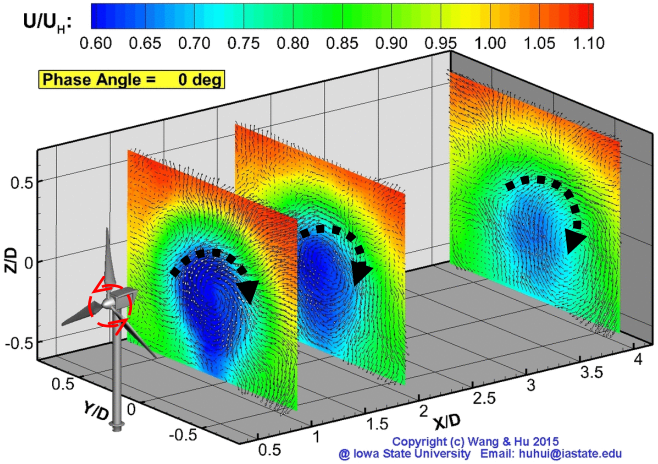

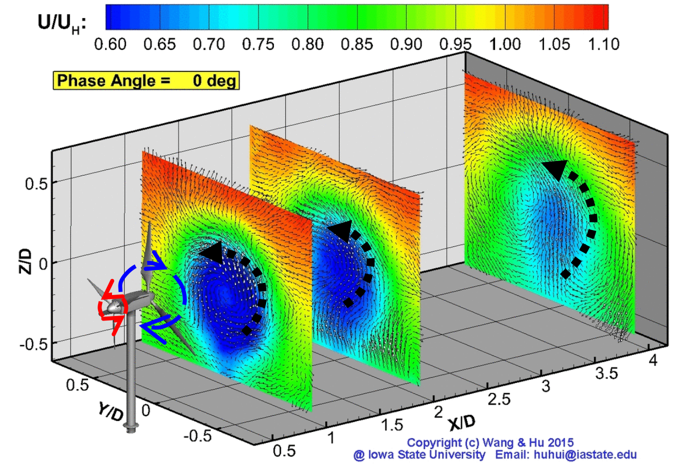

Wind Turbine Aeromechanics and Wind Farm Aerodynamics

Dr. Hui HU

Professor and Director

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2251 Howe Hall, Ames, IA 50011-2271
Email: huhui@iastate.edu

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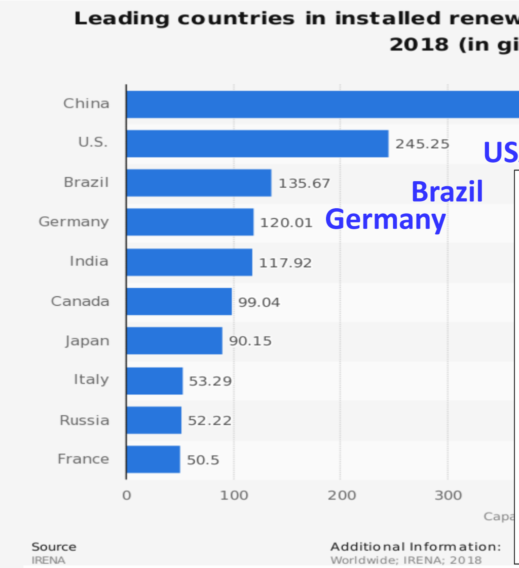
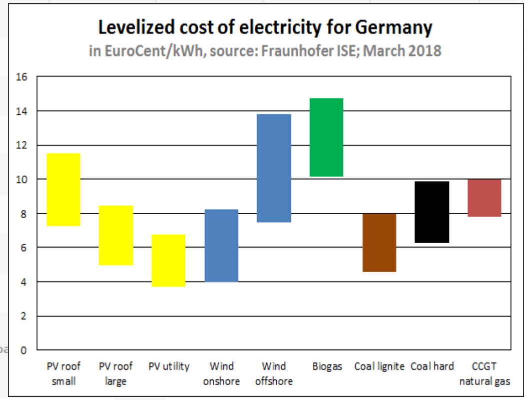
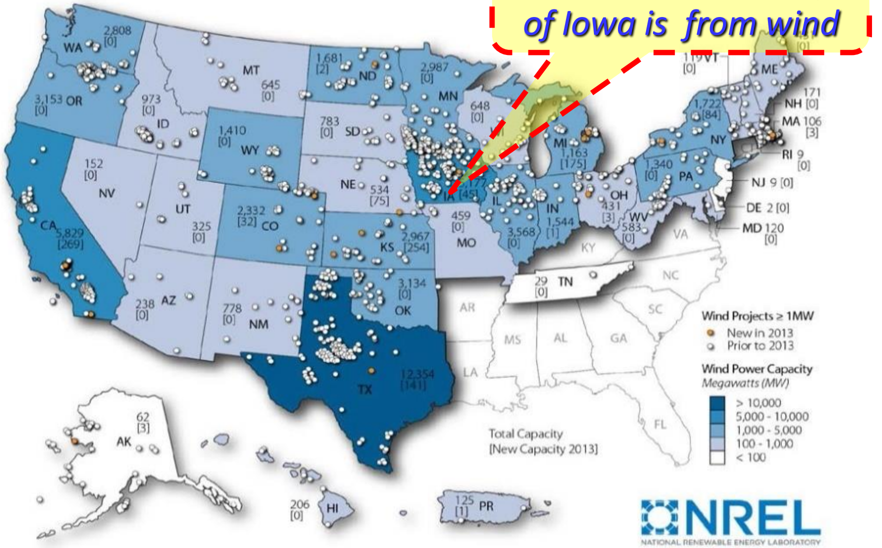
❑ Wind Energy Production and Wind Turbine Installations in USA

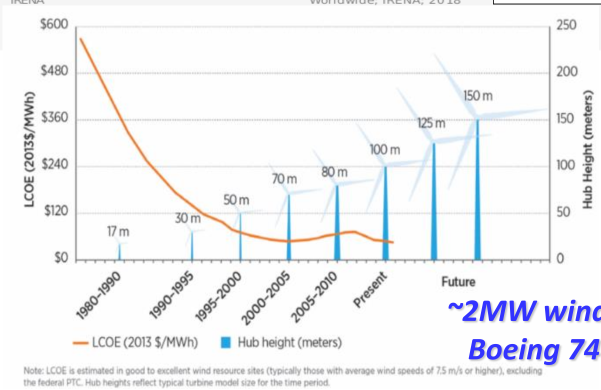


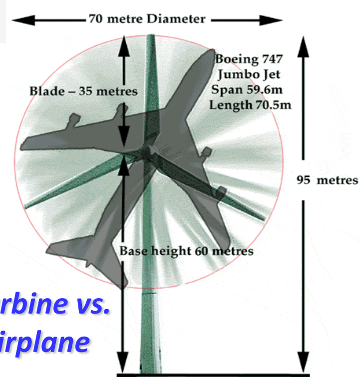


Wind farm sites in USA

Over 40% electricity of Iowa is from wind



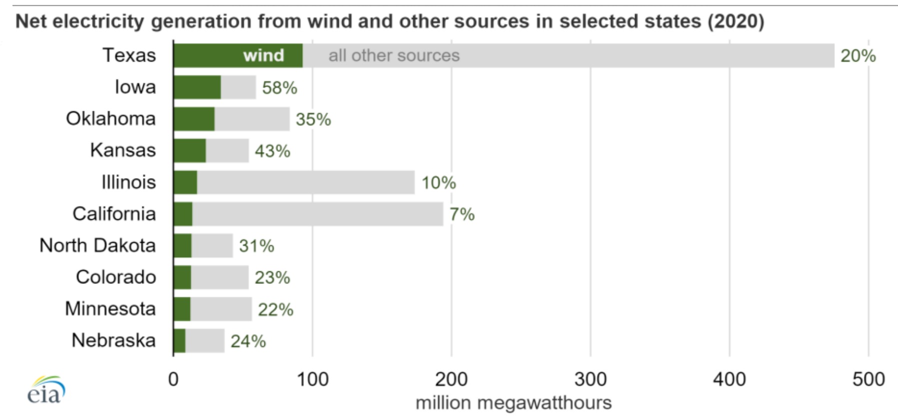




~2MW wind turbine vs. Boeing 747 airplane

- ***US Department of Energy sets up the targets of 20% of US electricity from wind energy by 2030; and 35% by 2050 (~8.4% by 2020).***

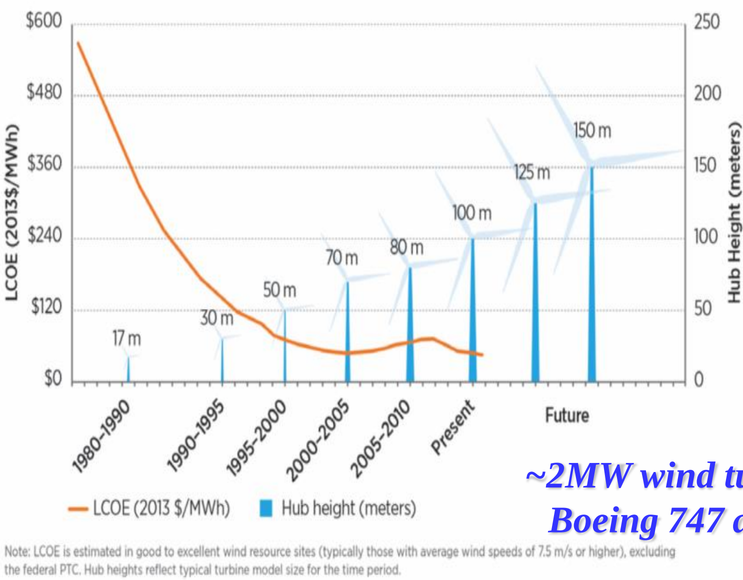
- U.S. Energy Information Administration, *Electric Power Monthly*

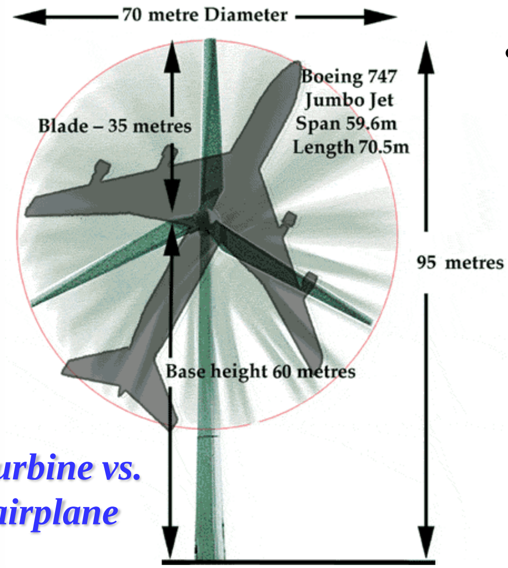


Horns Rev offshore wind farm

A typical Onshore wind farm

Technical Challenges Related to Wind Energy





~2MW wind turbine vs. Boeing 747 airplane

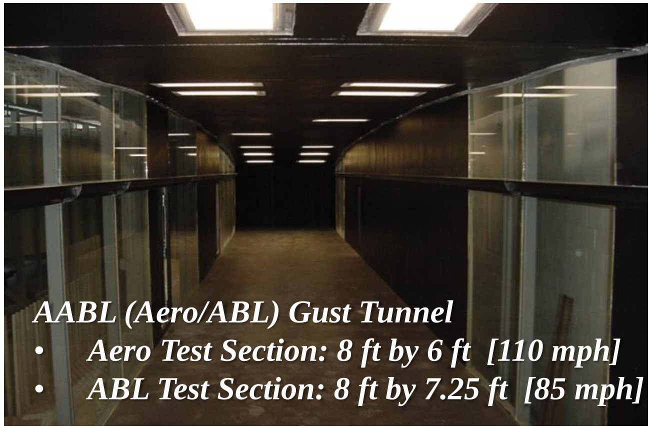
- ***Four focus areas identified in DoE Wind Energy Report:***
  - ***Turbine Dynamics***
  - ***Micro-siting and Array Effects***
  - ***Mesoscale Processes***
  - ***Climate Effects***

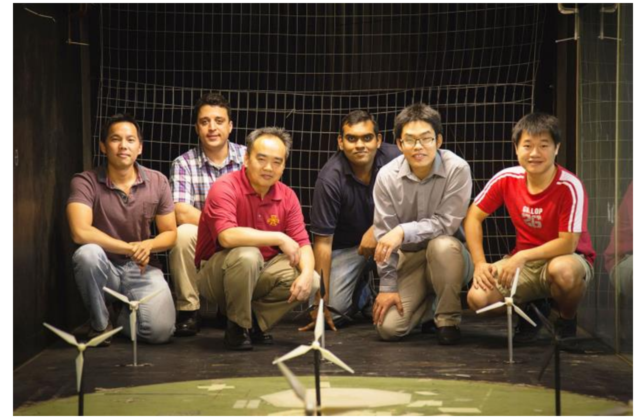
Horns Rev offshore wind farm near Denmark

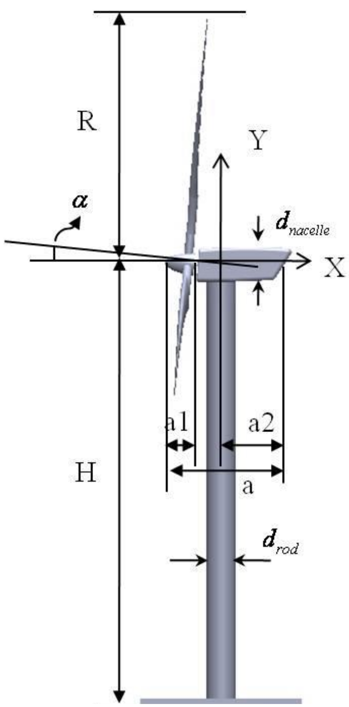
A typical Onshore wind farm

- *Schreck S, Lundquist J, and Shaw W (2008) U.S. Department of energy workshop report: research needs for wind resource characterization. Technical Report, NREL/TP-500-43521*

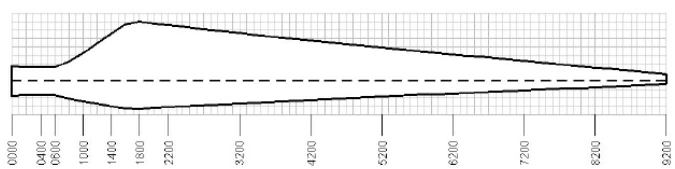
Aerodynamics and Atmospheric Boundary Layer (AABL) Wind Tunnel @ Iowa State University

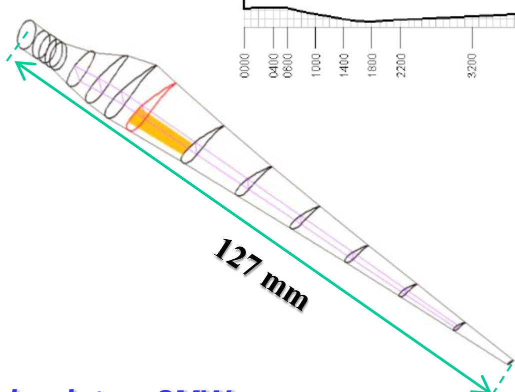


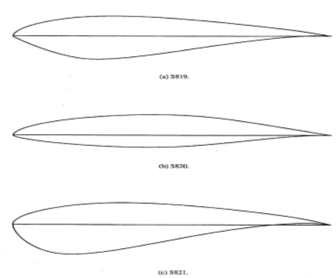


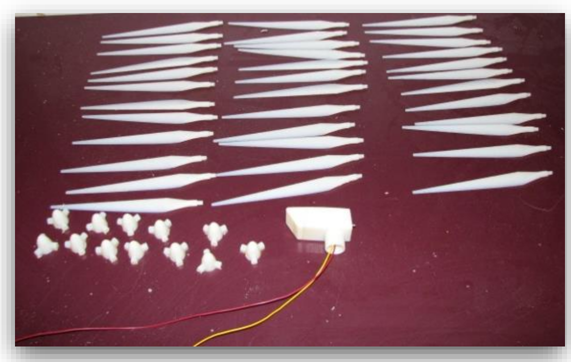


Parameter	R (mm)	H (mm)	d pole (mm)	d nacelle (mm)	α (deg.)	a (mm)	a1 (mm)	A2 (mm)
Dimension	140	225	18	18	5º	78	15	50







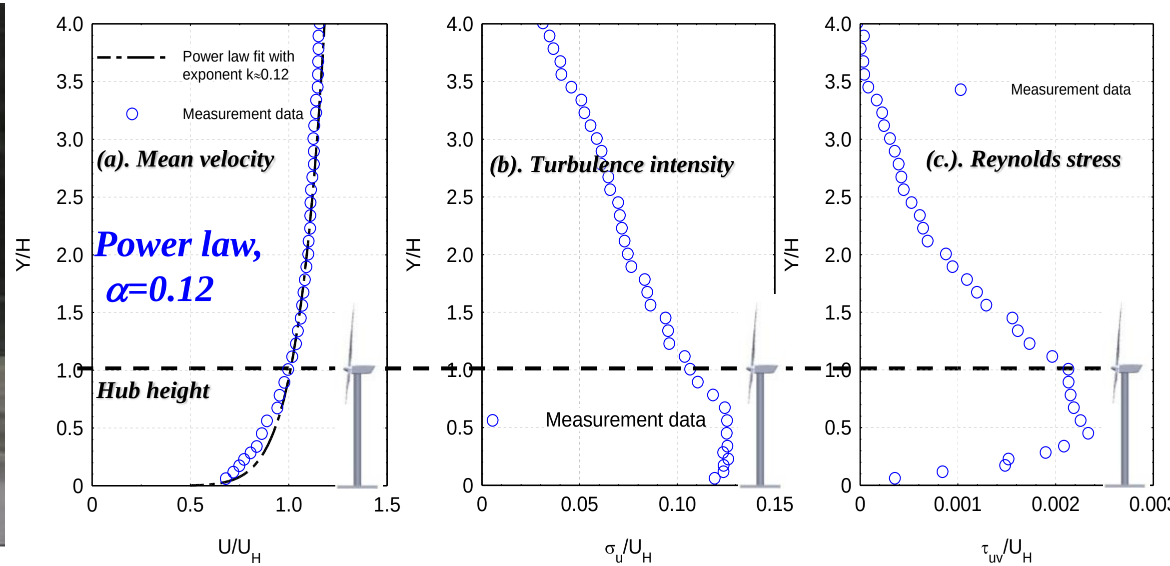


1:320 scaled model to simulate a 2MW wind turbine with 90m rotor blades

ERS-100 turbine blade design by TPI

IOWA STATE UNIVERSITY

Experimental Setup to Study Wind Turbine Aeromechanics

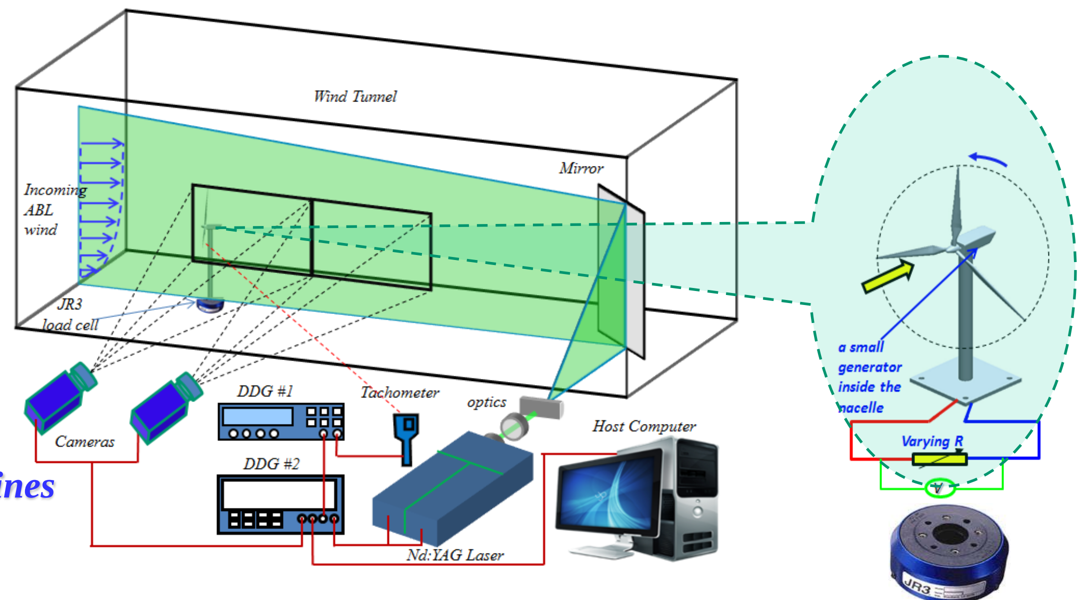


Test flow conditions:

- U_{hub} = 6 m/s,
- Re_c = 10,000
- *Tip speed ratio:* $\lambda = 0 \sim 6.5$.

Measured parameters:

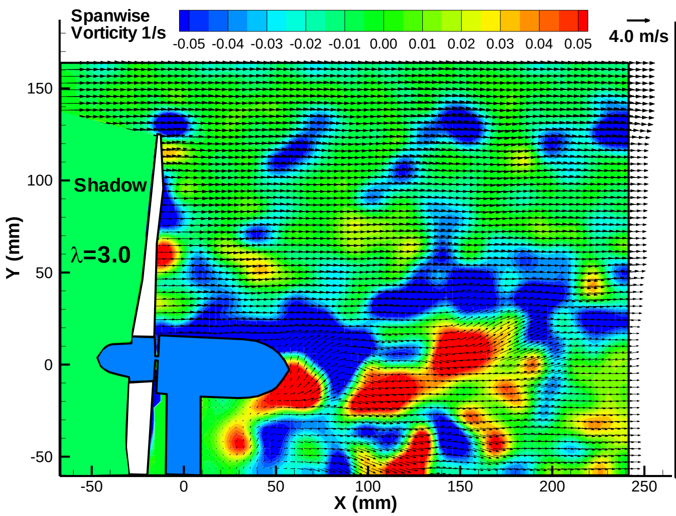
- *Characteristics of turbine wake flows*
- *Power output of wind turbine models*
- *Dynamic wind loads acting on wind turbines*



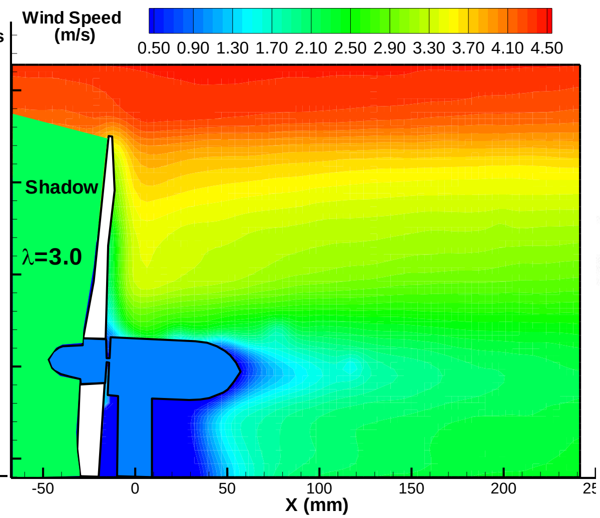
Experimental Setup

JR3 load cell

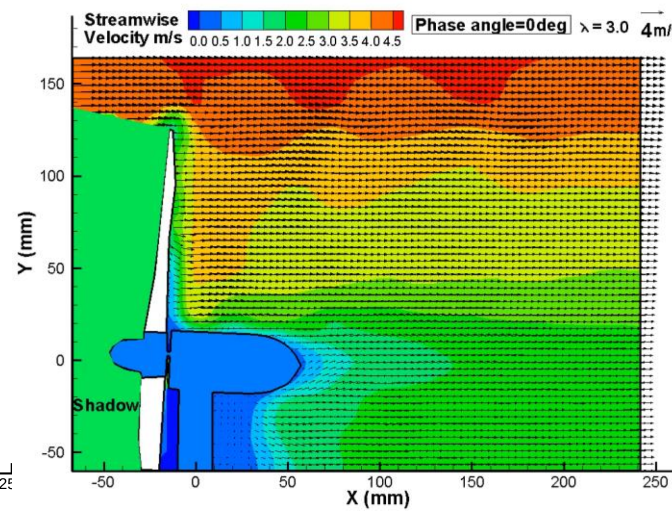
Near Wake Measurement Results at Tip-Speed Ratio, λ=3.0



