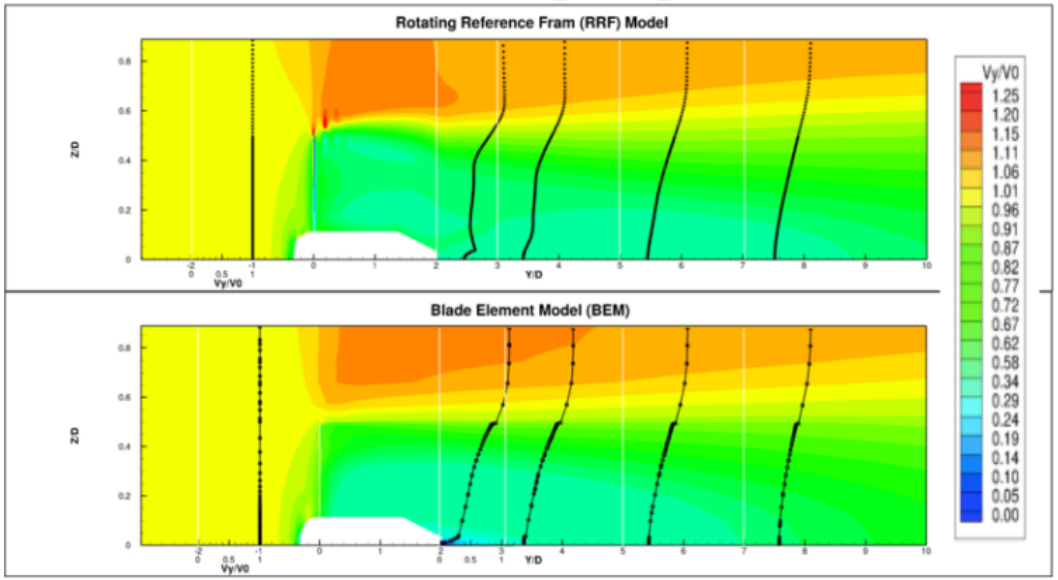




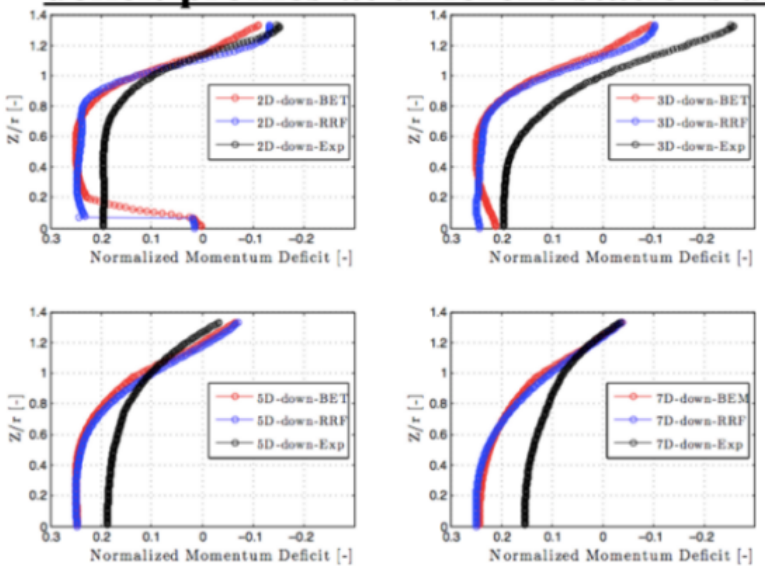
Good agreement between experimental and numerical results at Tip Speed Ratios (TSR) around the optimum TSR.
Disagreement between the numerical and experimental results at lower TSRs due to angular velocity fluctuations in the experiment.