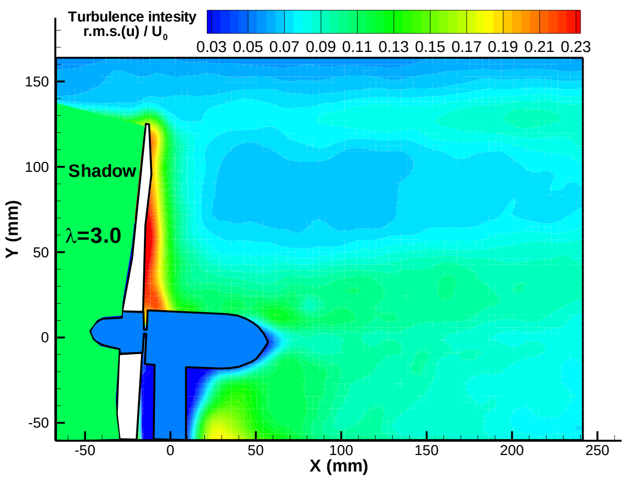
Instantaneous PIV results



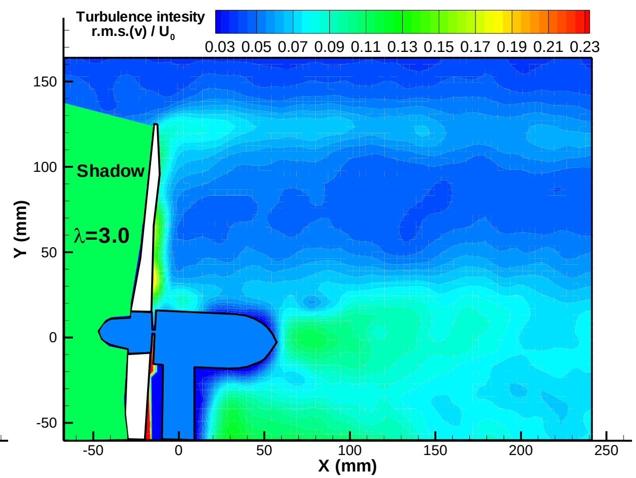
Time-averaged velocity distribution



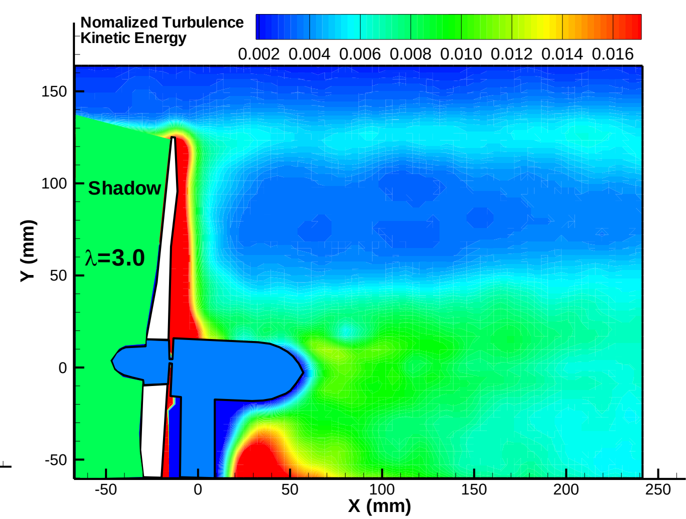
Phase-Locked PIV measurement results



Turbulence intensity r.m.s (u)/U_O

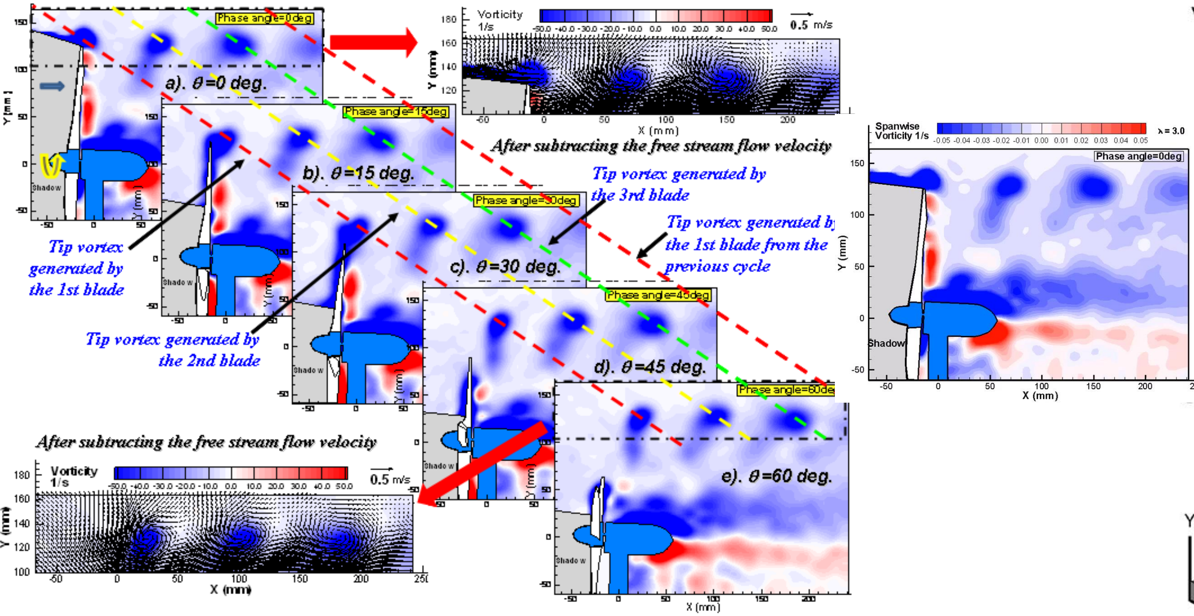


Turbulence intensity r.m.s. (v)/U_O

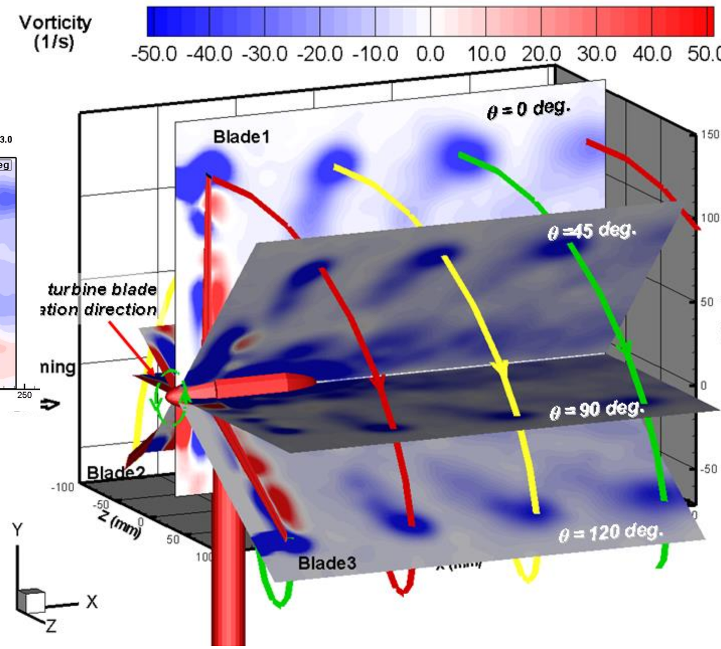


Normalized Turbulence kinetic energy $\frac{(u'u'+v'v')}{2U_o^2}$

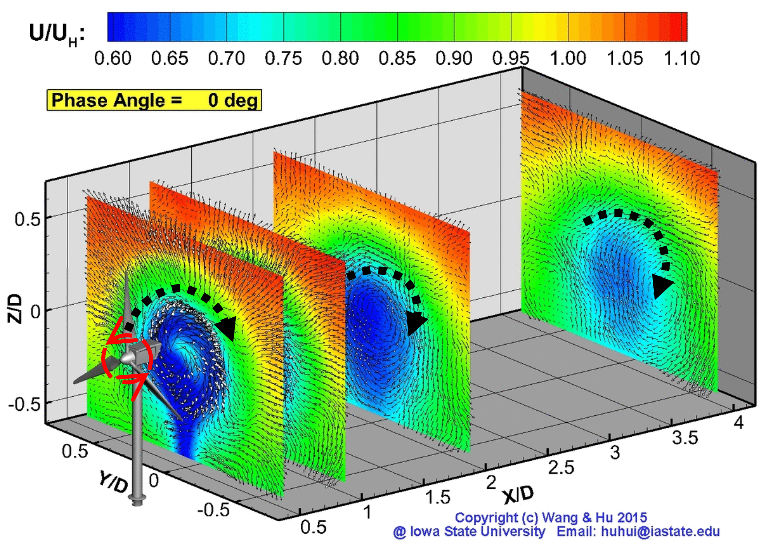
Phase-Locked PIV Measurement Results at Tip-Speed Ratio, λ=3.0

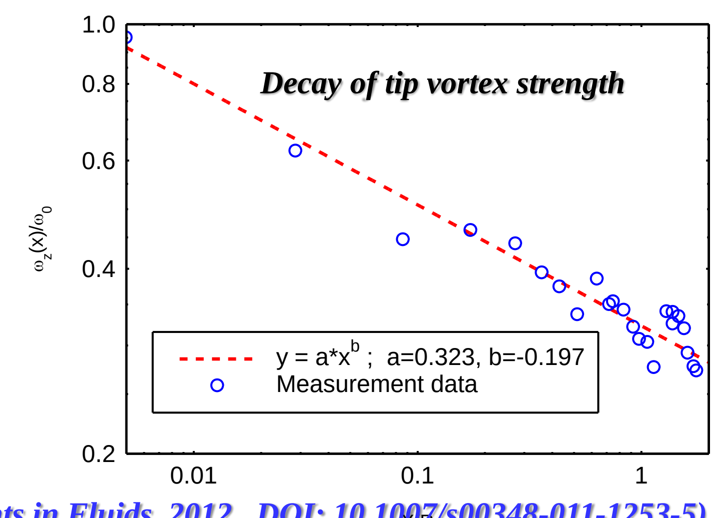


Wake vortex structures at different phase angles



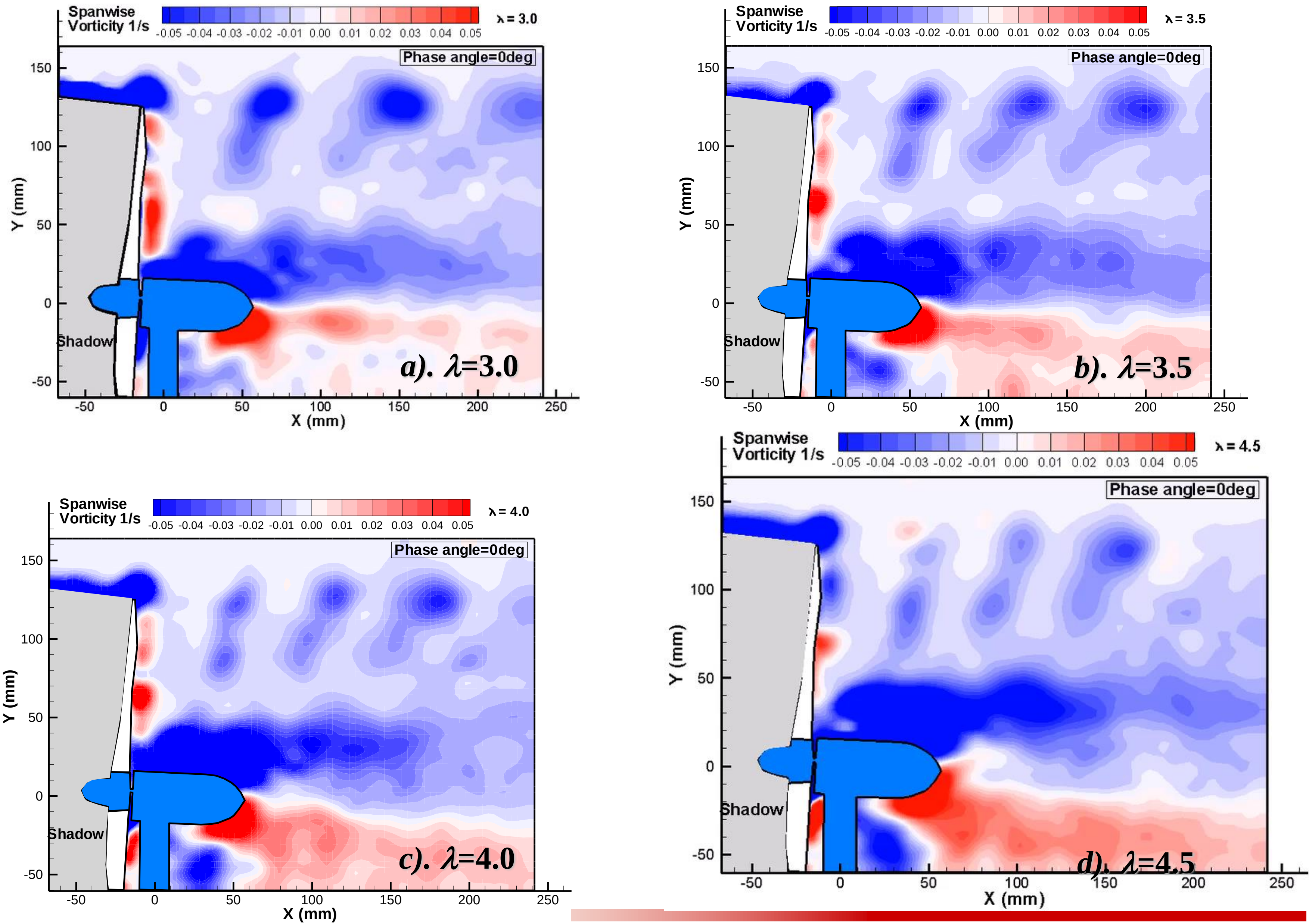
Reconstructed 3-D wake vortex structures





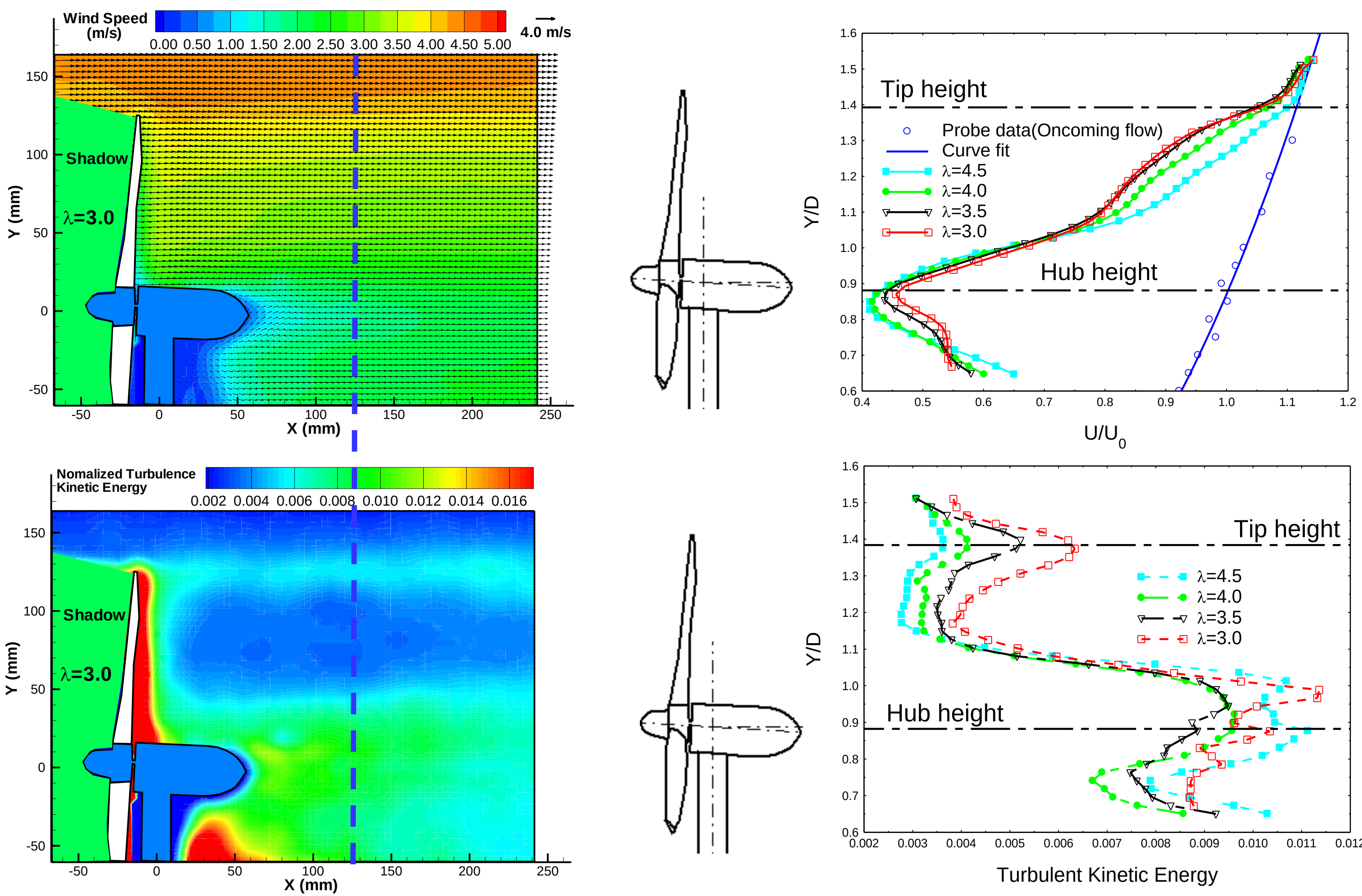
(Hu et al. Experiments in Fluids, 2012, DOI: 10.1007/s00348-011-1253-5)

Effects of Tip-speed Ratio on the Wake Vortex Structures



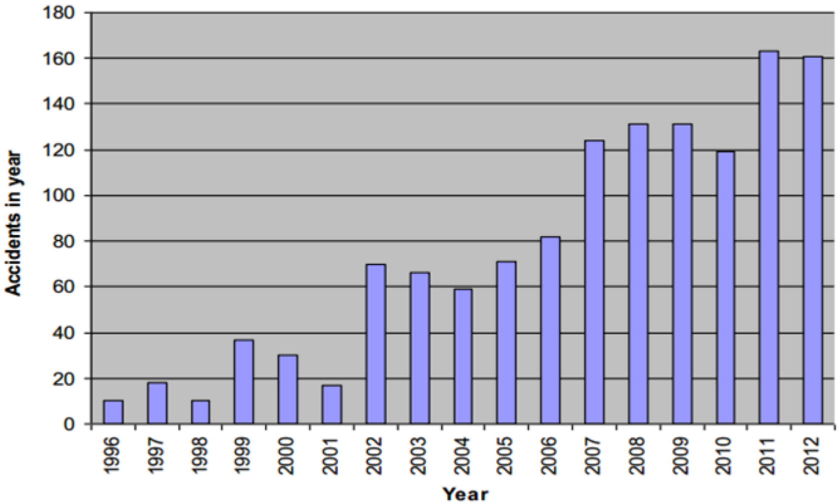
Wake Profiles at X/D=0.5 Downstream of the Wind Turbine Model

$$Wind\ \ Energy \propto \frac{1}{2} A \rho V^3 \qquad Aerodynamic\ Force \propto \frac{1}{2} A \rho V^2$$



(Hu et al., Experiments in Fluids, Vol. 52, No. 5, pp1277-1294, 2012)

Wind Turbine Failures



Caithness Wind Farm, UK

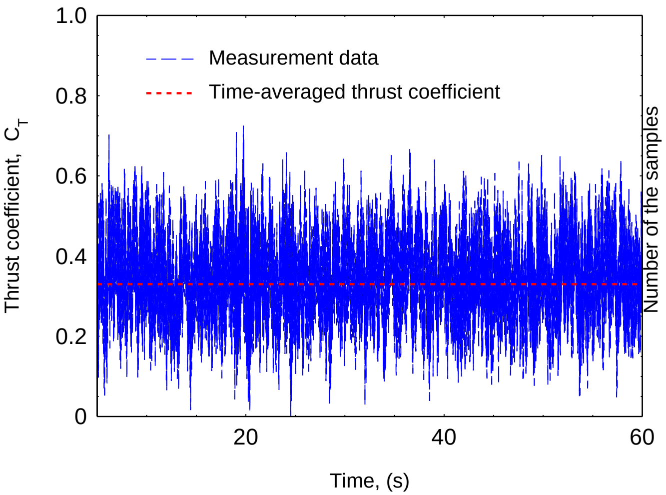
http://www.caithnesswindfarms.co.uk/

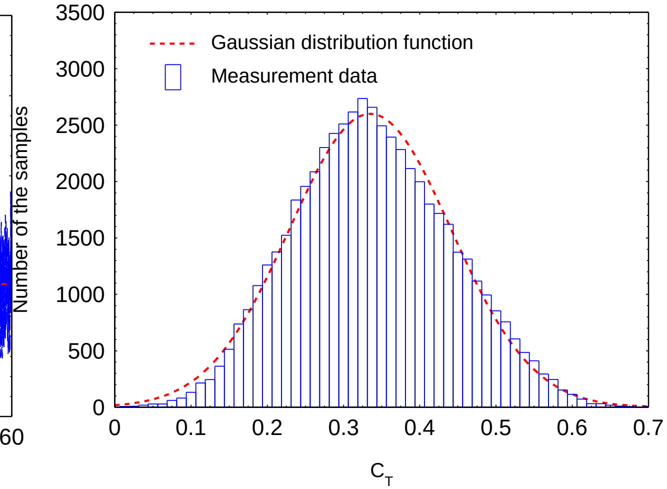
(202 WT in operation + 198 in construction)

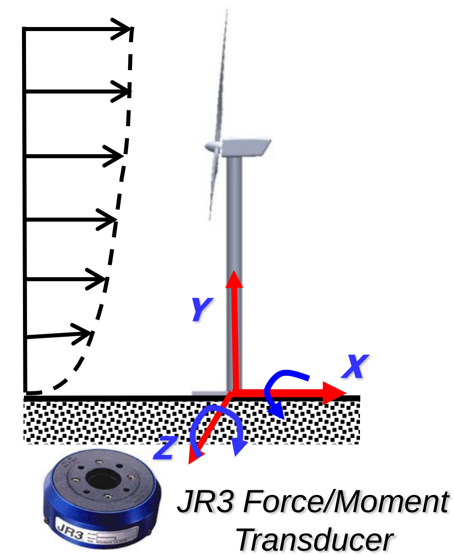
Total number of accidents: 1405

- ***Human fatalities & injuries: 136+145***
- ***Blade failure: 265***
- ***Fire: 202***
- ***Structural failure: 138***
- ***Ice throw: 34***
- ***Transport: 113***
- ***Environmental (bird death): 128***
- ***Others: 282***

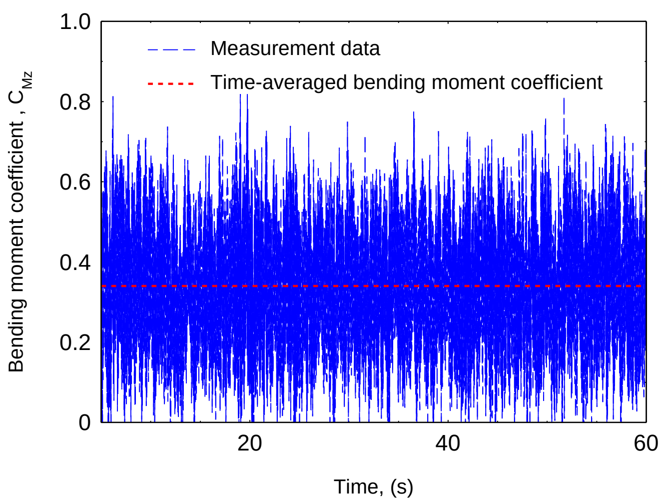
Dynamic Wind Loads Acting on Wind Turbines

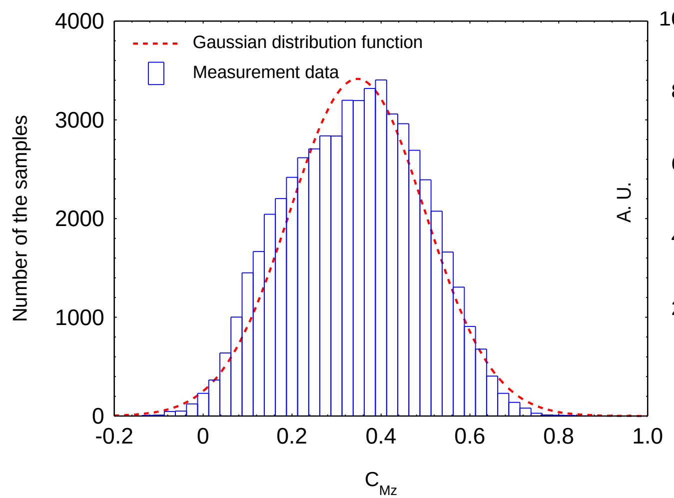


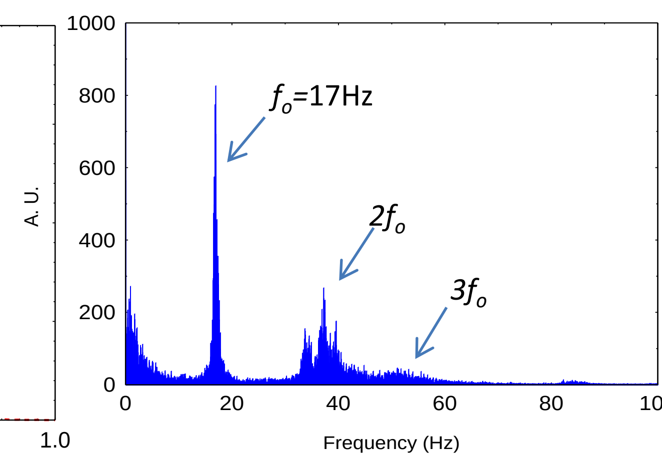




(a). Measured thrust coefficient data



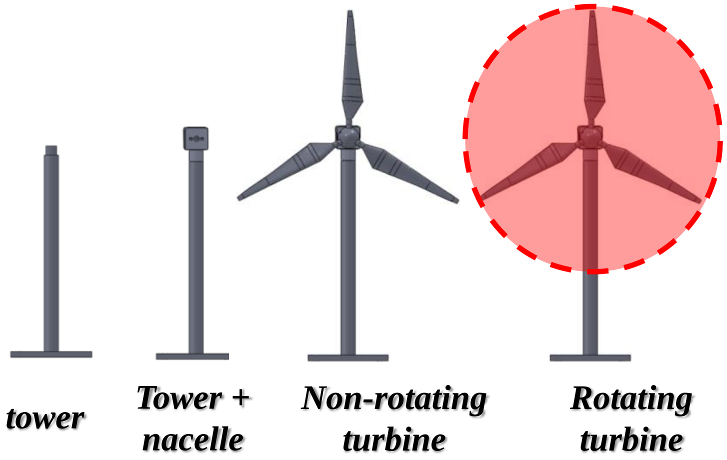


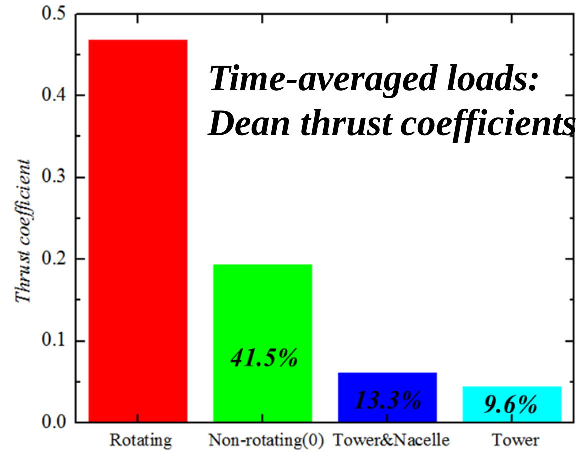


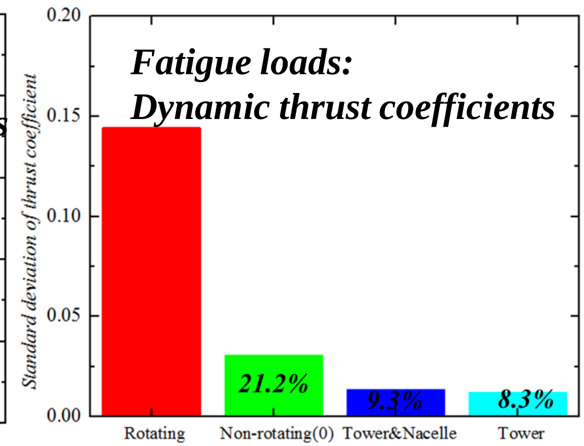
(b). Measured bending moment data

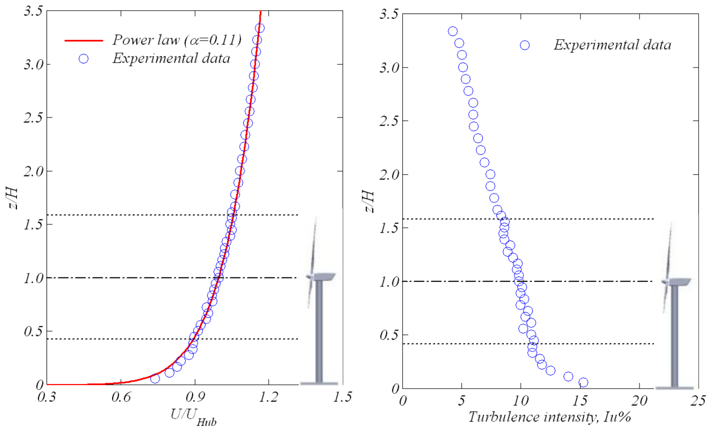
(Hu et al., Experiments in Fluids, Vol. 52, No. 5, pp1277-1294, 2012)

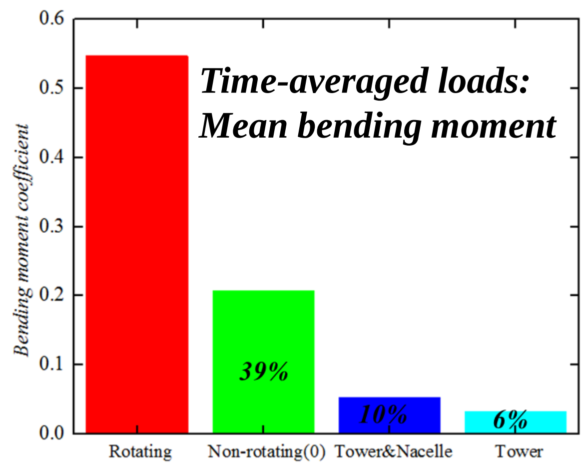
Wind Loads Acting on Various Components of Wind Turbine

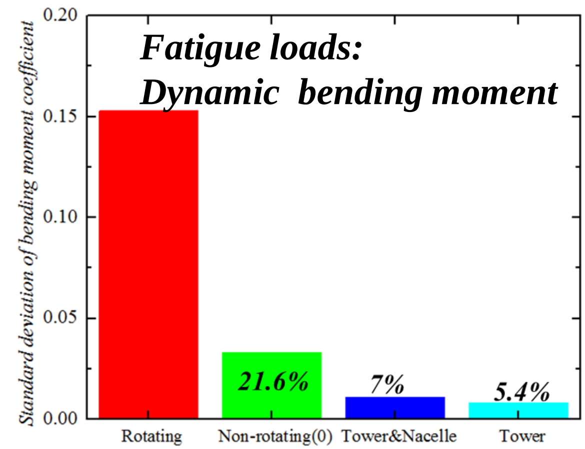








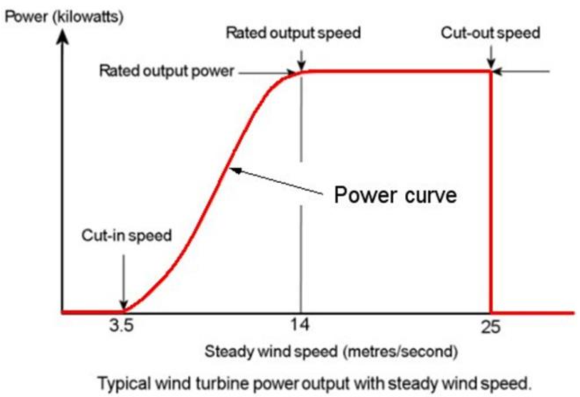


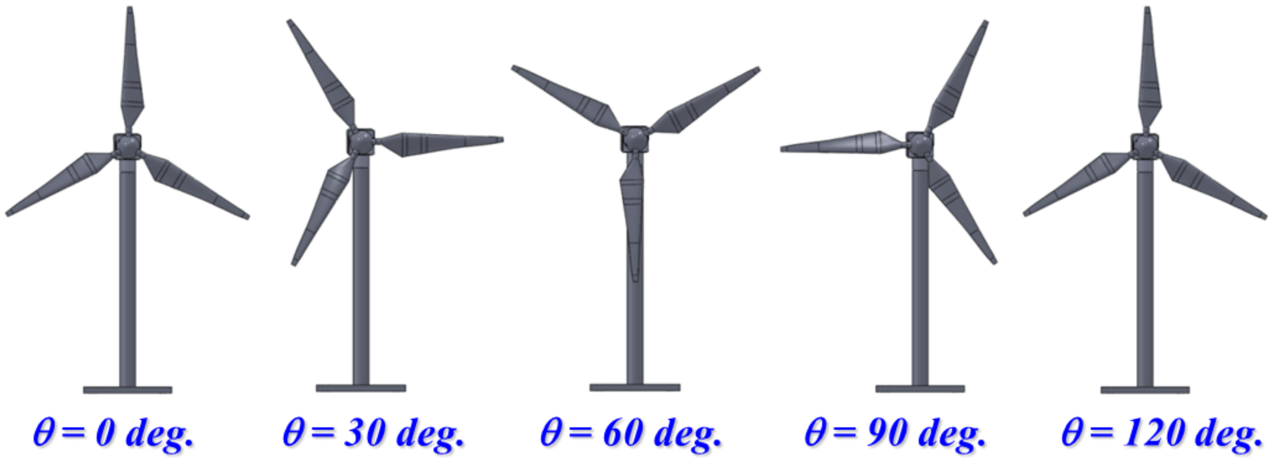


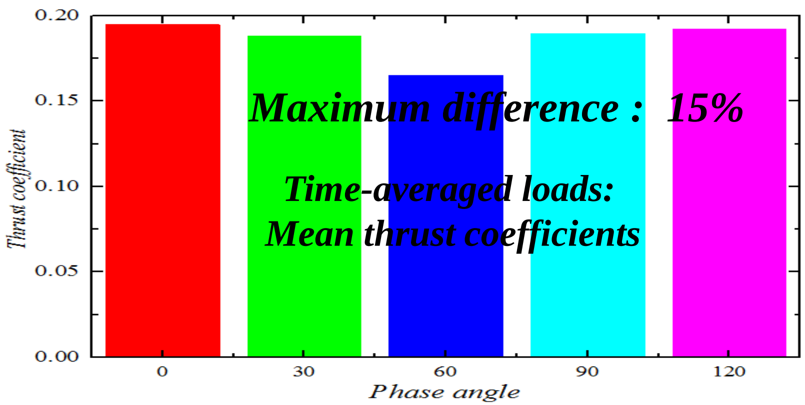
Test conditions:

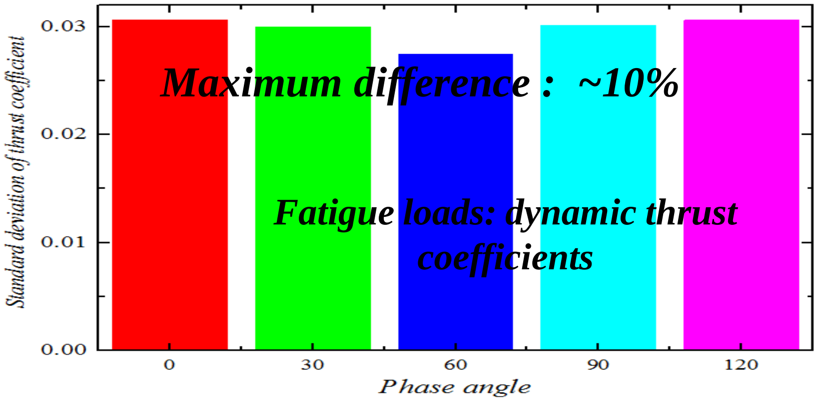
- *Oncoiming ABL wind*
- *Velocity at hub height U_{Hub}= 4.8 m/s*
- *Chord Reynolds number, Re≈7,200*
- *Tip-speed-ratio, λ = 4.6*

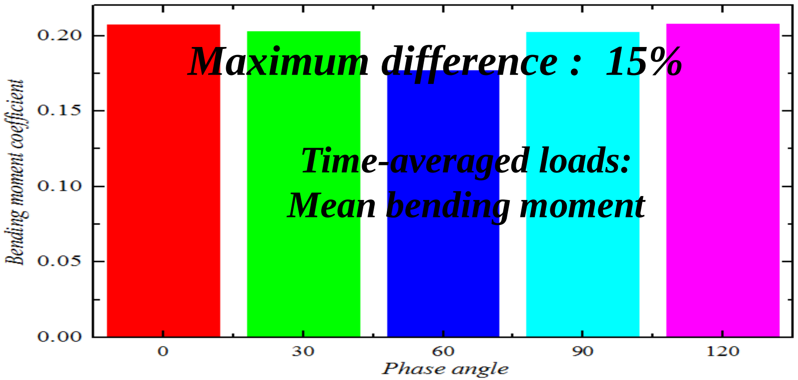
Wind Loads Acting on Wind Turbine at Different Phase Angles

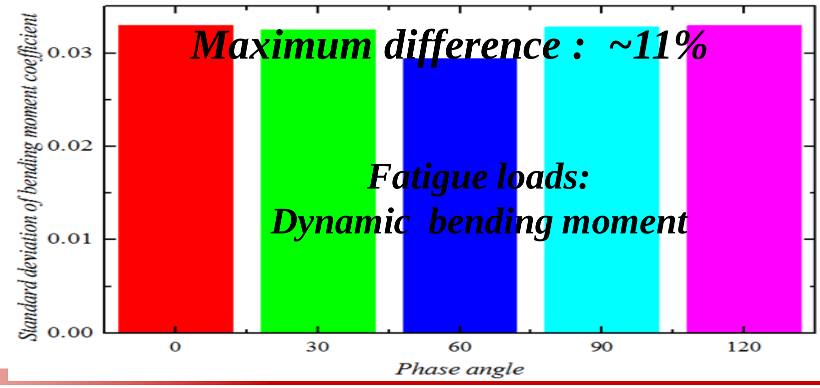




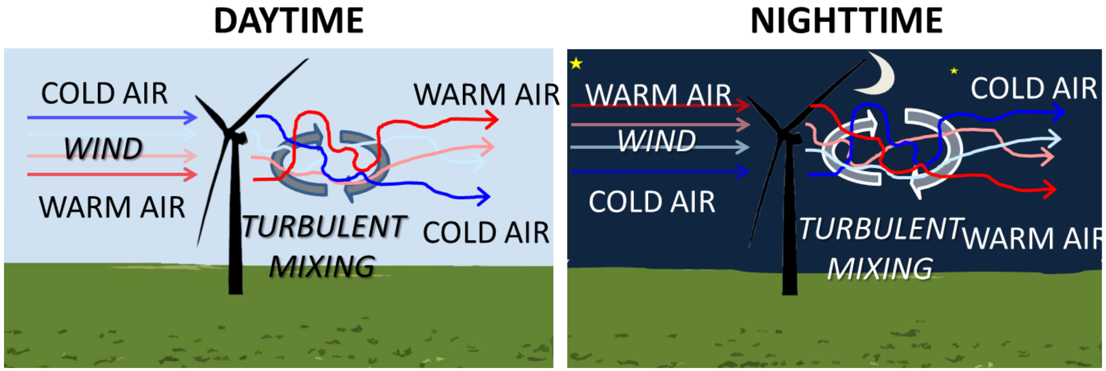








Wind Farm Aerodynamics: Wake Interferences of Multiple Wind Turbines



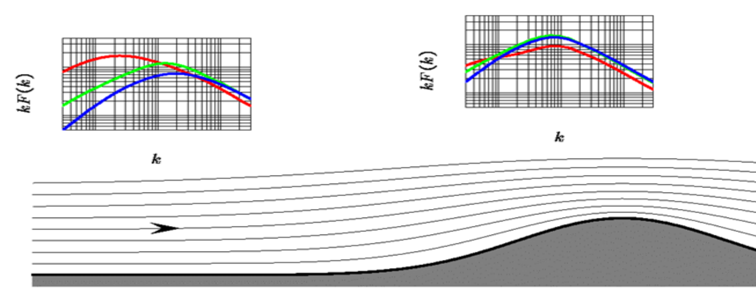

Horns Rev offshore wind farm near Denmark

- *Offshore wind farms:*
  - ***Wind turbine sitting on flat ocean surface.***
  - ***High wind speed with relatively low ambient turbulence.***
  - ***Near neutral atmospheric boundary layer winds.***

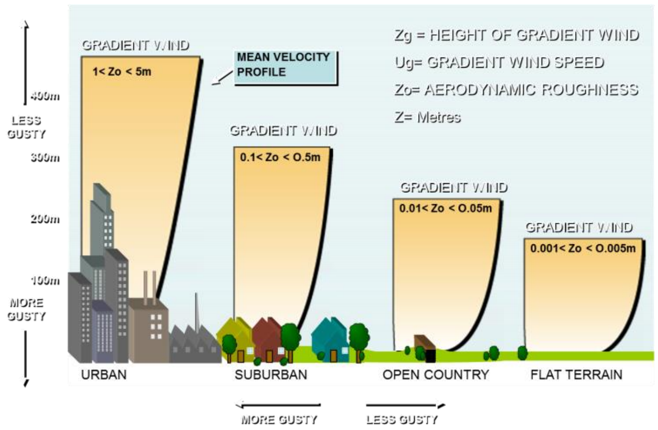

Onshore wind farm

- *Onshore wind farms:*
  - ***Atmospheric stability is rarely close to near-neutral, varying significantly between highly convective daytime conditions and highly stable nocturnal conditions.***
  - ***Much higher turbulence level.***
  - ***Wind turbine sitting over complex terrains.***

- ***Most of the existing wind farm design criterion and standards are derived based on the researches of offshore wind farms. They may not be applicable for onshore wind farms.***

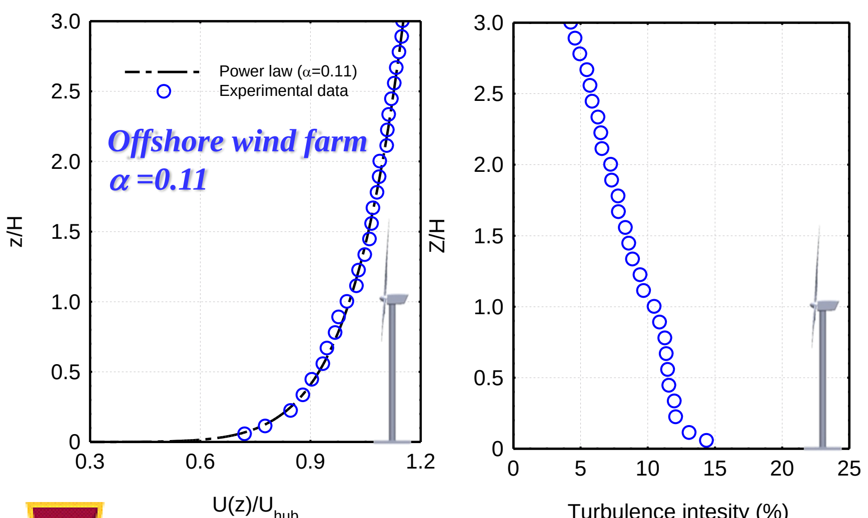


Atmospheric Boundary Layer Winds: Offshore vs. Onshore Wind Farms

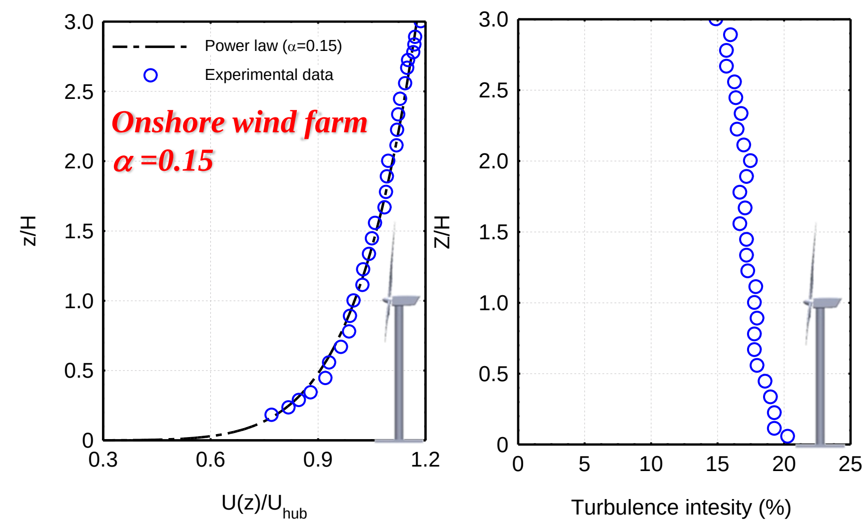


$$U(z) = U_{Z_G}\left(\frac{Z}{Z_G}\right)^{\alpha}$$

Terrain Category	Terrain description	Gradient height, Z_G (m)	Roughness length, Z_O (m)	Wind Speed exponent, α
1	Open sea, ice, tundra desert	250	0.001	0.11
2	Open country with low scrub or scattered trees	300	0.03	0.15
3	Suburban area, small towns, wooded areas	400	0.3	0.25
4	Tall buildings, city centers, developed industrial areas	500	3.0	0.36



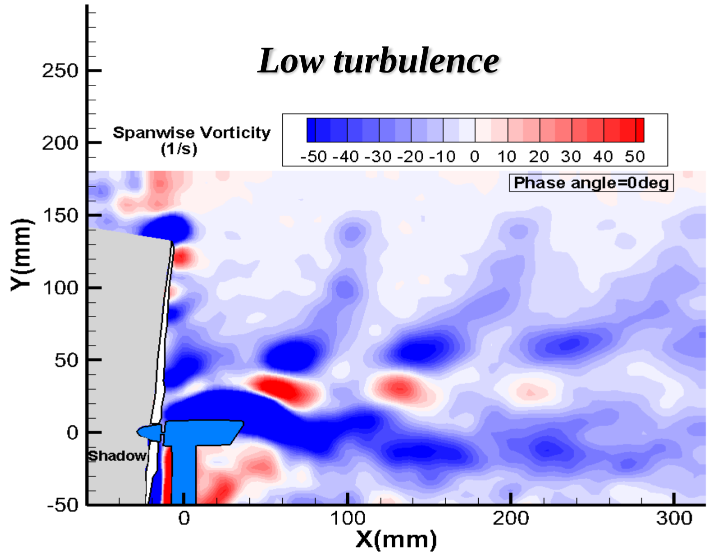
Low turbulence intensity case (10% at hub height)

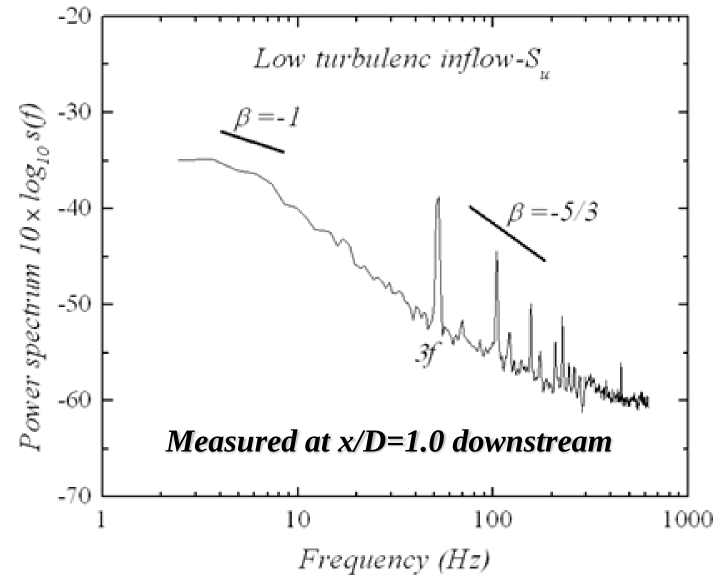


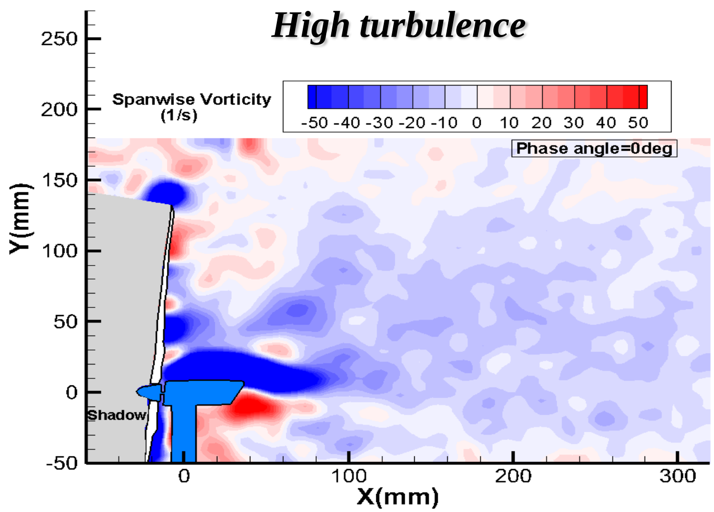
High turbulence intensity case (18% at hub height)

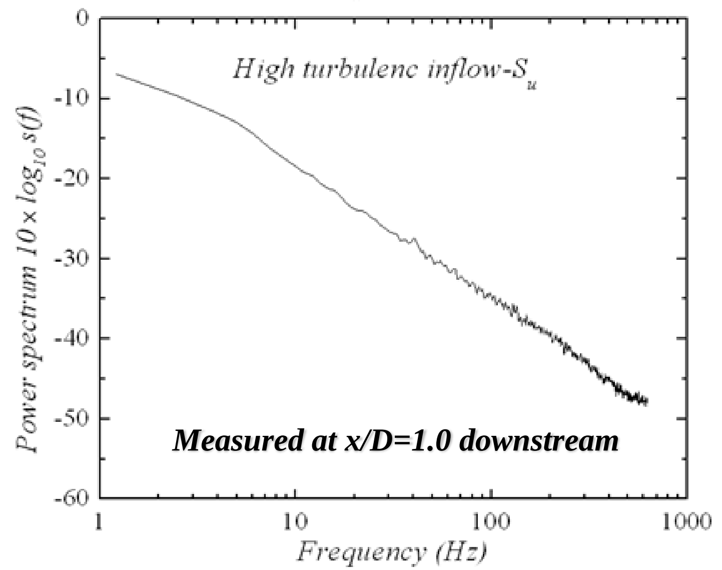
SITY

The Effects of ABL Turbulence Level on the Wake Vortex Dissipation



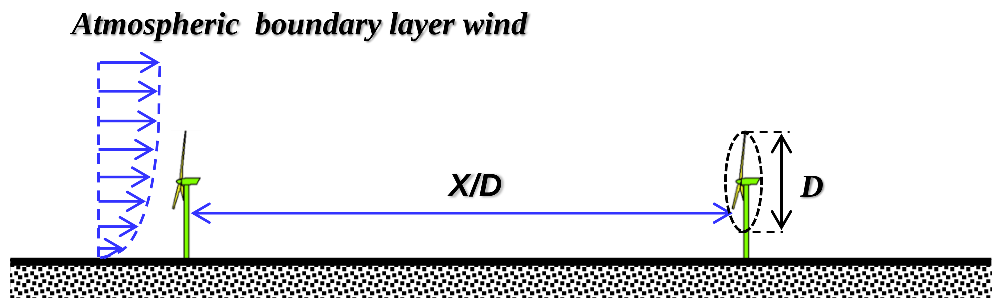


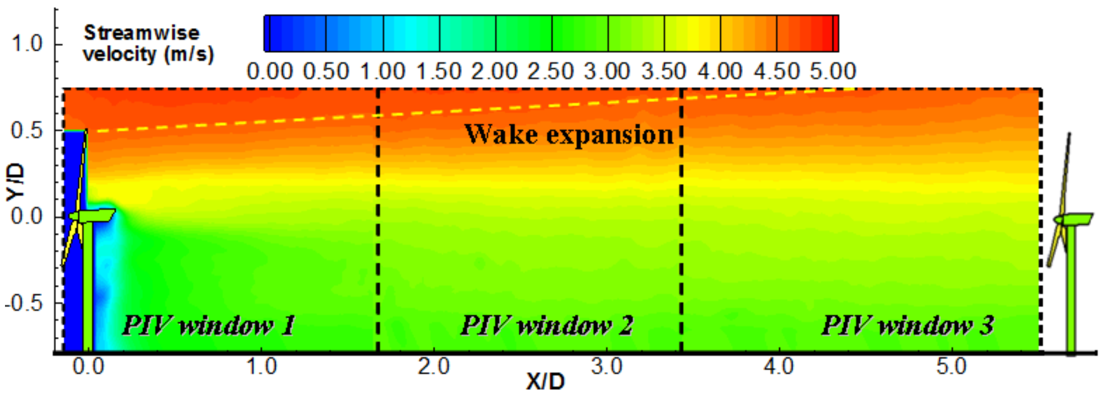


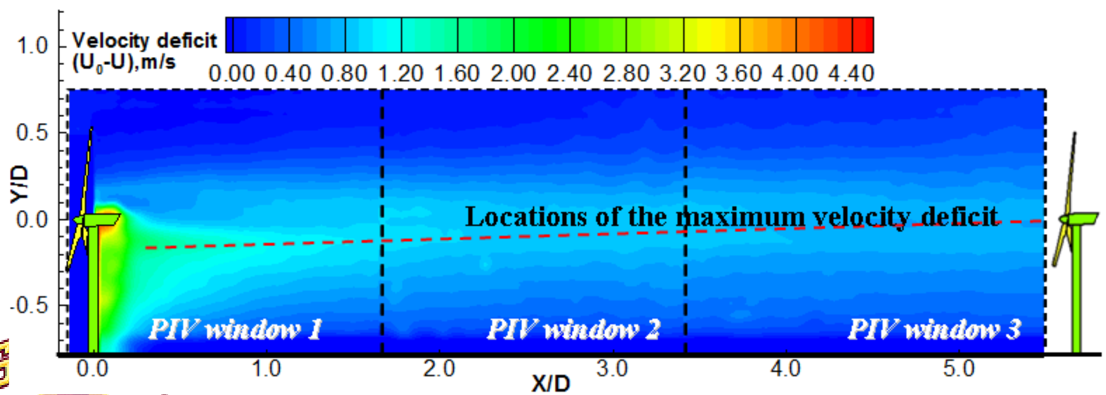


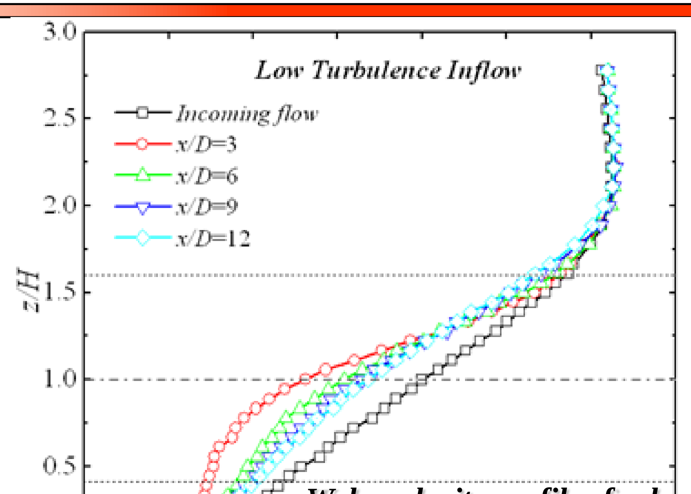
The evolution of the tip vortex structures in the wake of wind turbine model