Normalized velocity contours superimposed by velocity deficits



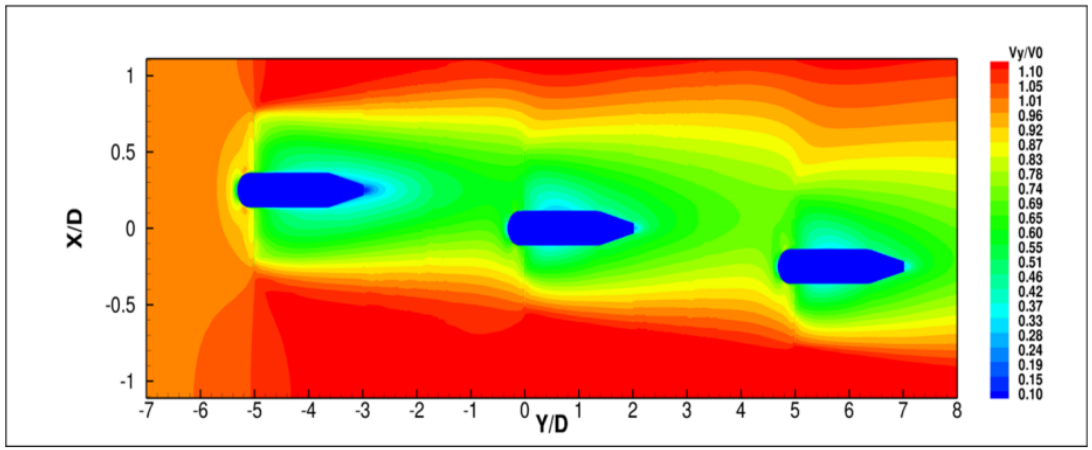
Comparison between the measured and predicted momentum deficit profiles at different stations downstream the turbine.



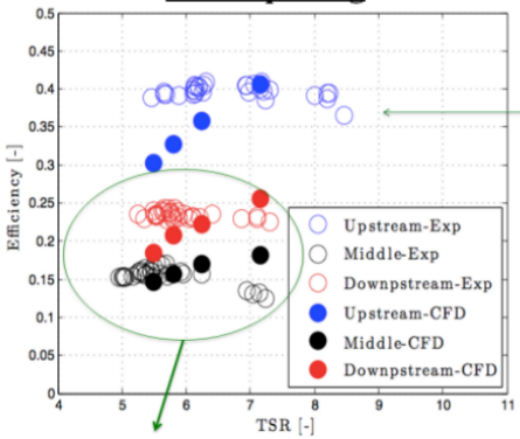
The RRF and BEM both predict slower wake recovery process in the turbulent wake due to:

1) Boundary conditions idealization.
2) Potential limitations of the closure model (SST k-w).