The Effects of ABL Turbulence Level on the Wake Characteristics

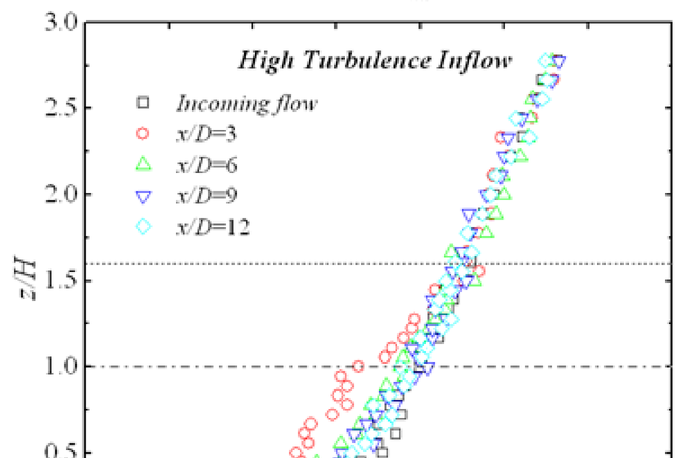






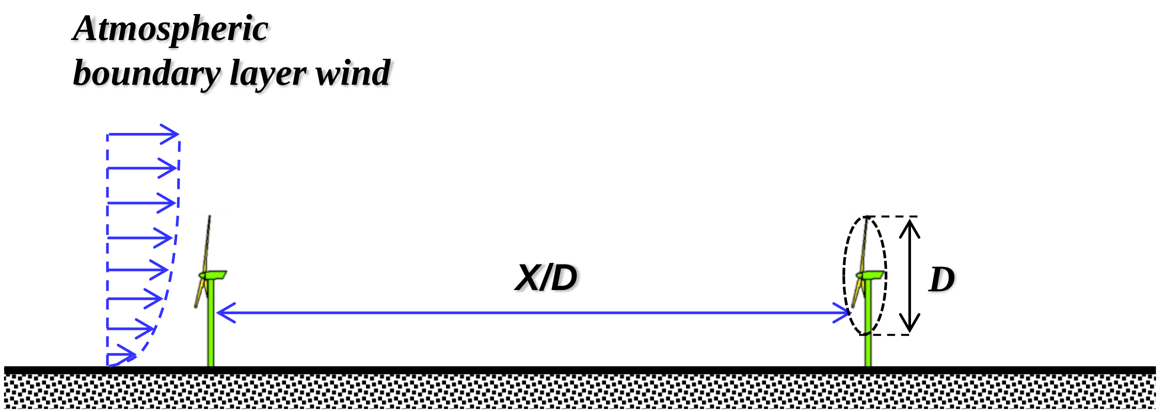


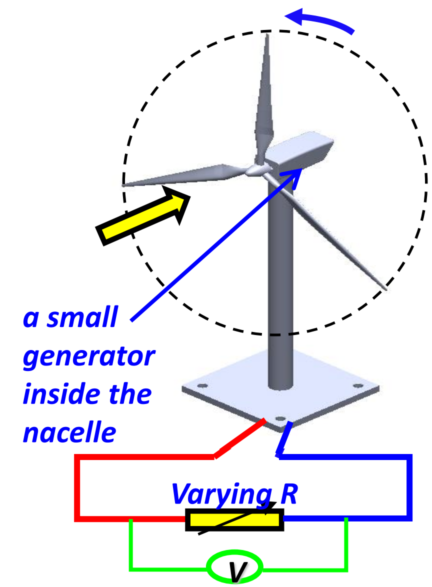
Wake velocity profiles for low turbulence inflow case

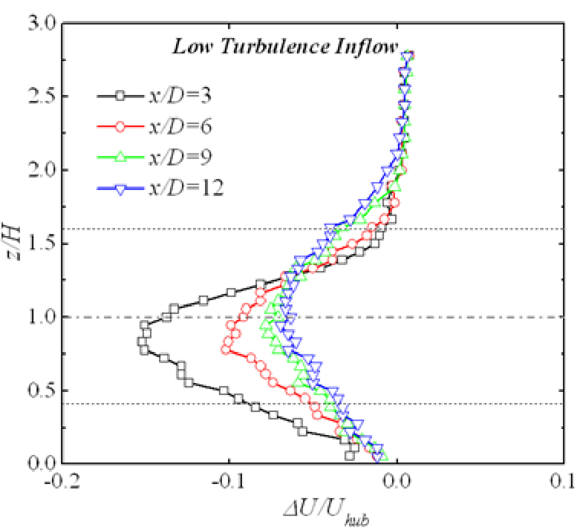


Wake velocity profiles for high turbulence inflow case

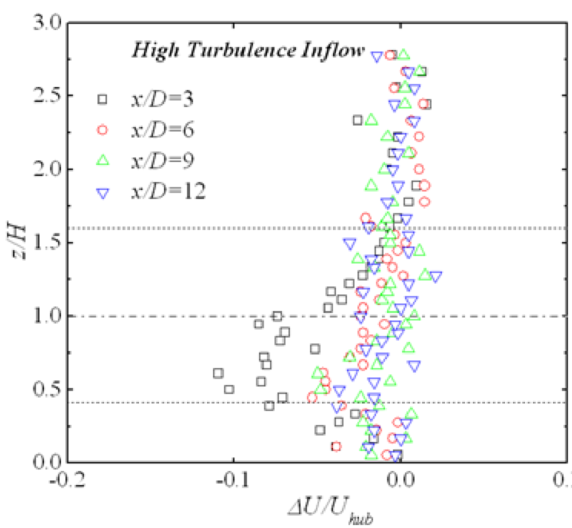
The Effects of ABL Turbulence Level on the Wake Characteristics



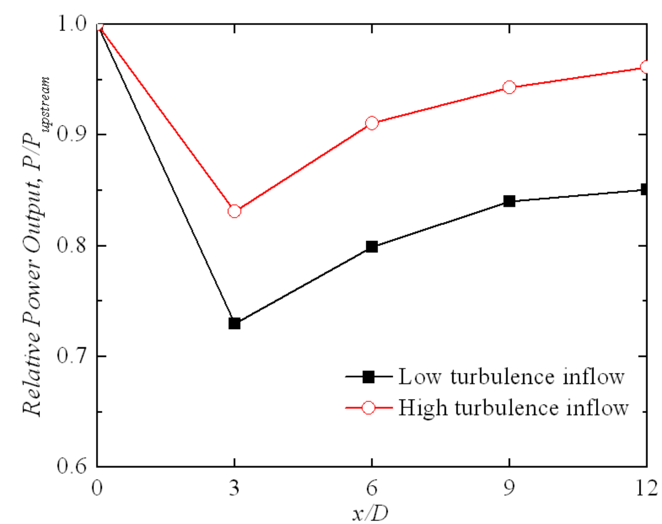




Wake velocity deficit profiles for low turbulence inflow case

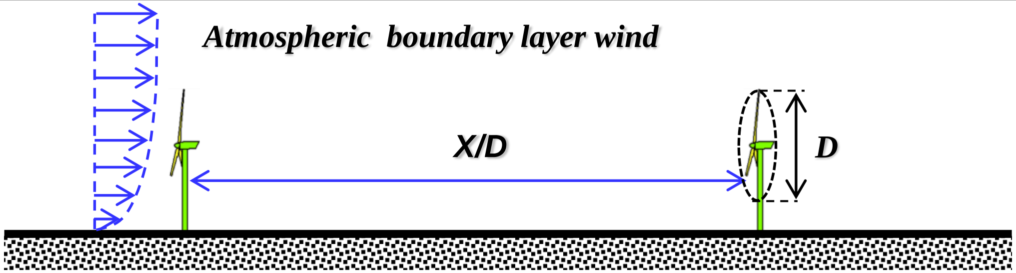


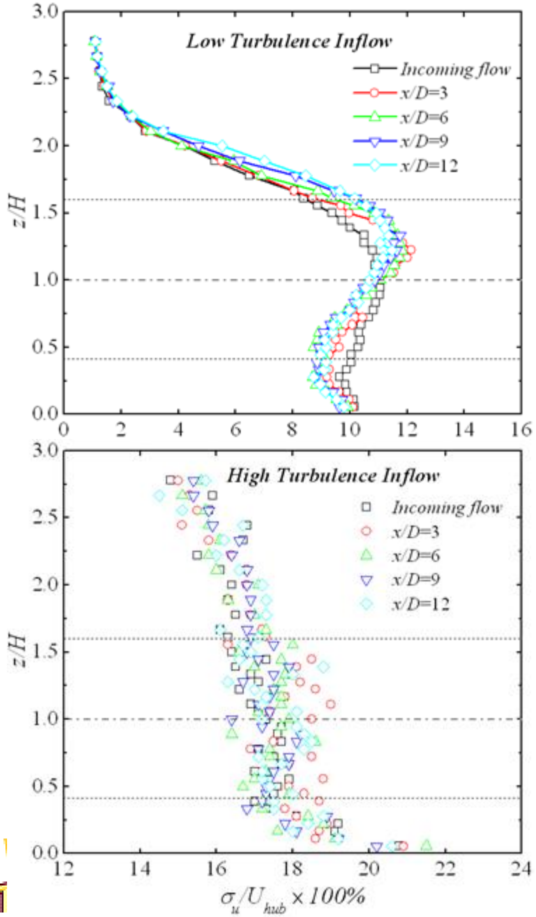
Wake velocity deficit profiles for high turbulence inflow case



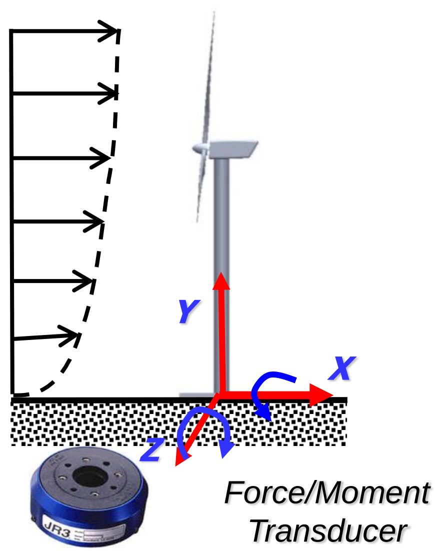
Power output of the downstream wind turbine vs. X/D

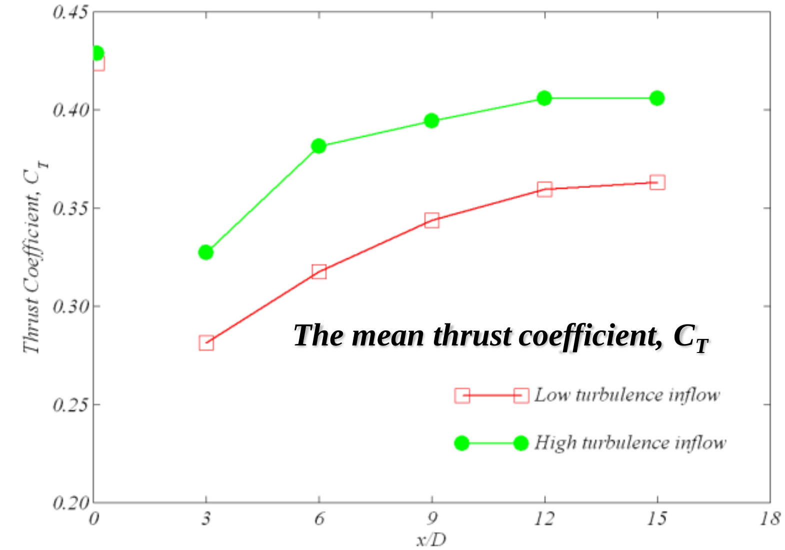
The Effects of Oncoming Turbulence Level on the Wake Characteristics

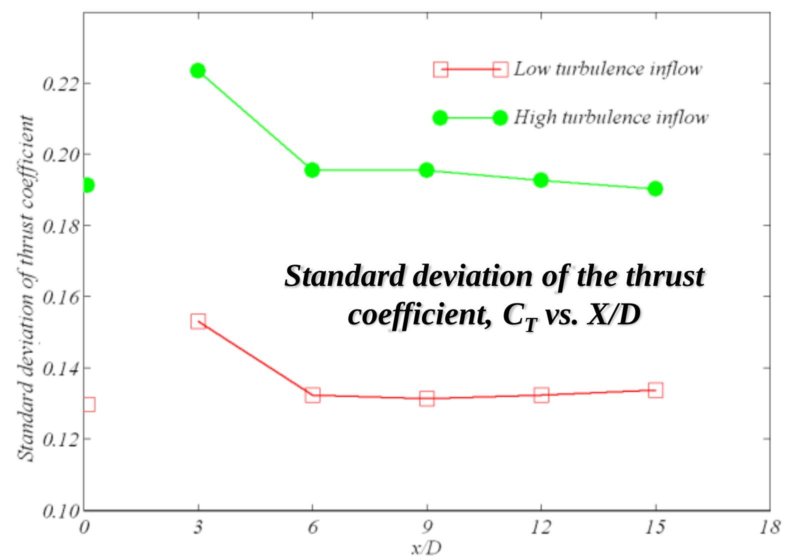




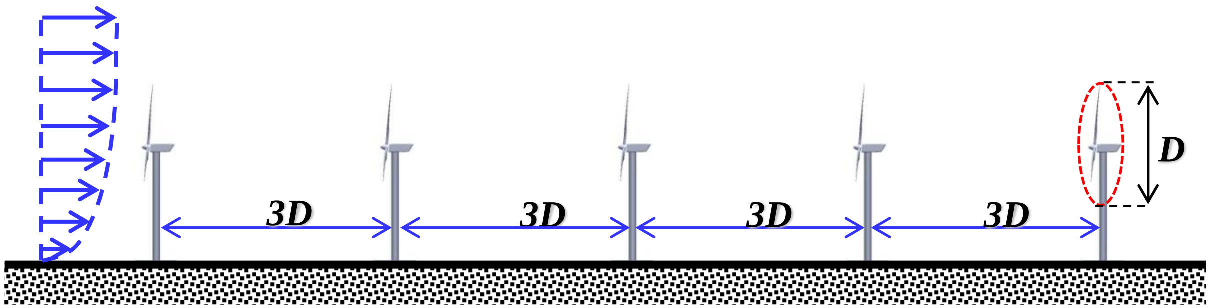
Turbulence shear stress in the wakes

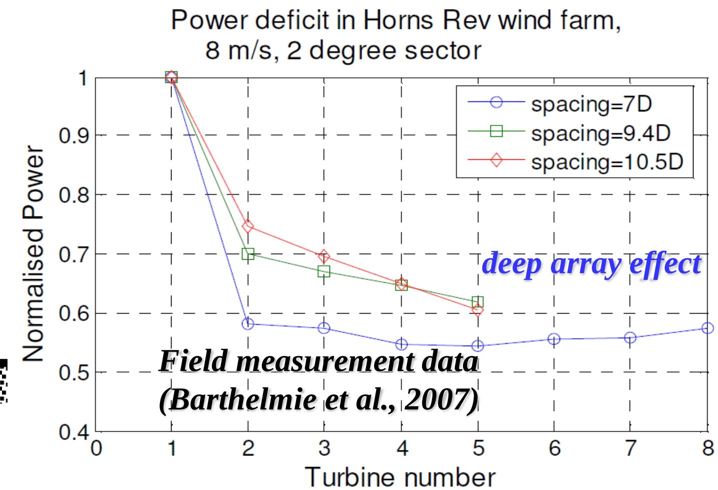


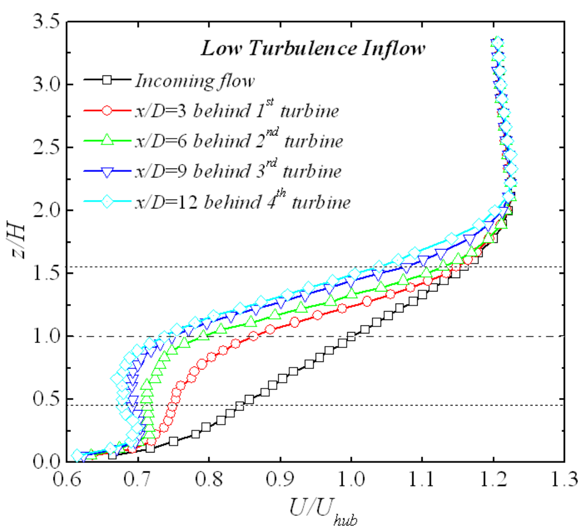




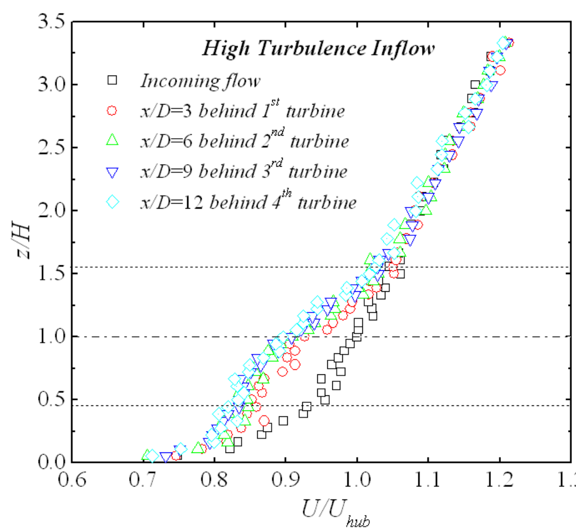
Wake Interferences among Multiple Wind Turbines



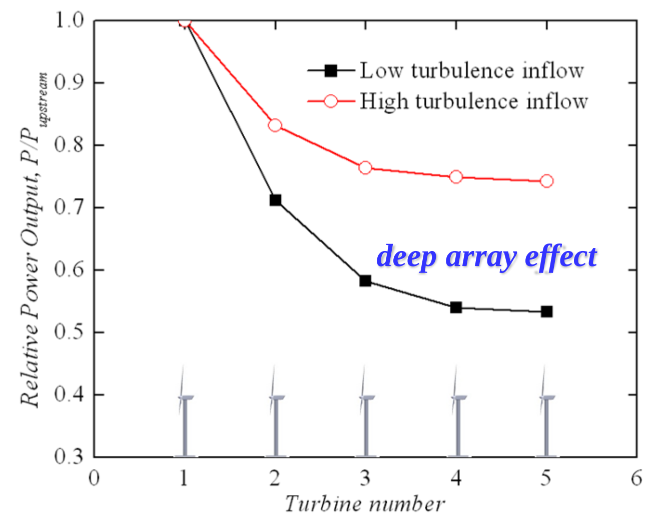




Velocity profiles in the wake for low turbulence inflow case



Velocity profiles in the wake for high turbulence inflow case



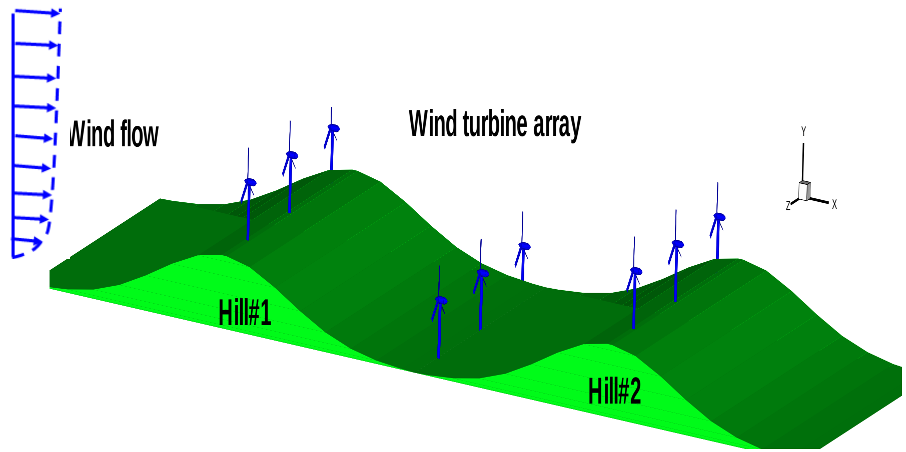
Power outputs of the wind turbines in a line

Effects of Terrain Topology on the Performances of Wind Turbines

- *Quantifying the flow characteristics of surface winds (both mean and turbulence characteristics) over a flat surface (baseline case) and complex terrains for the optimal site design of turbines.*

- *Characterizing the turbulent wake flows and dynamic wind loads (both forces and moments) as well as their relationships for single wind turbine sited over a flat surface (baseline case) and complex terrains for the optimal mechanical design of wind turbines.*

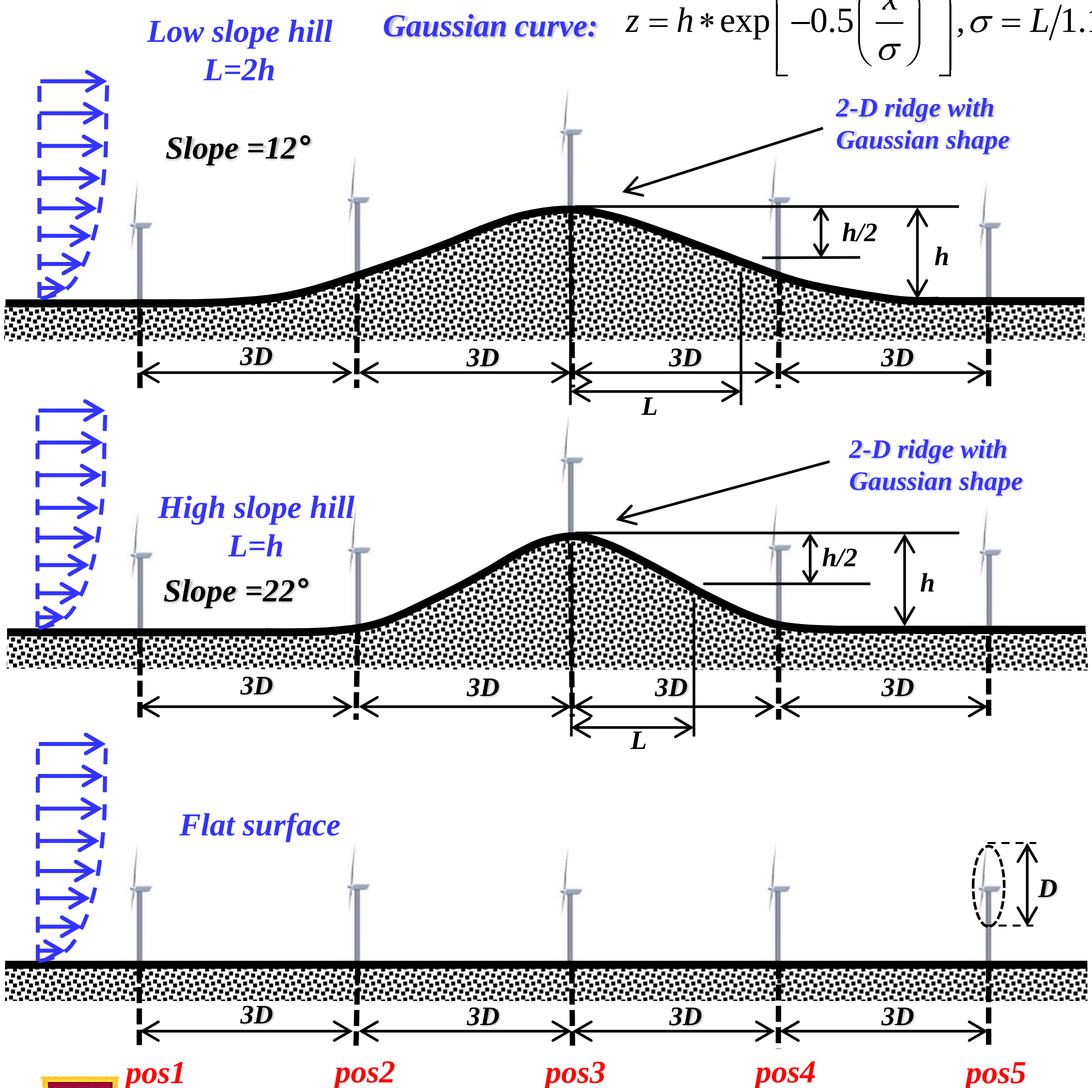
- *Investigating the effects of array spacing and layout on the wake interferences among multiple wind turbines sited over a flat surface (baseline case) and complex terrains for higher total power yield and better durability of wind turbines.*

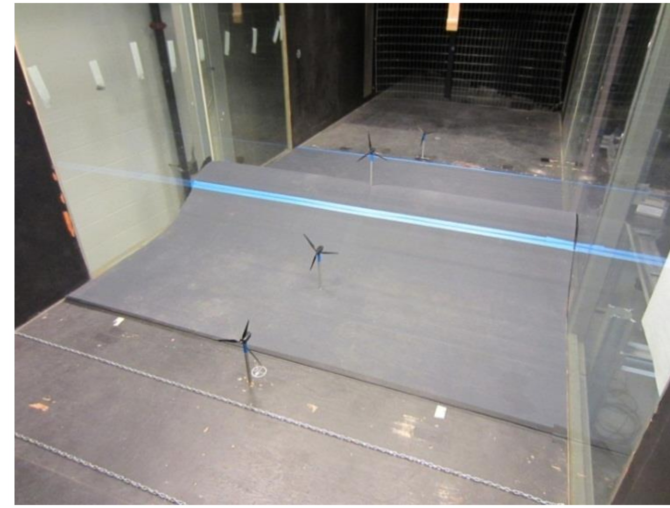


Wind turbines over complex terrains

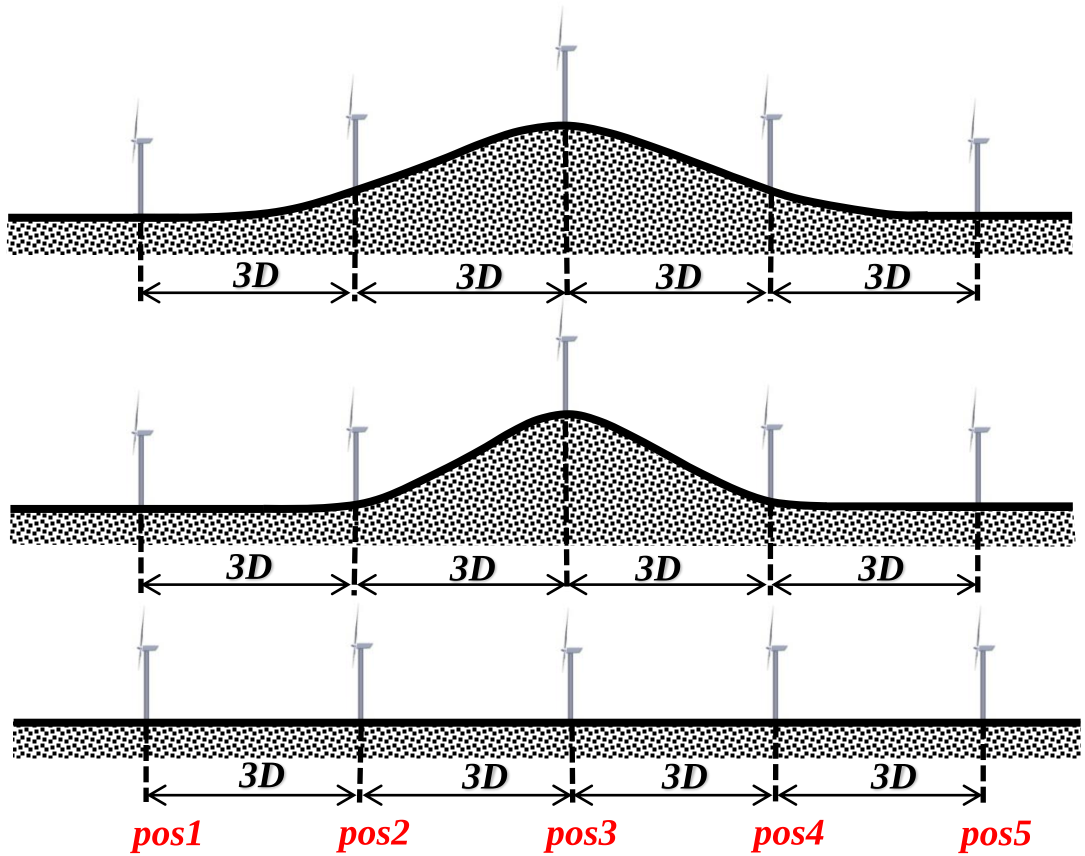
Effects of Complex Terrains on the Wind Turbine Performance

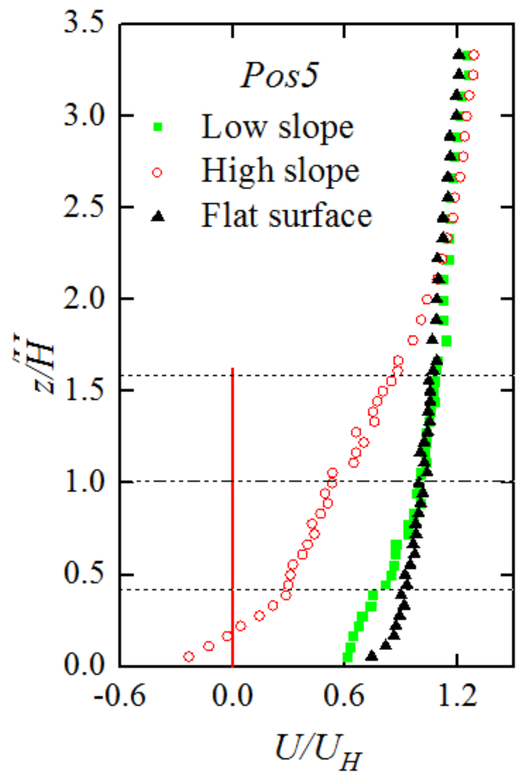
Gaussian curve: $$z = h * \exp\left[-0.5\left(\frac{x}{\sigma}\right)^2\right], \sigma = L/1.1774$$





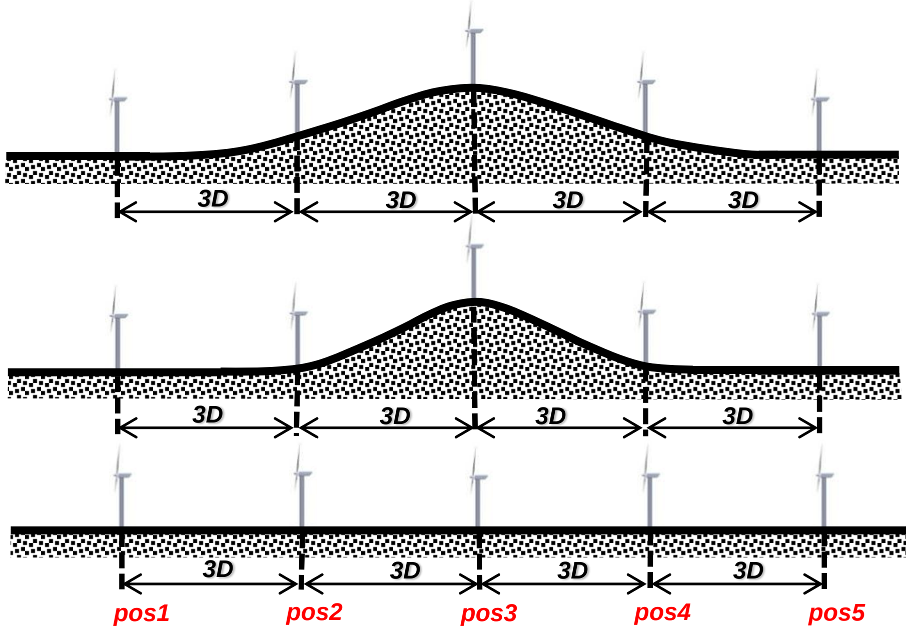
Performances of Single Wind Turbine Sited over Complex Terrains





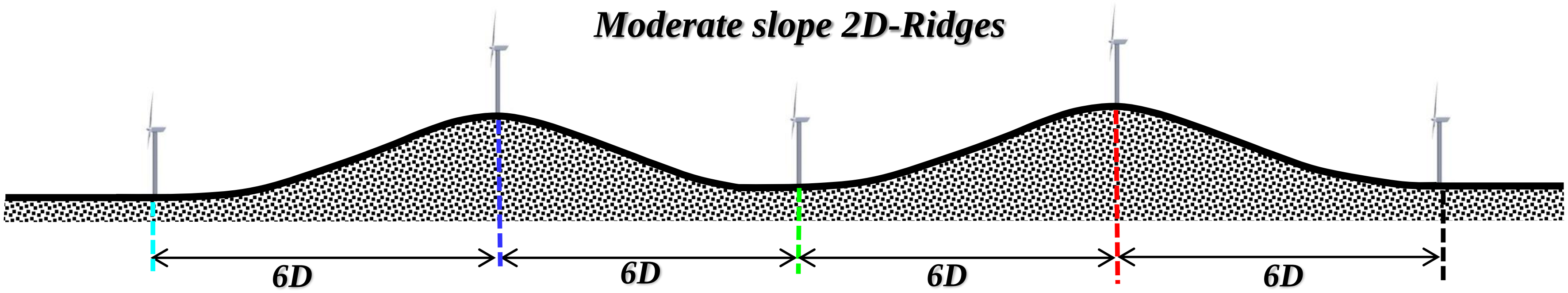
Wind turbine position	pos1	pos2	pos3	pos4	pos5
Power output low slope hill (normalized with power output of single wind turbine sited on flat surface)	0.91	0.93	1.82	1.28	0.94
Power output high slope hill (normalized with power output of single wind turbine sited on flat surface)	0.92	0.79	1.45	0.04	0.20

Power Outputs of Wind Turbines over Flat Surface vs. Complex Terrains



Wind turbine position	pos1	pos2	pos3	pos4	pos5	Total
Power output flat surface (normalized with power output of single wind turbine sited on flat surface)	*1.00*	*0.85*	*0.79*	*0.73*	*0.72*	*4.09*
Power output low slope hill (normalized with power output of single wind turbine sited on flat surface)	*0.91*	*0.82*	*1.69*	*1.02*	*0.73*	*5.17 (~26% more)*
Power output high slope hill (normalized with power output of single wind turbine sited on flat surface)	*0.92*	*0.63*	*1.33*	*0.04*	*0.19*	*3.11 (~24% less)*

Performances of Wind Turbines over Complex Terrains

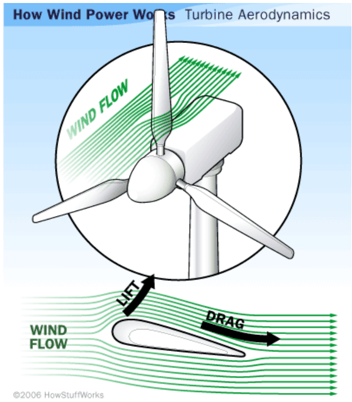


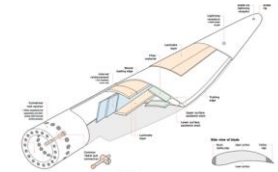
Wind turbine position	pos1	pos2	pos3	pos4	pos5
Power output wind turbines (normalized with power output of single wind turbine sited on flat surface)	0.90	1.91	0.67	2.13	0.91

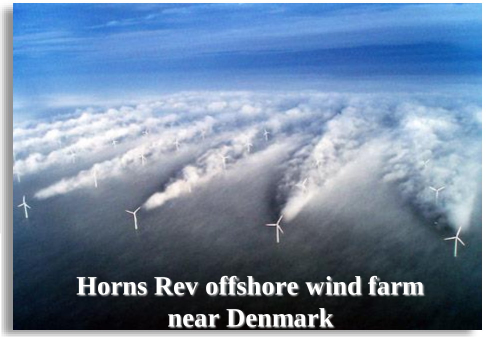
Wind turbine position		pos1	pos2	pos3	pos4	pos5
Two hills	Thrust Coefficient C_T	0.117	0.282	0.093	0.298	0.131
	Bending moment Coefficient C_{MZ}	0.124	0.258	0.096	0.284	0.130

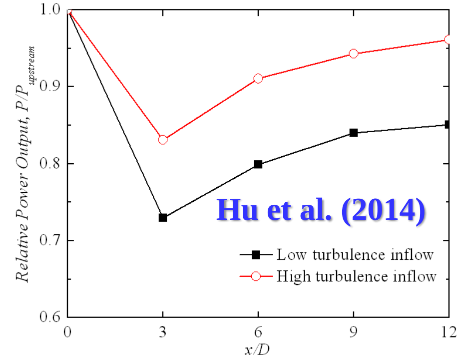
Root Loss and Wake Loss of Wind Turbines

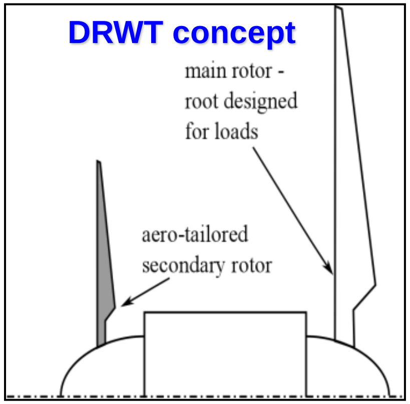
- ***Root Loss (~5%):***
  - ***Inner 25% of rotor blades are designed to provide structural integrity.***
  - ***The aerodynamically poor design at the root region would result in a "dead" wind zone where virtually no energy is extracted from the incoming wind.***
- ***Wake Loss (up to 40%):***
  - ***Aerodynamic interaction between wind turbines will results in significant energy loss (up to 40%).***
  - ***Wake loss is due to the ingestion of low-momentum air in wakes from upstream turbines by the downstream turbines.***



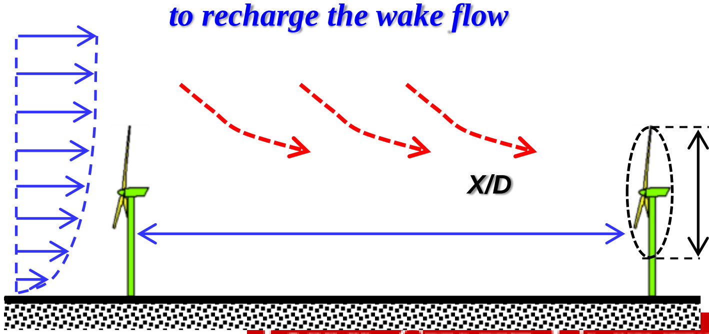






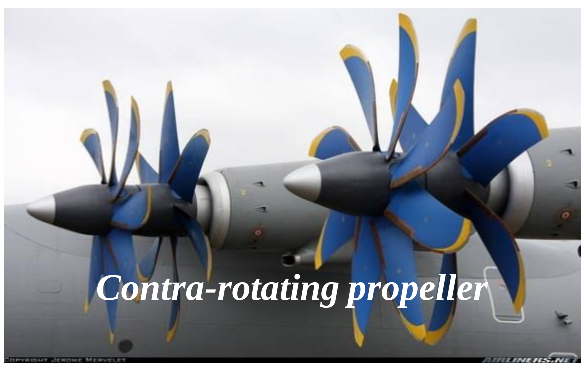


SRWT ***DRWT***

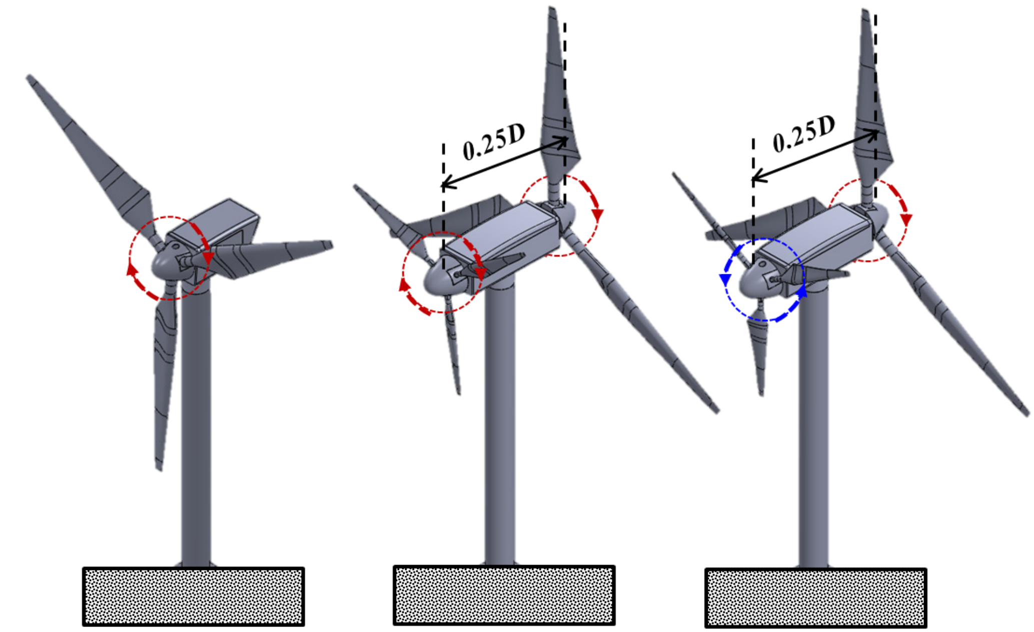


Dual-Rotor Wind Turbine Models and Counter-Rotating Rotor Concept

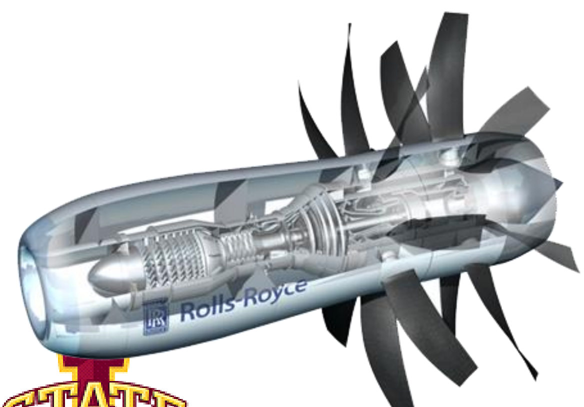
Soviet Ka-2 helicopter with counter-rotating rotors



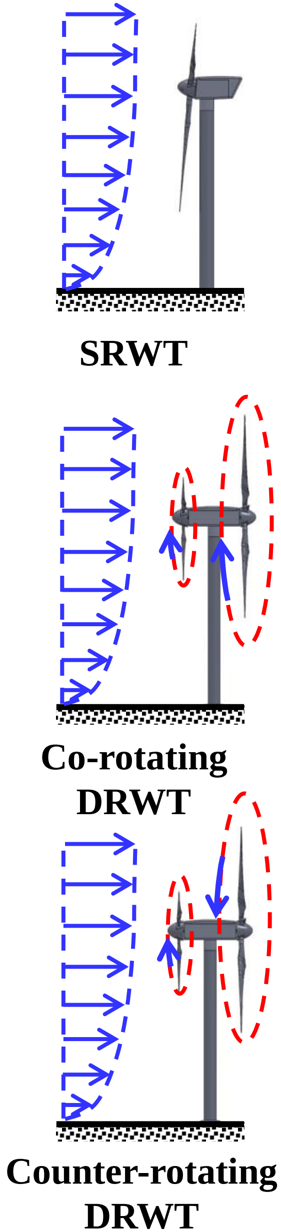
Contra-rotating propeller



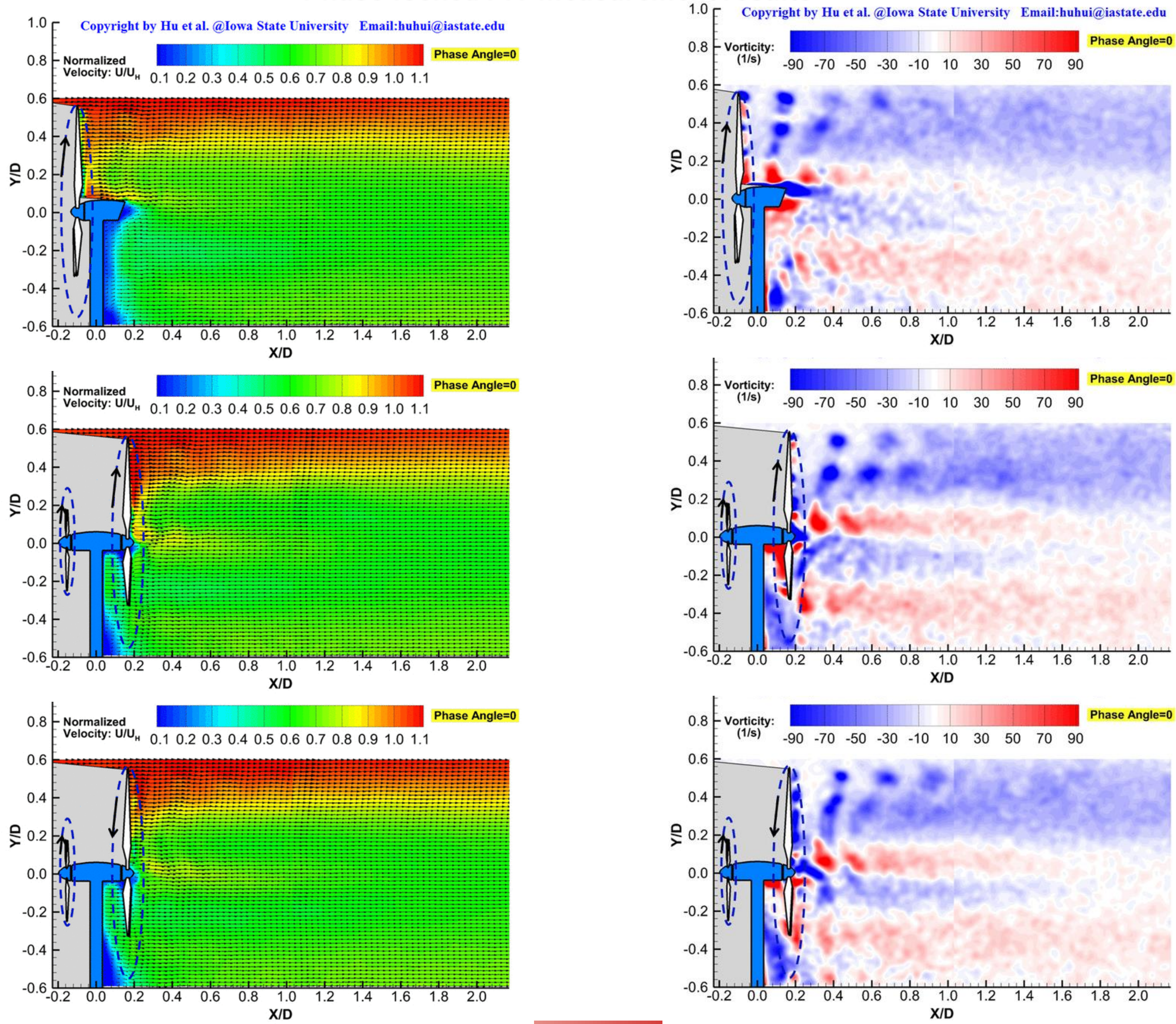
SRWT | *Co-rotating DRWT* | *Counter-rotating DRWT*



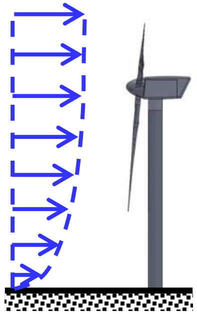
SRWT vs. Co-Rotating DRWT vs. Counter-rotating DRWT



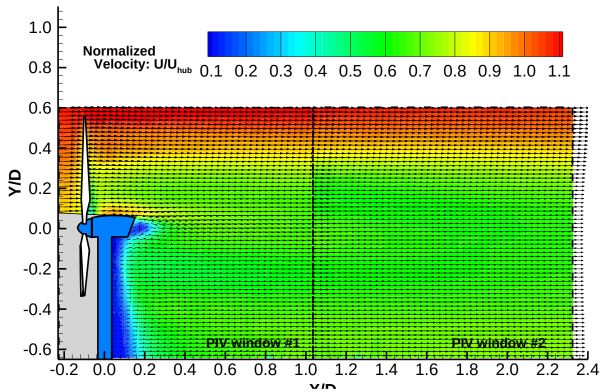
Phase-locked PIV measurement results

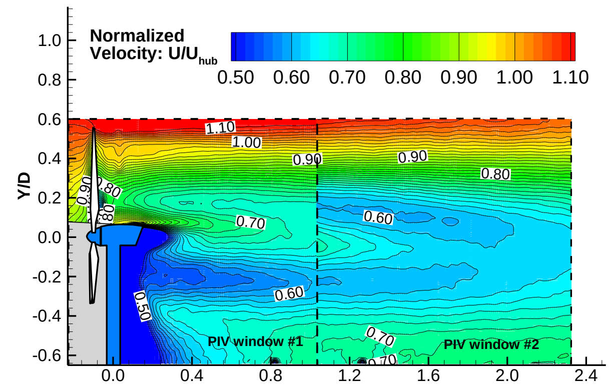


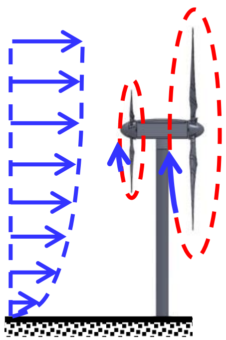
SRWT vs. Co-Rotating DRWT vs. Counter-rotating DRWT