Normalized velocity contours by the velocity at the inlet

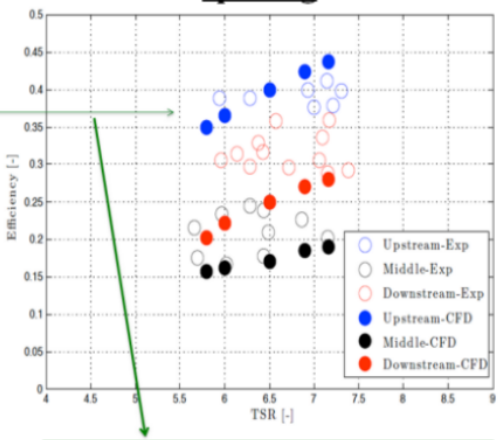


Performance curves of three coaxial turbines with 5D fixed spacing

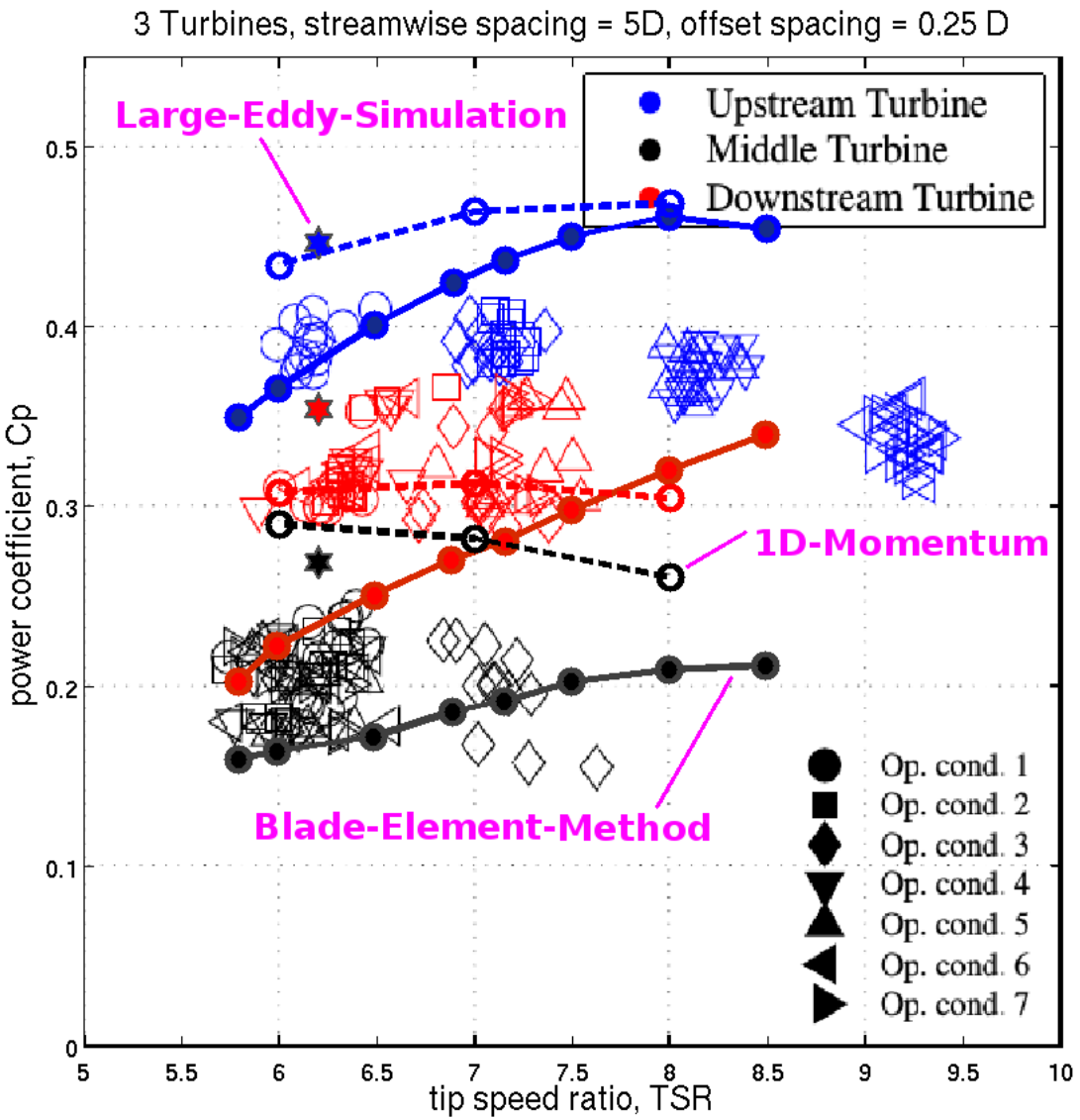


Middle turbine enhances the turbulent mixing in the wake of the upstream turbine. This leads in to higher efficiency for the downstream turbine.

Performance curves of three offseted turbines with 5D fixed spacing



In the offset configuration the shear in the flow field and blockage effect increases the efficiency of each turbine in the array.


3 Turbines, streamwise spacing = 5D, offset spacing = 0.25 D
Large-Eddy-Simulation
Upstream Turbine
Middle Turbine
Downstream Turbine
1D-Momentum
Blade-Element-Method
Op. cond. 1
Op. cond. 2
Op. cond. 3
Op. cond. 4
Op. cond. 5
Op. cond. 6
Op. cond. 7
power coefficient, Cp
tip speed ratio, TSR
0
0.1
0.2
0.3
0.4
0.5
5
5.5
6
6.5
7
7.5
8
8.5
9
9.5
10

Thanks to SOWFA developers! Thanks to everybody involved with modeling and validation of DOE Reference Model turbines!