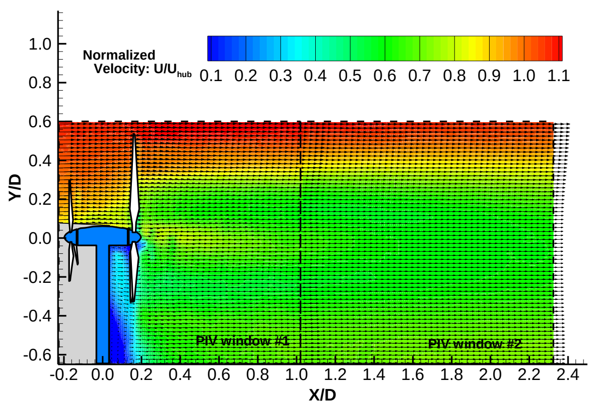
SRWT

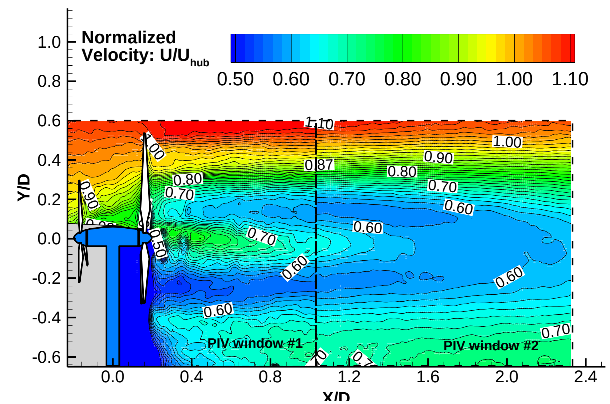


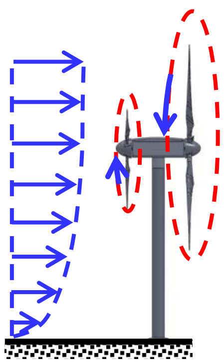




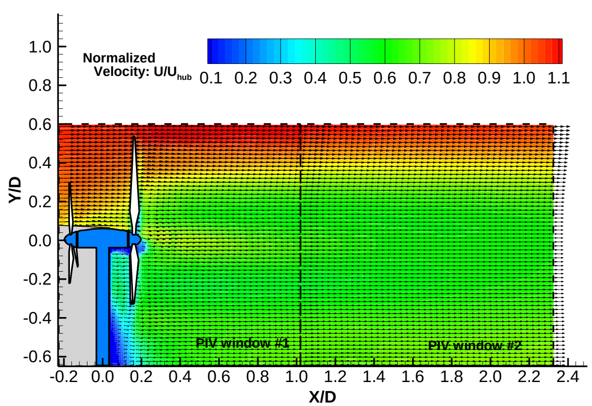
Co-rotating DRWT

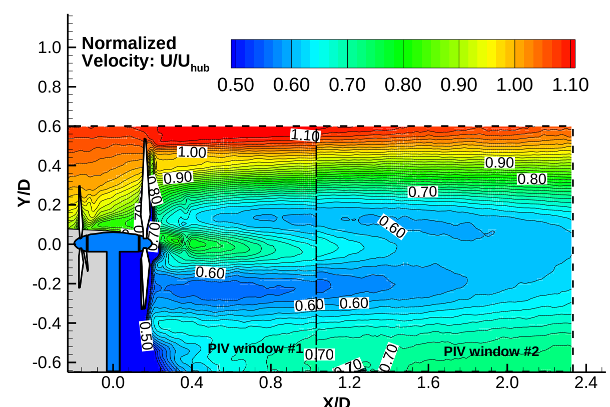




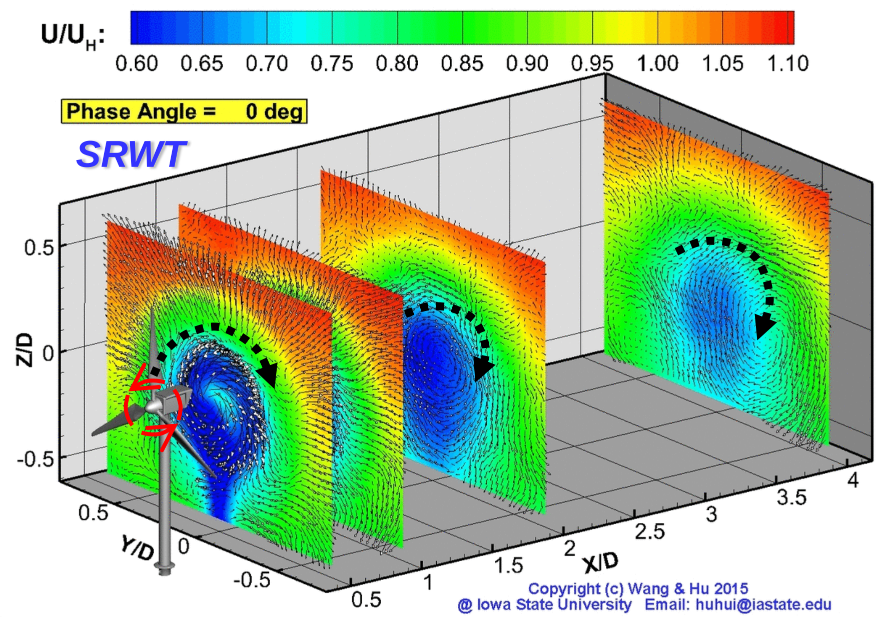


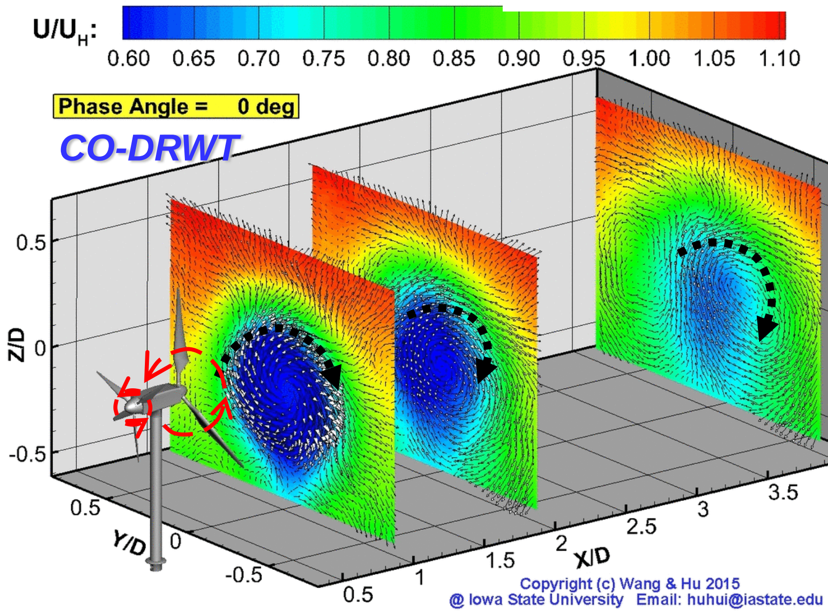
Counter-rotating DRWT

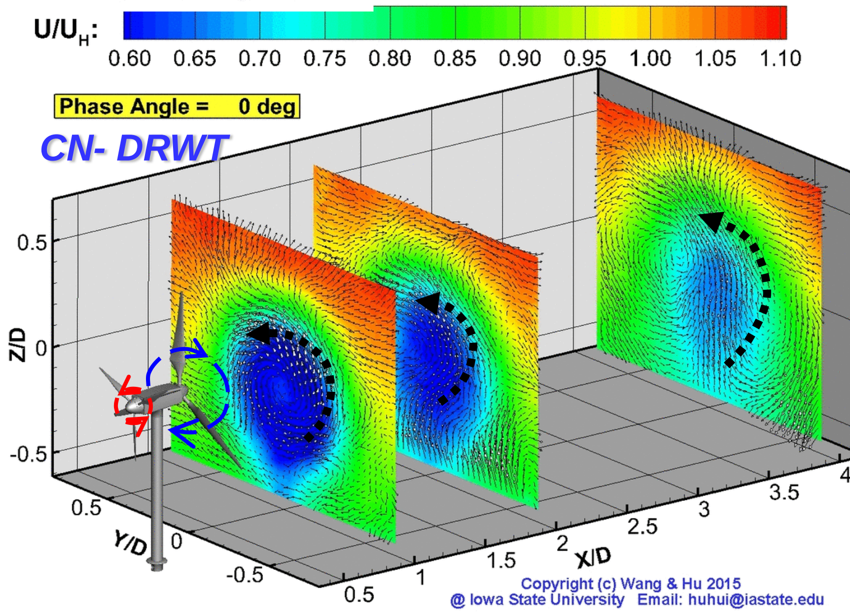




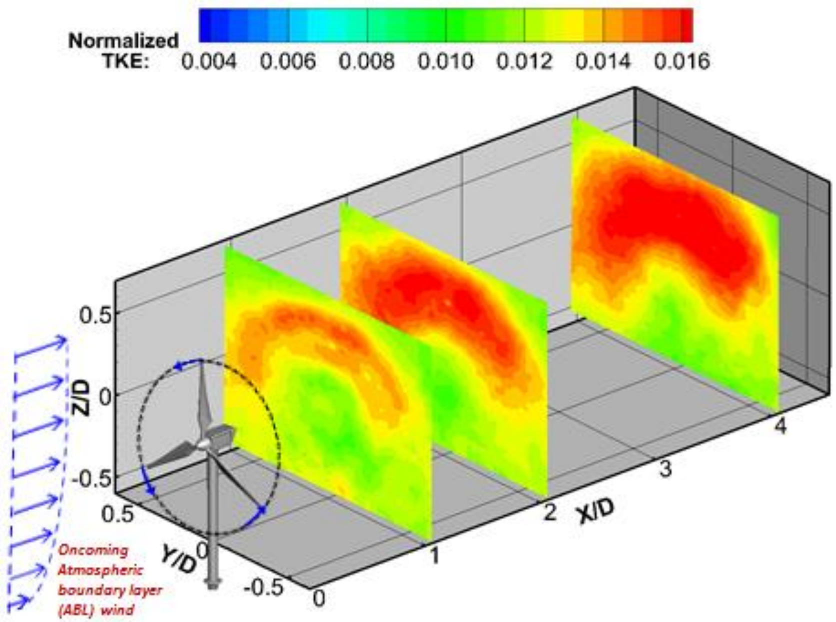
Stereo-PIV measurement Results: SRWT and DRWTs

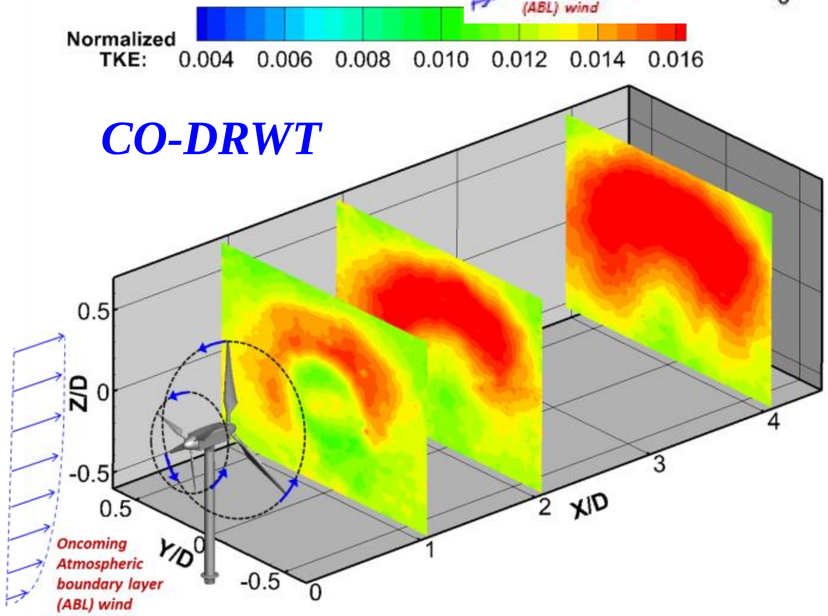


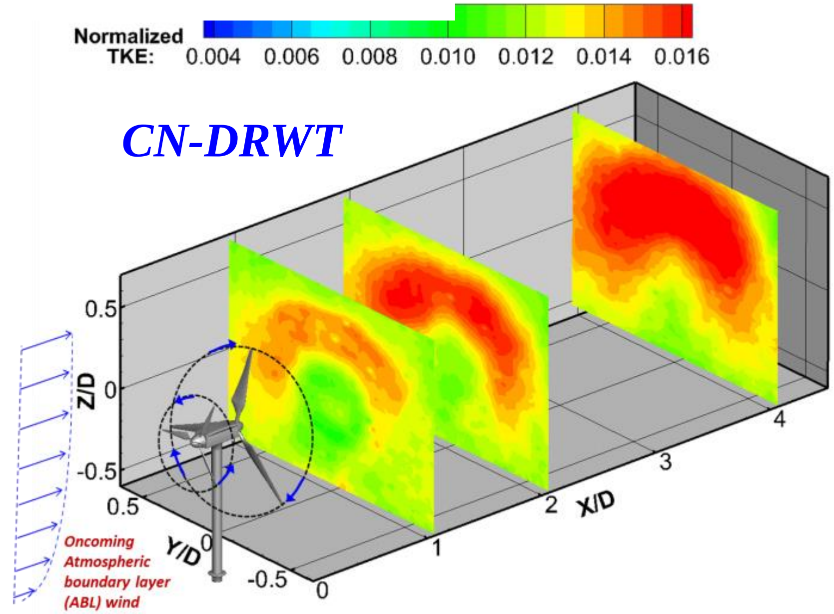




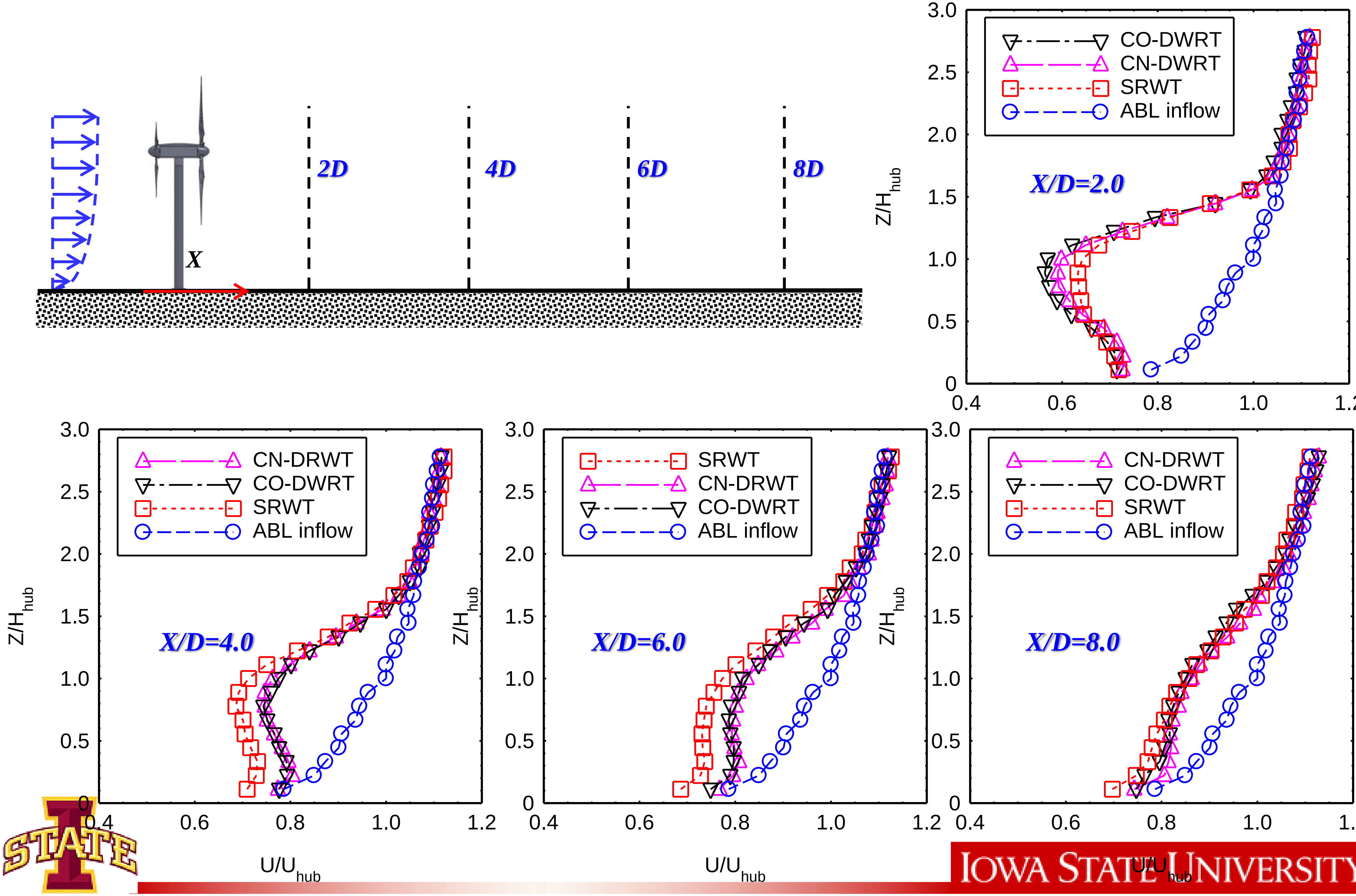
Stereo-PIV measurement Results: SRWT and DRWTs



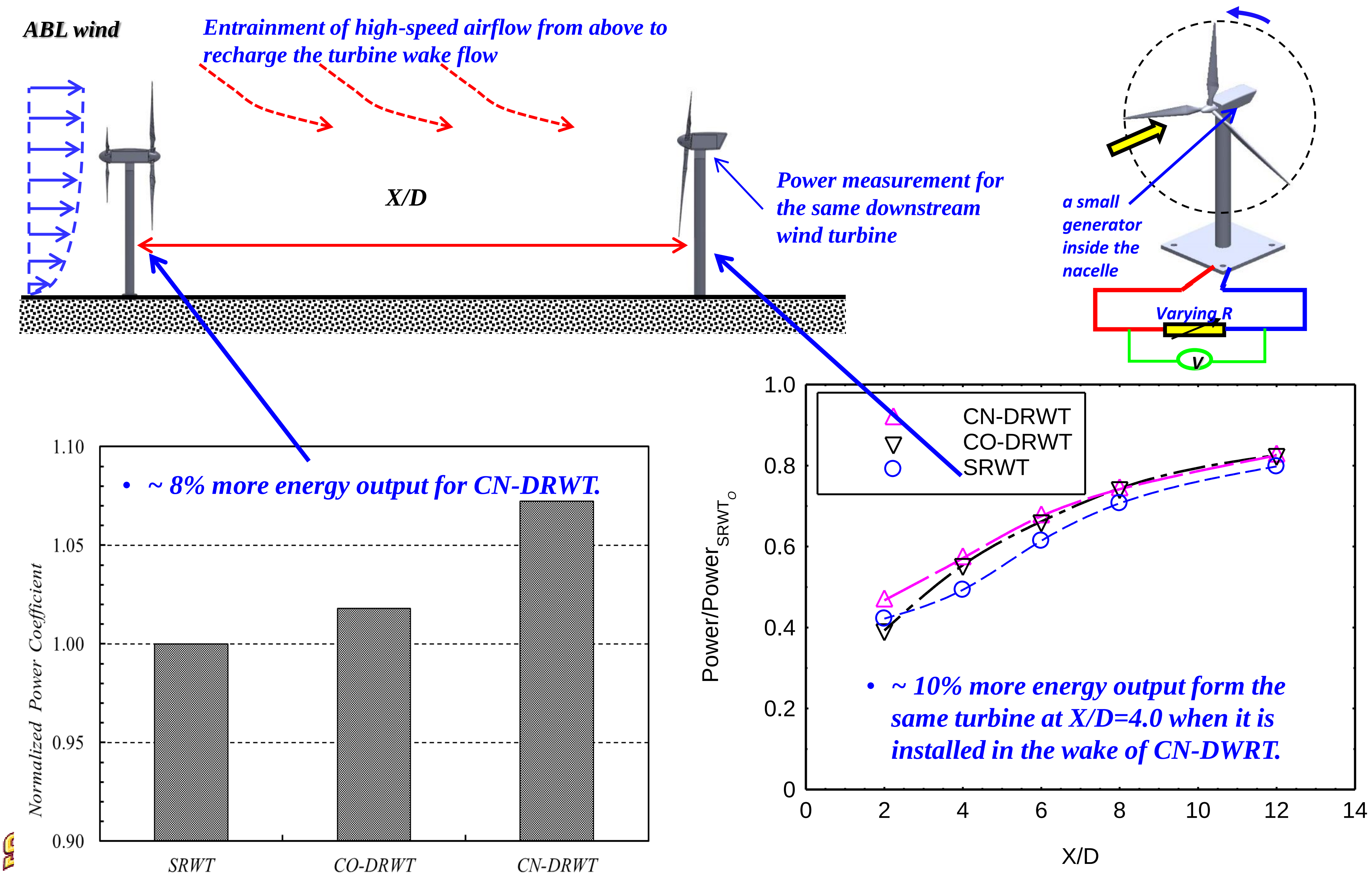




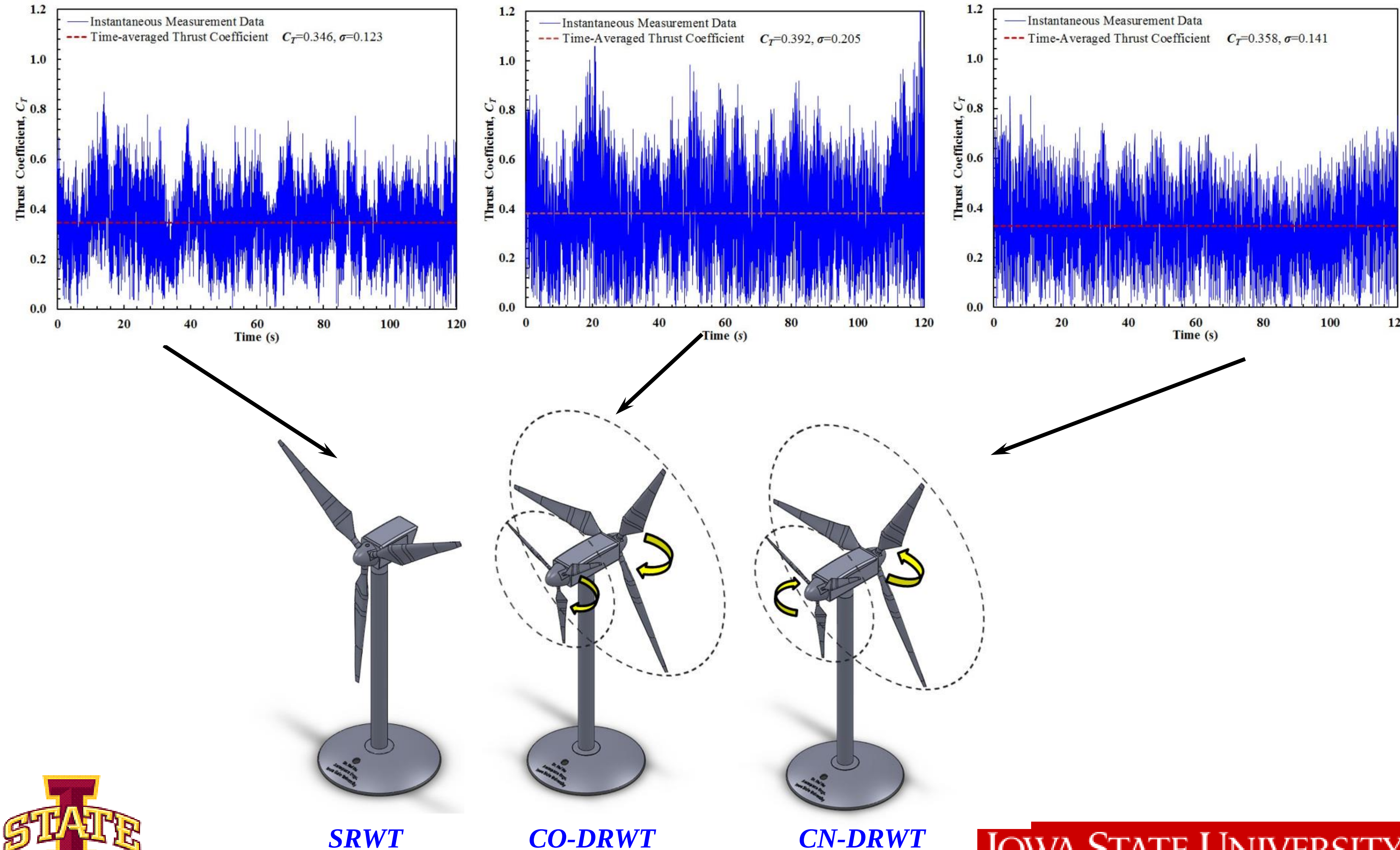
SRWT vs. Co-Rotating DRWT vs. Counter-rotating DRWT



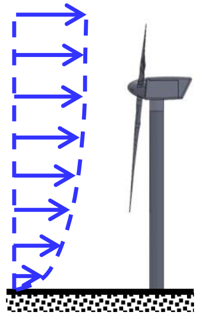
SRWT vs. Co-rotating DRWT vs. Counter-rotating DRWT



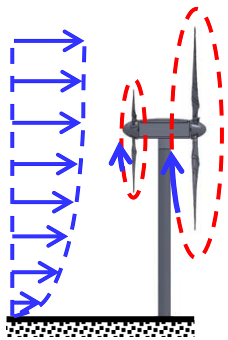
Dynamic wind loads for SRWT and DRWTs



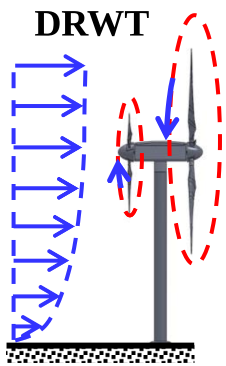
Comparison of SRWT and DRWT: Thrust Force and Bending Moment



SRWT



Co-rotating DRWT



Counter-rotating DRWT

- ***Time-averaged wind loads acting on the wind turbines:***

Configurations	Thrust loading (C_{Fx})	Bending Moment (C_{My})
SRWT	0.35	0.42
Co-rotating DRWT	0.39	0.44
Counter-rotating DRWT	0.36	0.43

- ***~10% more mean wind loads for DRWTs***

- ***Fluctuations of the dynamic wind loads acting on the wind turbines:***

Configurations	σC_{Fx}	σC_{My}
SRWT	0.123	0.133
Co-rotating DRWT	0.161	0.178
Counter-rotating DRWT	0.132	0.151

- ***10%~30% higher wind load fluctuations for DRWTs***

- *Surge motion*

- *Pitch motion*

- *Heave motion*

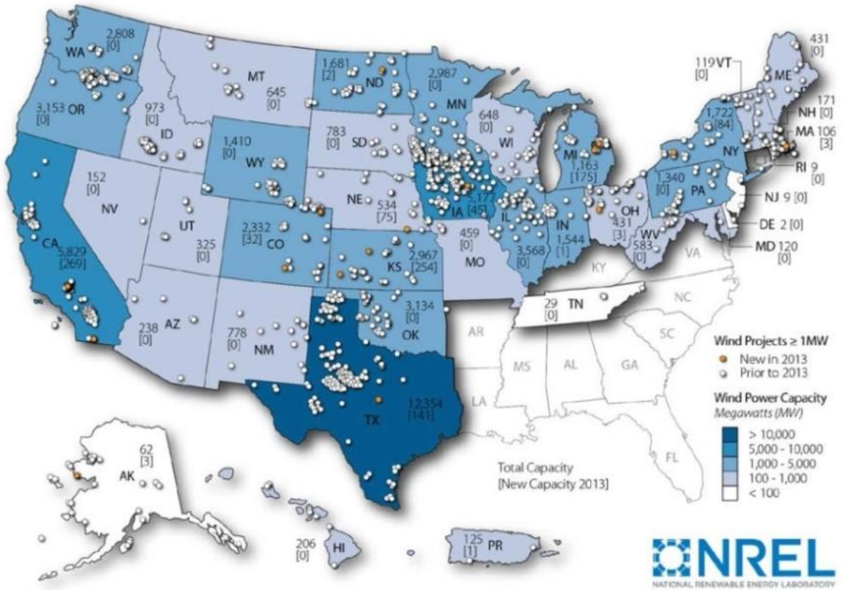
An Experimental Study on the Effects of Wave-Induced Base Motions on the Aeromechanic Performance of Floating Wind Turbines

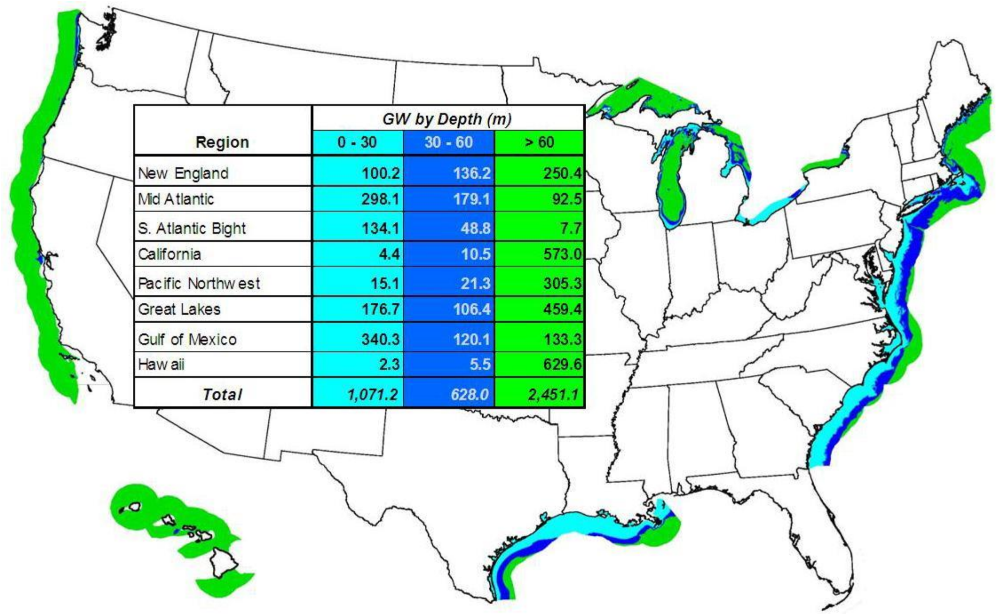
Morteza Khosravi, Hui Hu (✉)

Department of Aerospace Engineering

Iowa State University
2251 Howe Hall, Ames, IA 50011-2271
✉ Email: huhui@iastate.edu

Onshore and Offshore Wind Energy in USA





Region	GW by Depth (m)		
	0 - 30	30 - 60	> 60
New England	100.2	136.2	250.4
Mid Atlantic	298.1	179.1	92.5
S. Atlantic Bight	134.1	48.8	7.7
California	4.4	10.5	573.0
Pacific Northwest	15.1	21.3	305.3
Great Lakes	176.7	106.4	459.4
Gulf of Mexico	340.3	120.1	133.3
Hawaii	2.3	5.5	629.6
Total	*1,071.2*	*628.0*	*2,451.1*

- **The U.S. wind power installed capacity is over 65 GW as of the end of 2014, entirely based on onshore wind farms.**

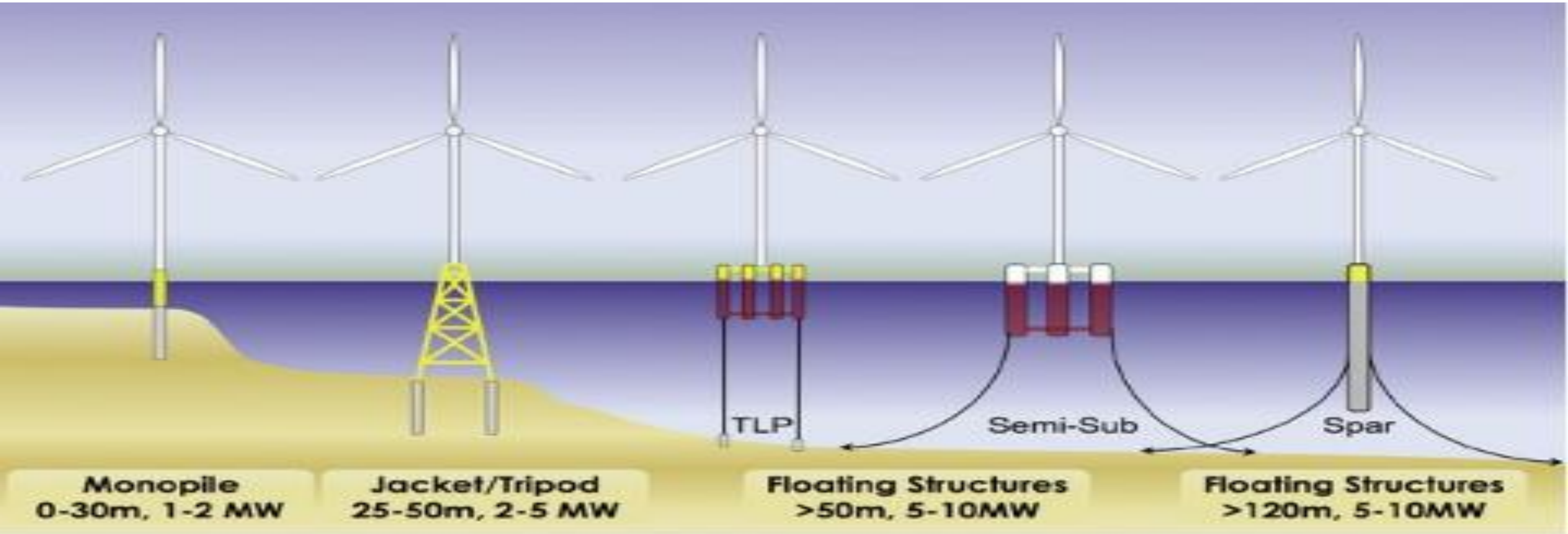
http://www.nrel.gov/gis/wind.html

A typical Onshore wind farm

Horns Rev offshore wind farm near Denmark

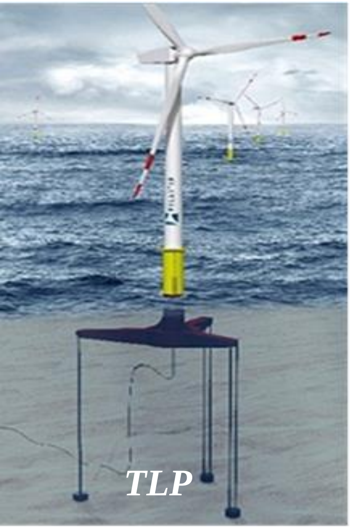
Offshore Wind Turbines

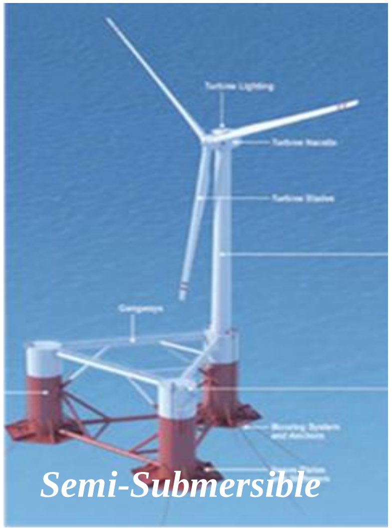
- ***Offshore wind technology is divided into three main categories depending on the depth of the water where the turbines will be placed, as follow:***
  - ***Shallow water:*** *Any water depth up to 25 meters.*
  - ***Transitional water:*** *Water depths between 25 to 50 meters.*
  - ***Deep water:*** *Any water depth greater than 50 meters. (Tension-Leg Platform (TLP), Spar Buoy, Semi-Submersible*

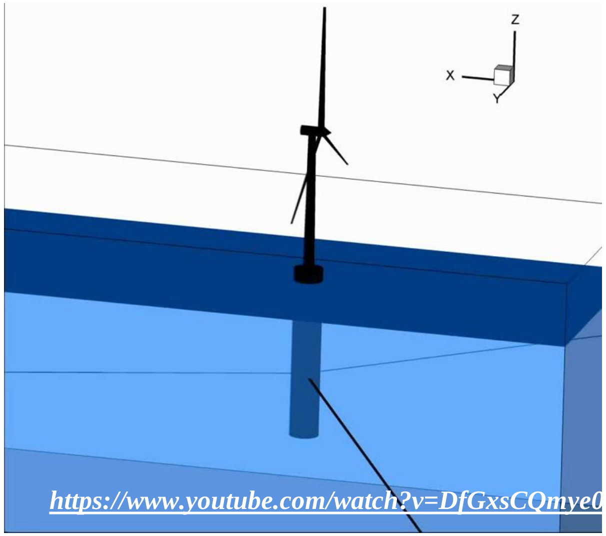


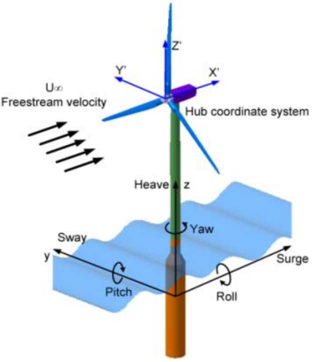
http://www.rya.org.uk/newsevents/news/Pages/Offshorewindenergymovingtofloatingwindturbines.aspx

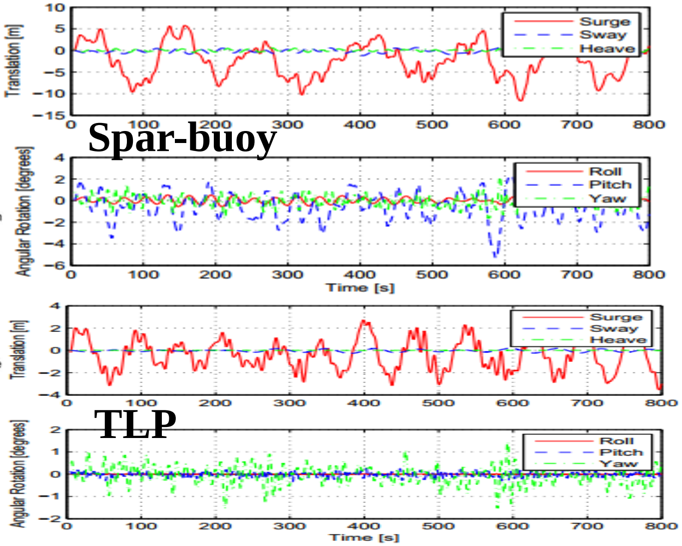
Aeromechanics of Offshore Wind Turbines





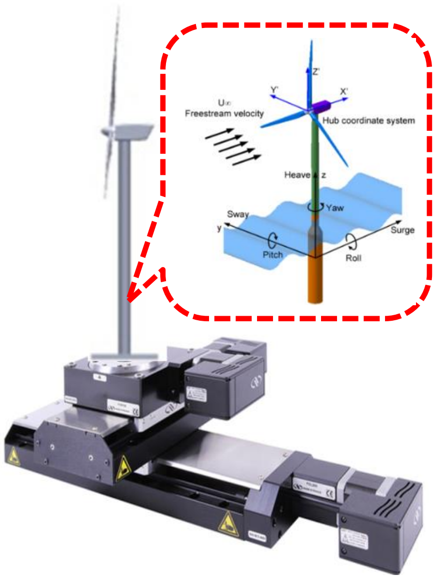




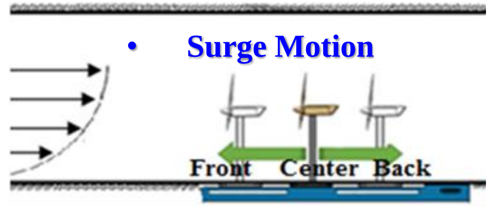


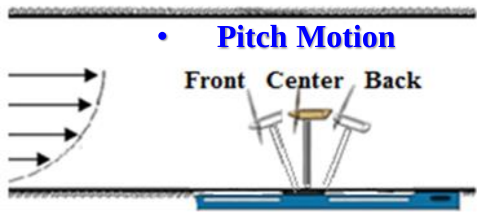
- *Sebastian & Lackner (2013), "Characterization of the unsteady aerodynamics of offshore floating wind turbines," Wind Energy, 16(3), pp. 339–352.*

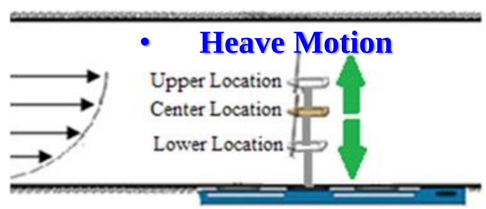
Simulated Base Motions of a Floating Wind Turbine

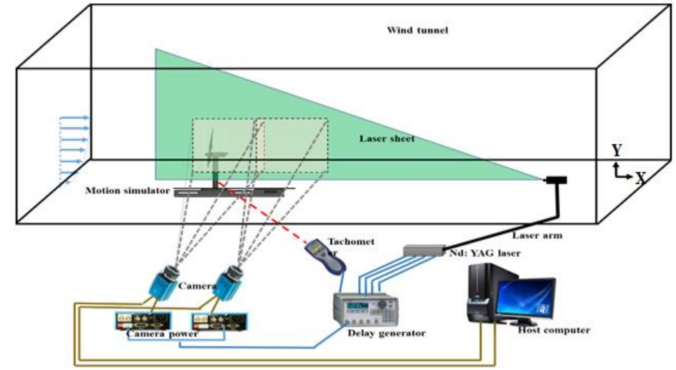


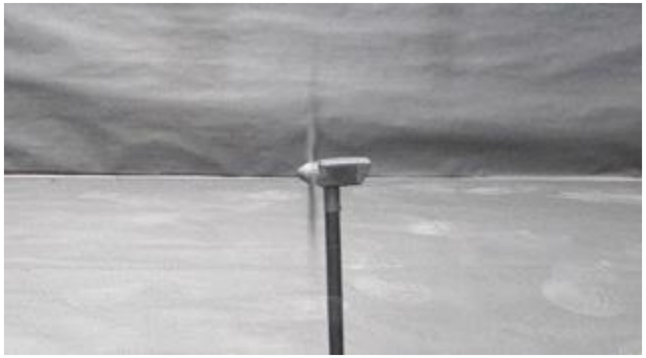
Test model turbine mounted on a translational stage to simulate wave-induced base motions of floating offshore wing turbine











- *Combined motion*

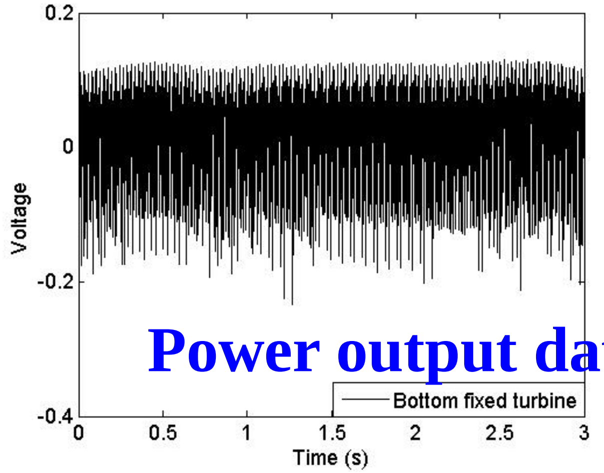
- *Surge motion*

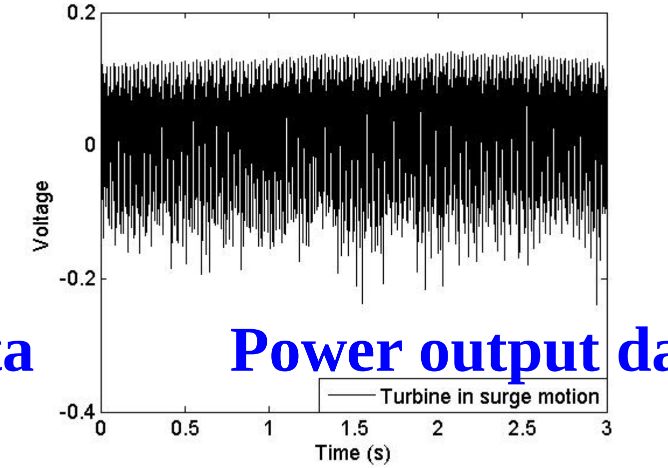
- *Pitch motion*

- *Heave motion*

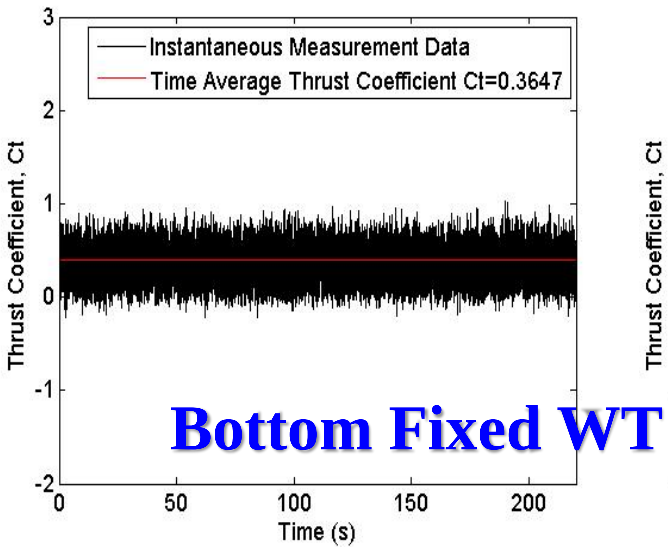
Bottom Fixed WT vs. the WT in Surge Motion

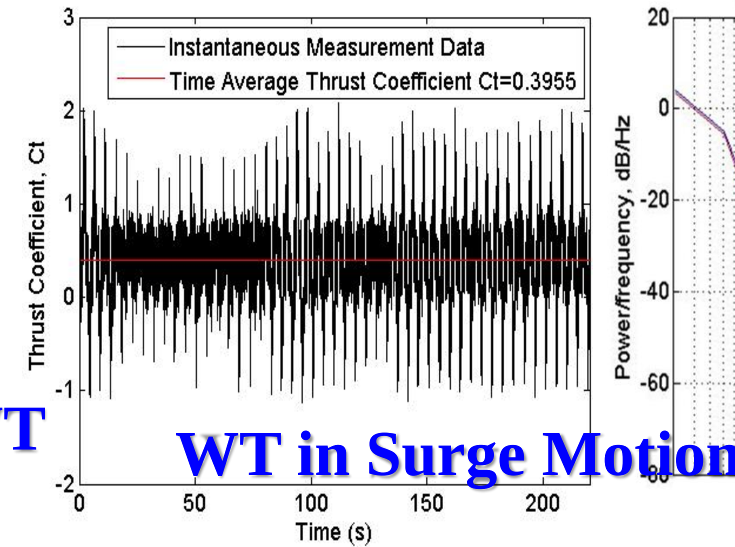
- *Surge motion*

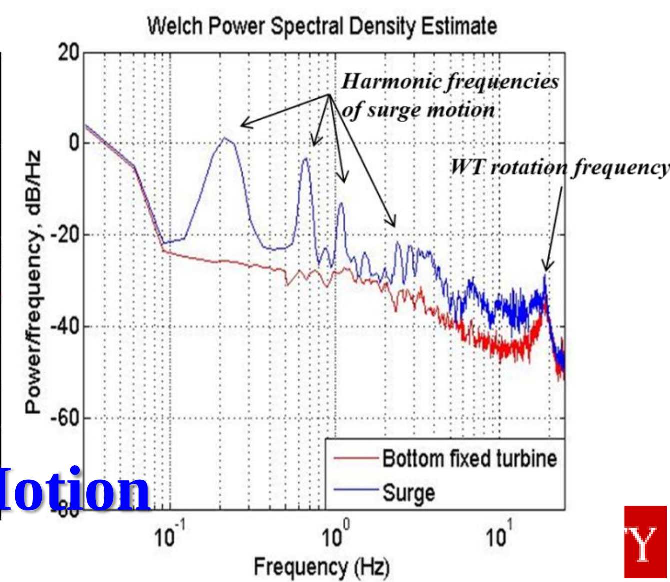




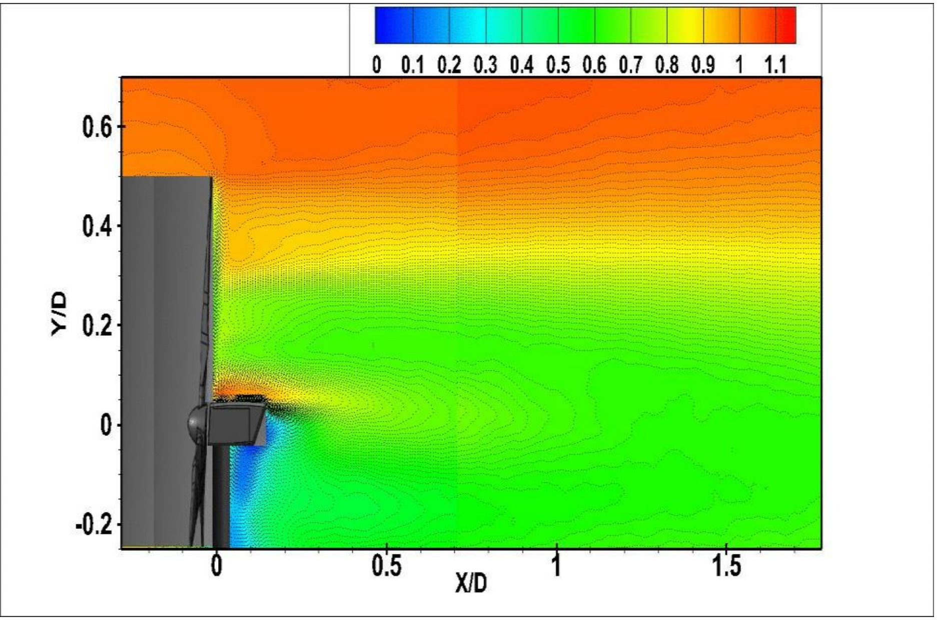
	Bottom fixed turbine	*Surge motion*
Thrust coefficient: C_T	*0.36*	*0.40*
R.M.S. value : σ_{CT}	*0.14*	*0.42*

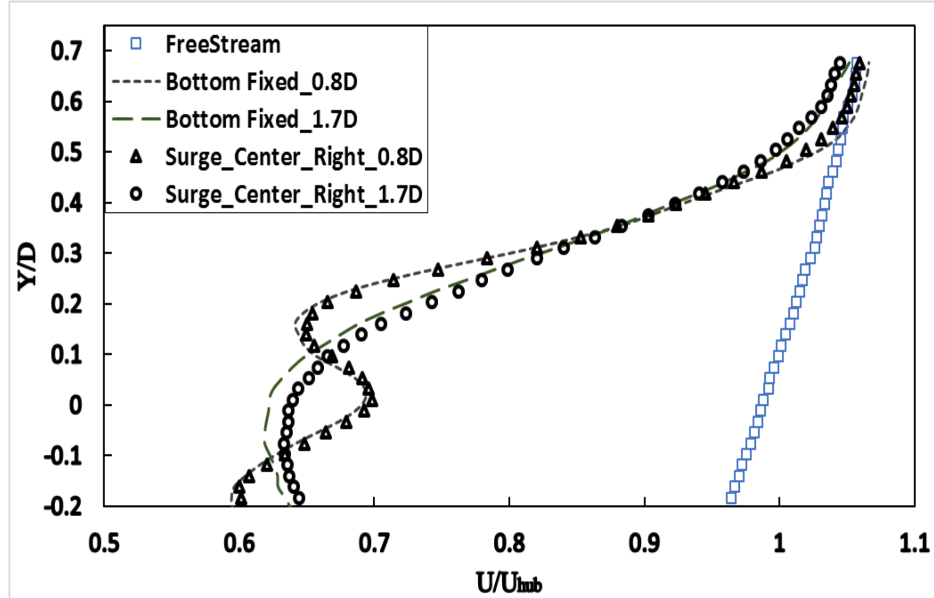


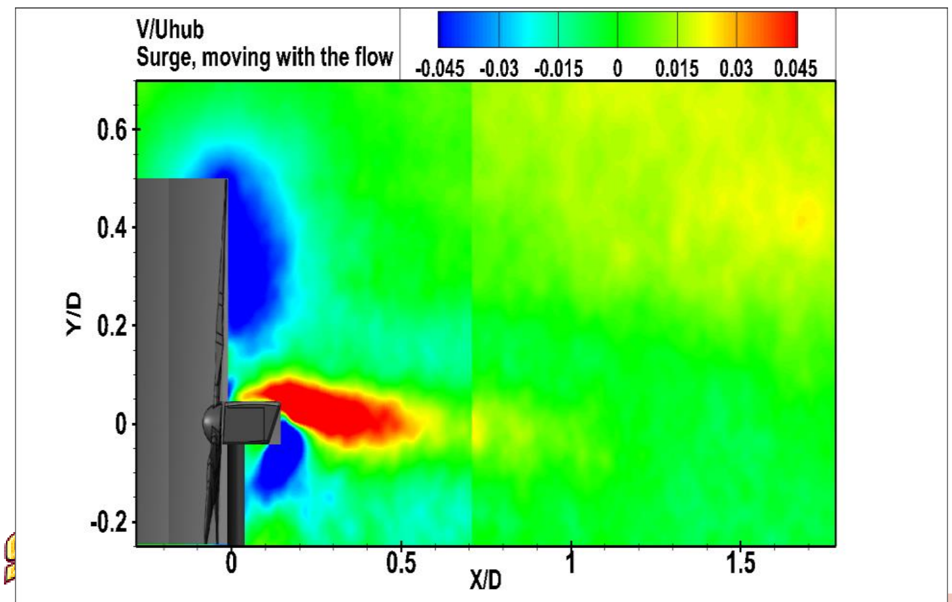


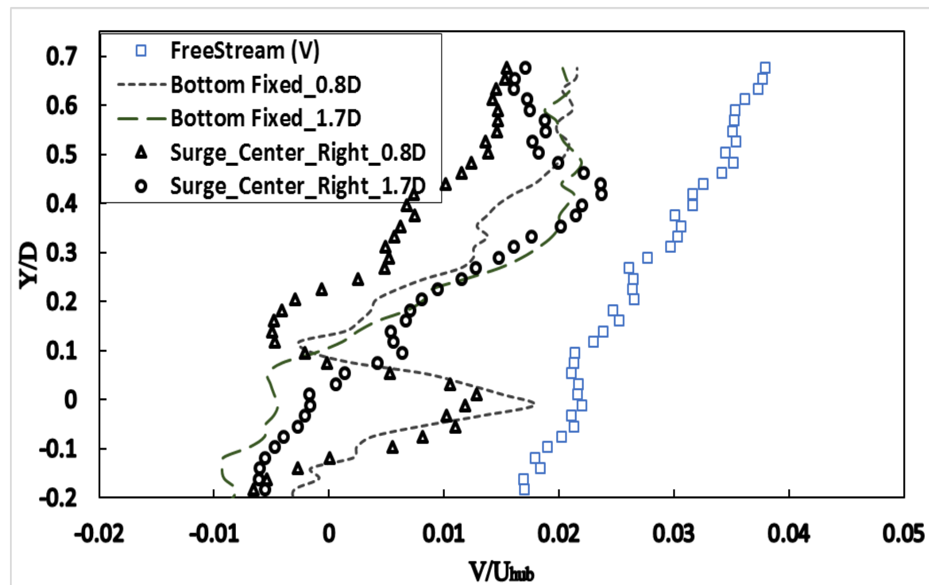


Effects of Surge Motion on the Wake Characteristics



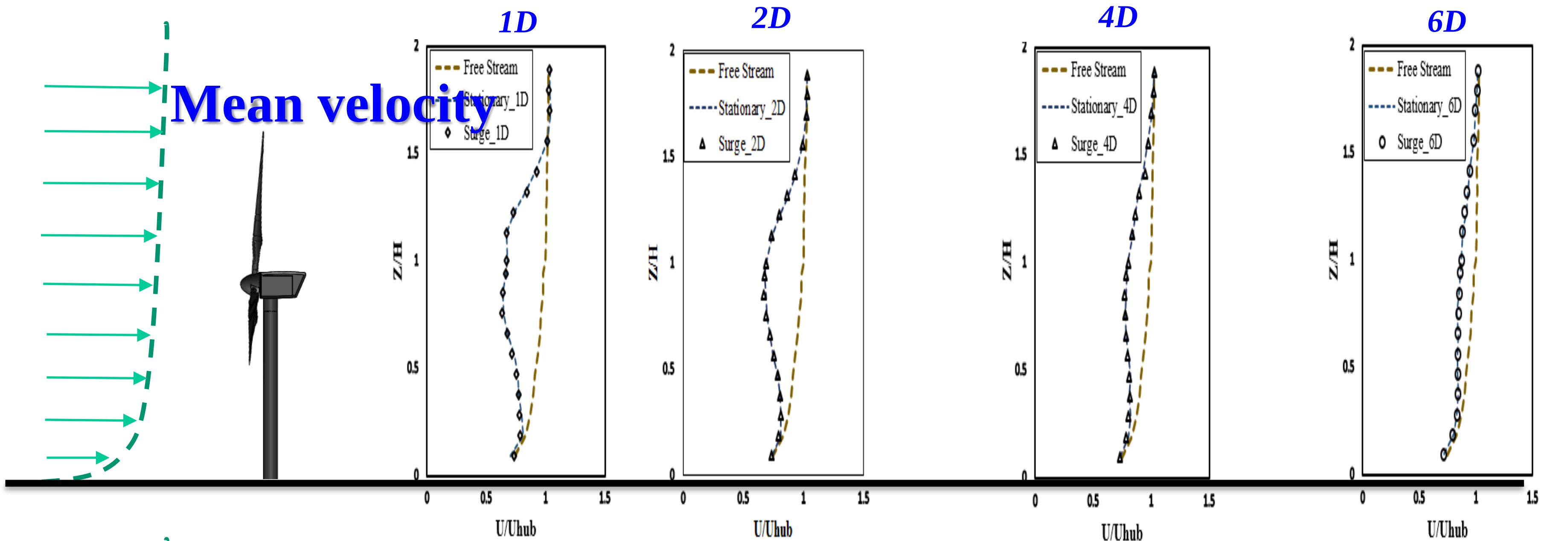






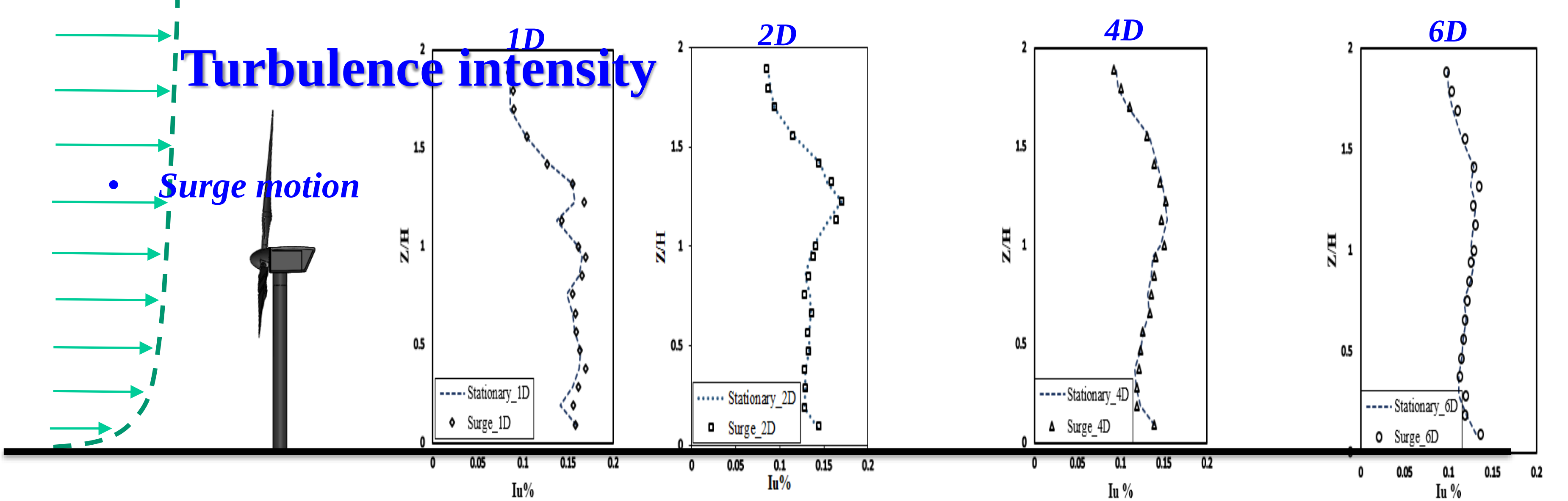
Wake Characteristics of the Wind Turbine in Surge Motion

Mean velocity

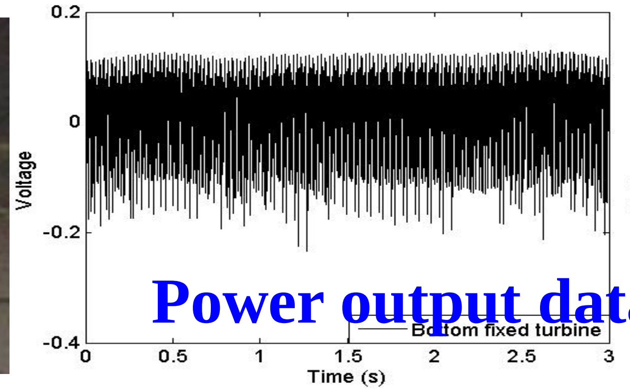


Turbulence intensity

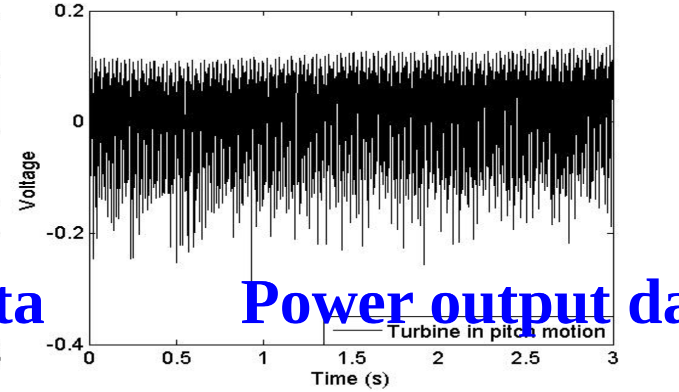
- *Surge motion*



Power Outputs of the Bottom Fixed WT vs. the WT in Pitch Motion



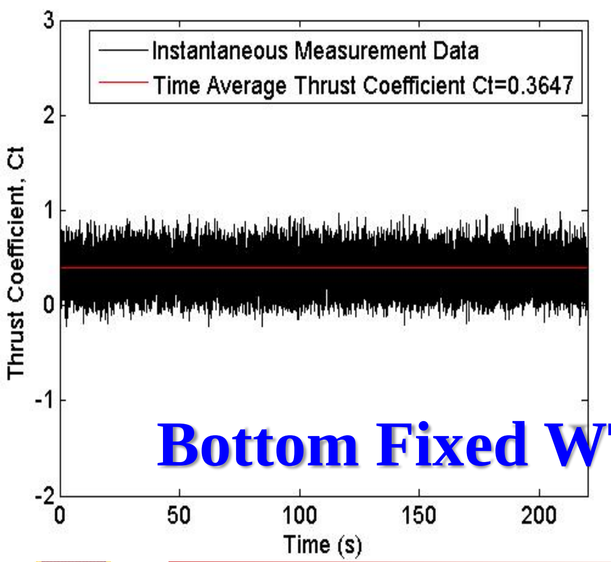
Power output data



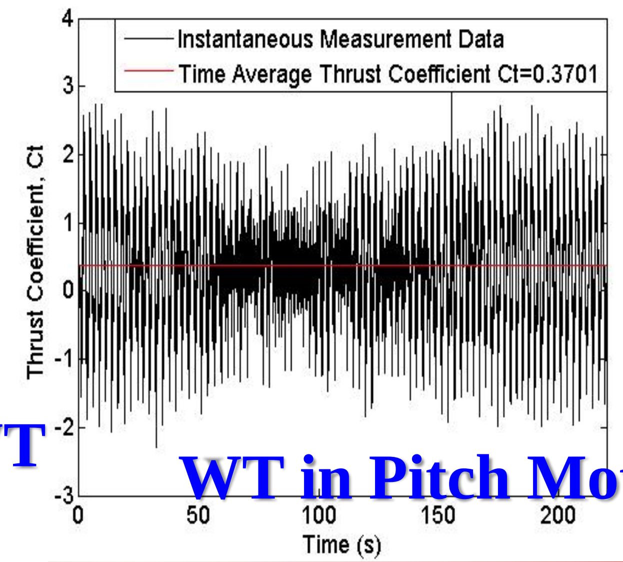
Power output da

- *Pitch motion*

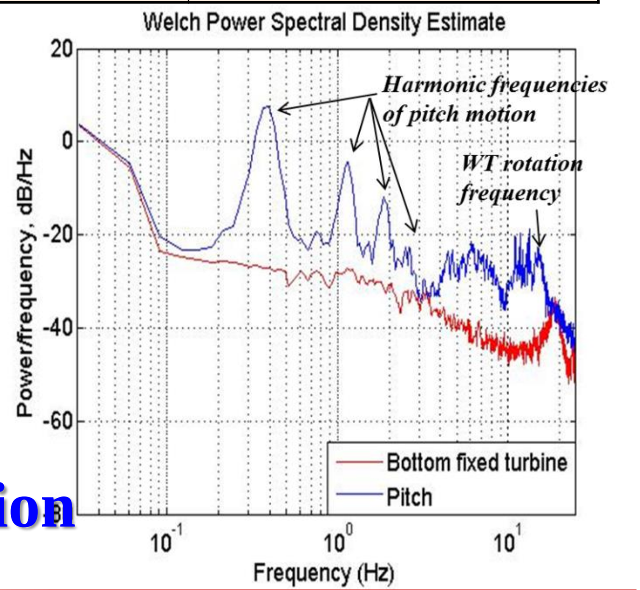
	Bottom fixed turbine	*Pitch motion*
Thrust coefficient: C_T	*0.36*	*0.37*
R.M.S. value : σ_{CT}	*0.14*	*0.77*



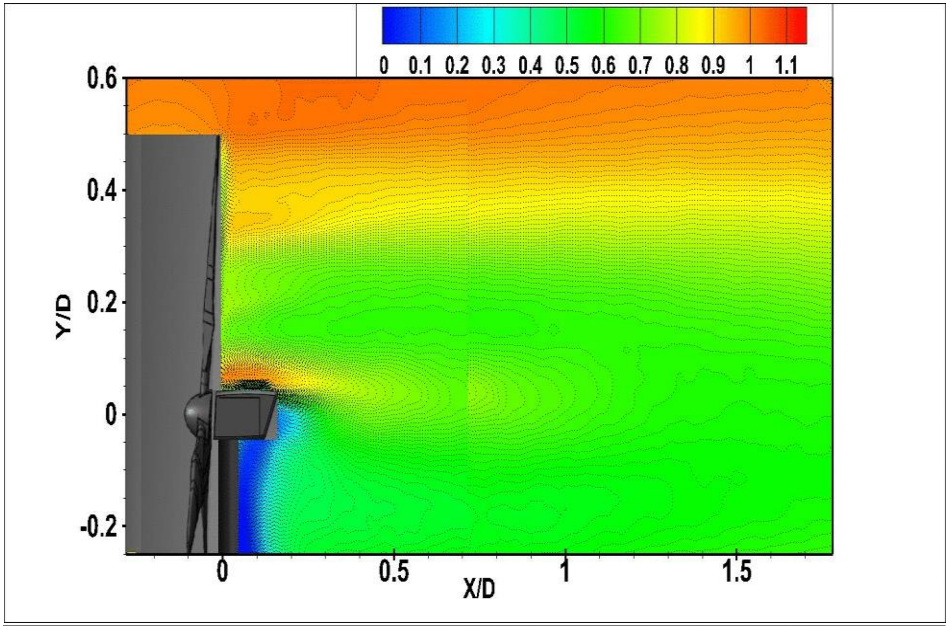
Bottom Fixed WT

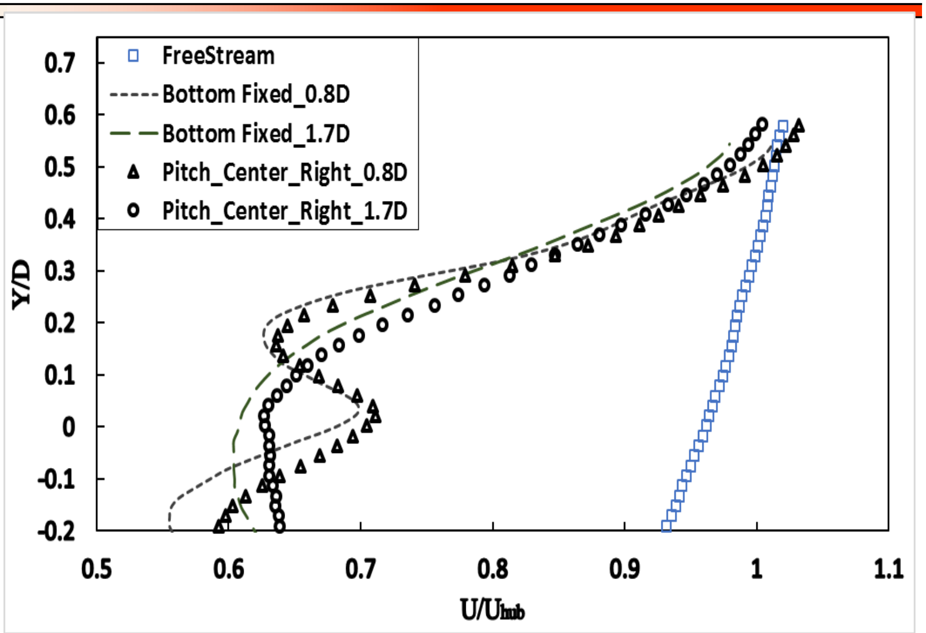


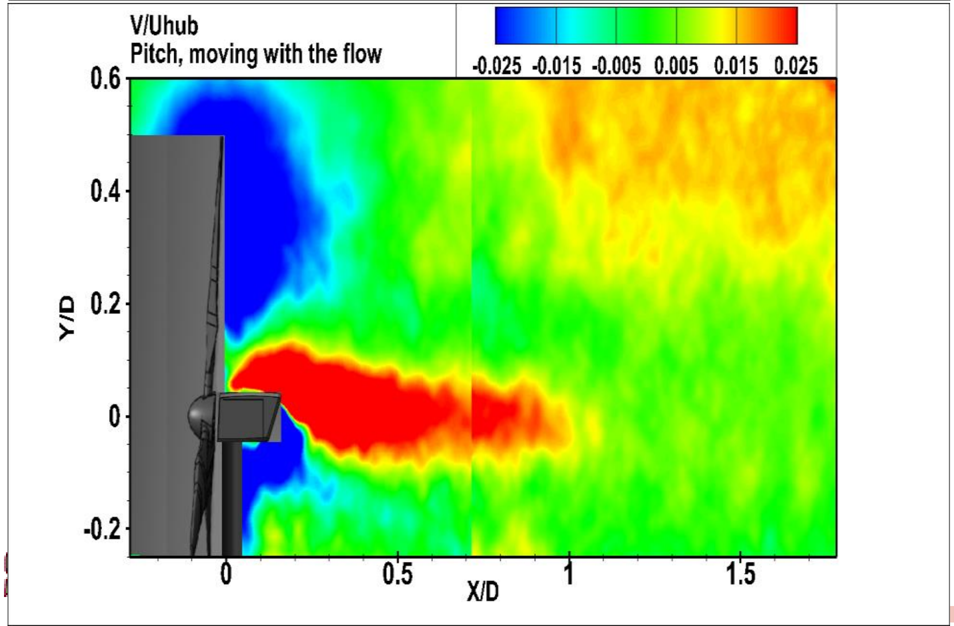
WT in Pitch Motion

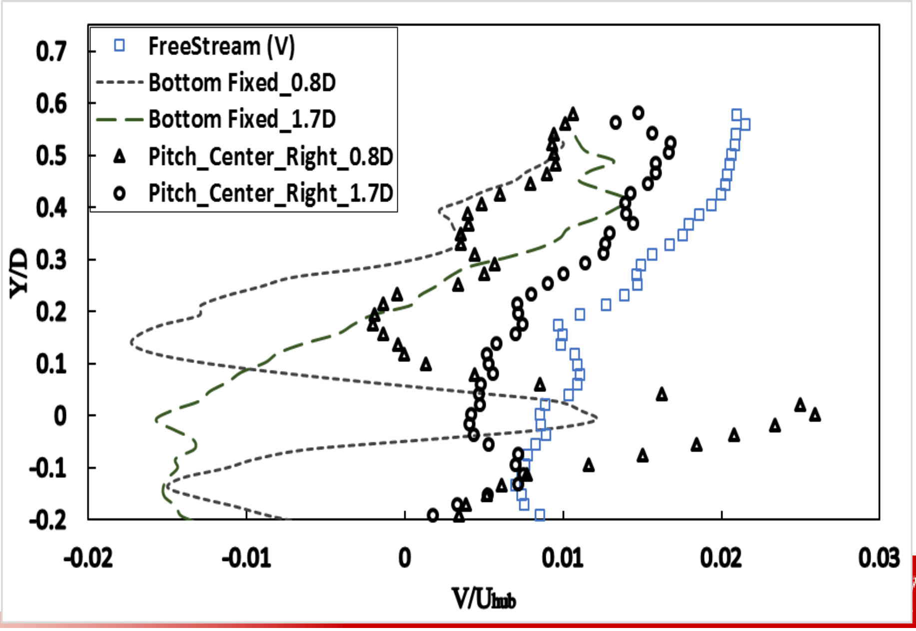


Effects of Pitch Motion on the Wake Characteristics

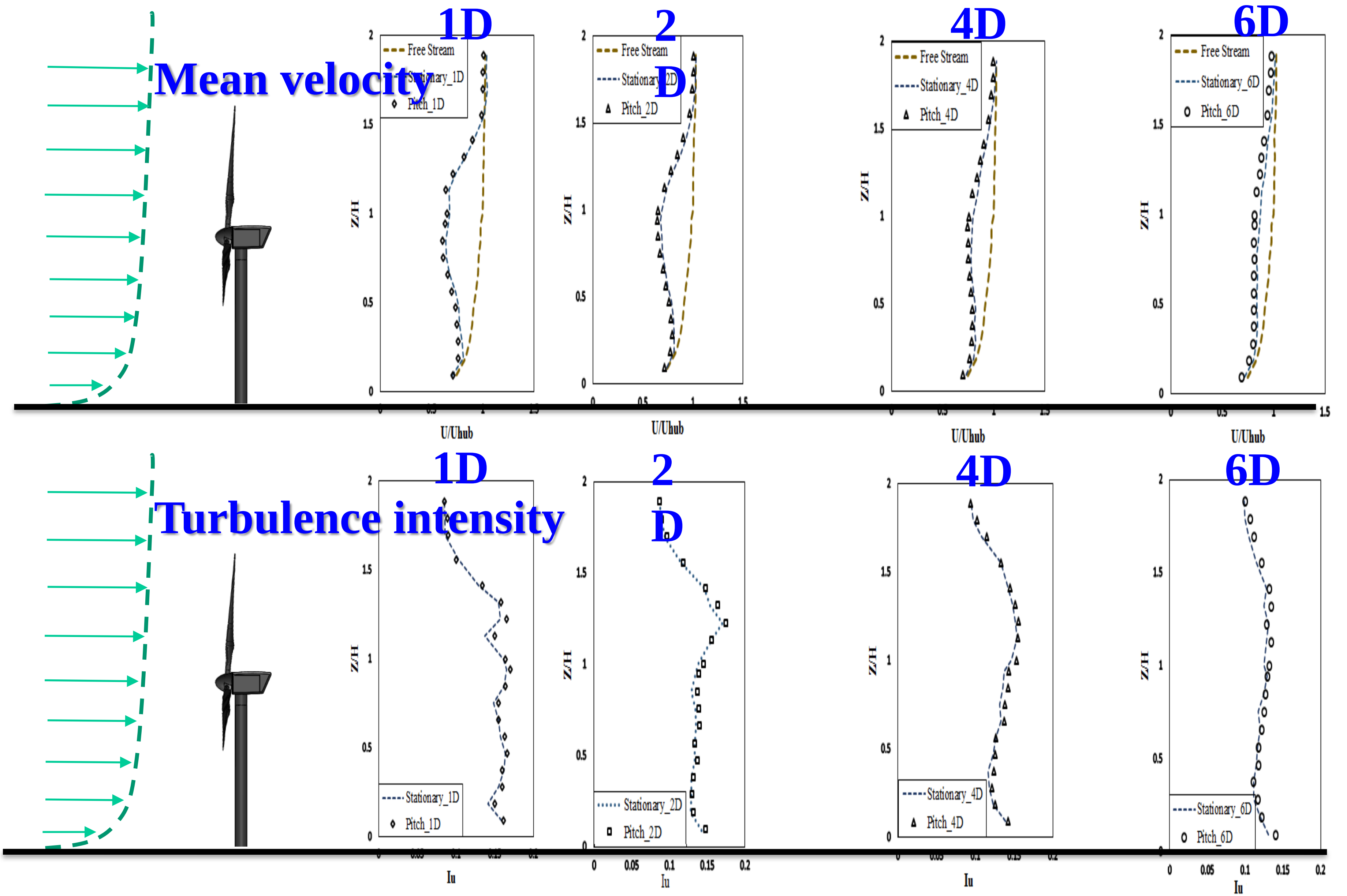






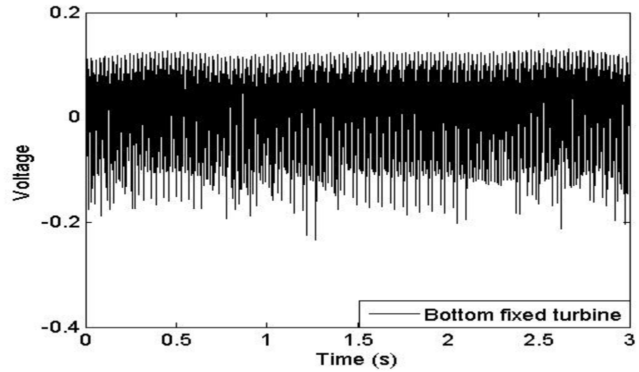


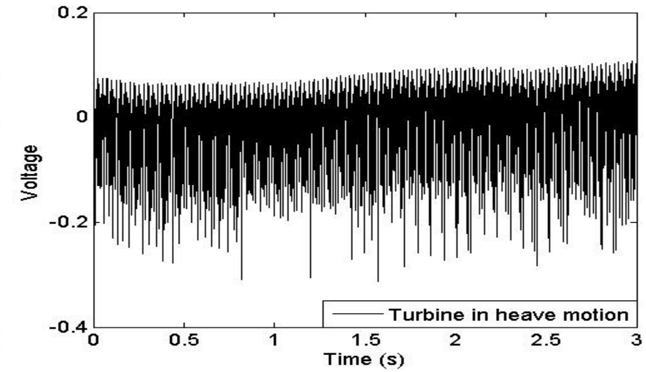
Wake Characteristics of the Wind Turbine in Pitch Motion



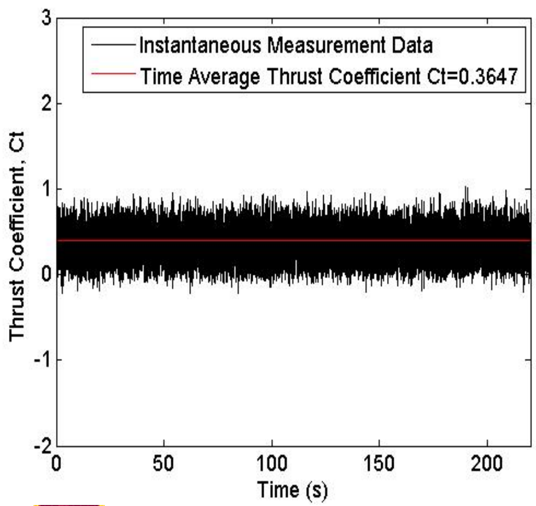
Bottom Fixed WT vs. the WT in Heave Motion

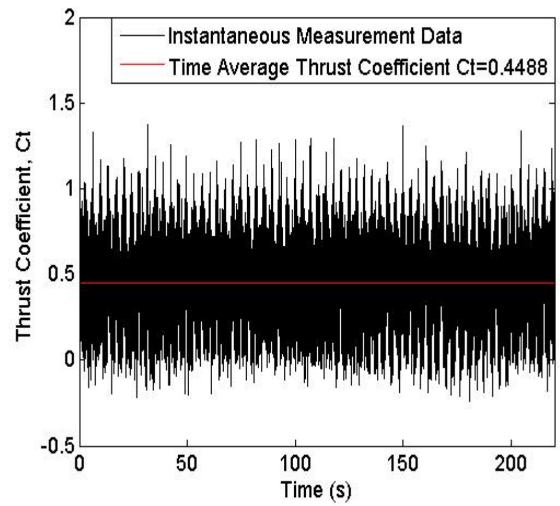
- *Heave motion*

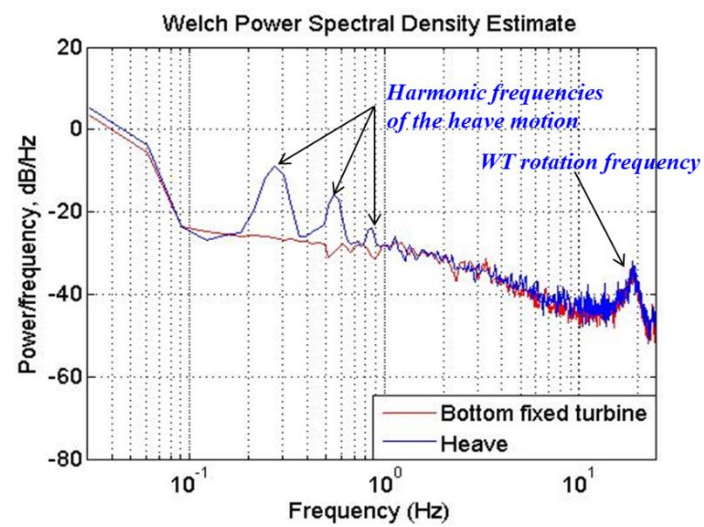




	Bottom fixed turbine	Heave motion
Thrust coefficient: C_T	0.36	0.48
R.M.S. value : σ_{CT}	0.14	0.96

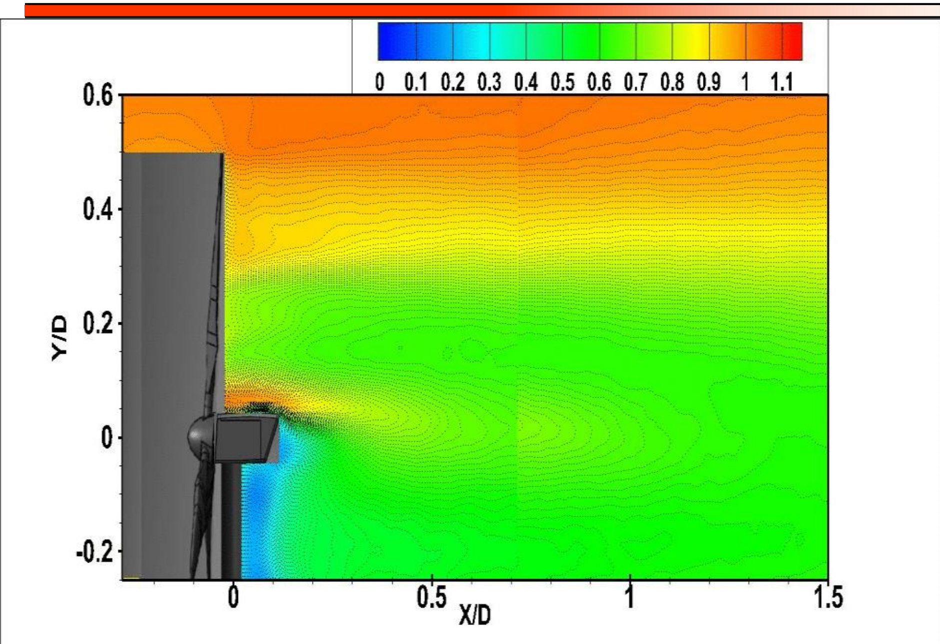


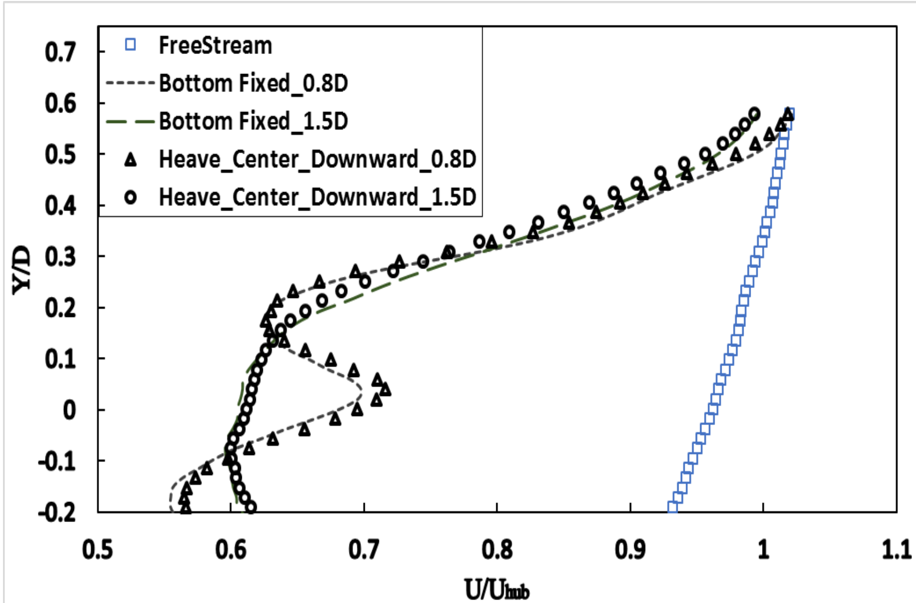


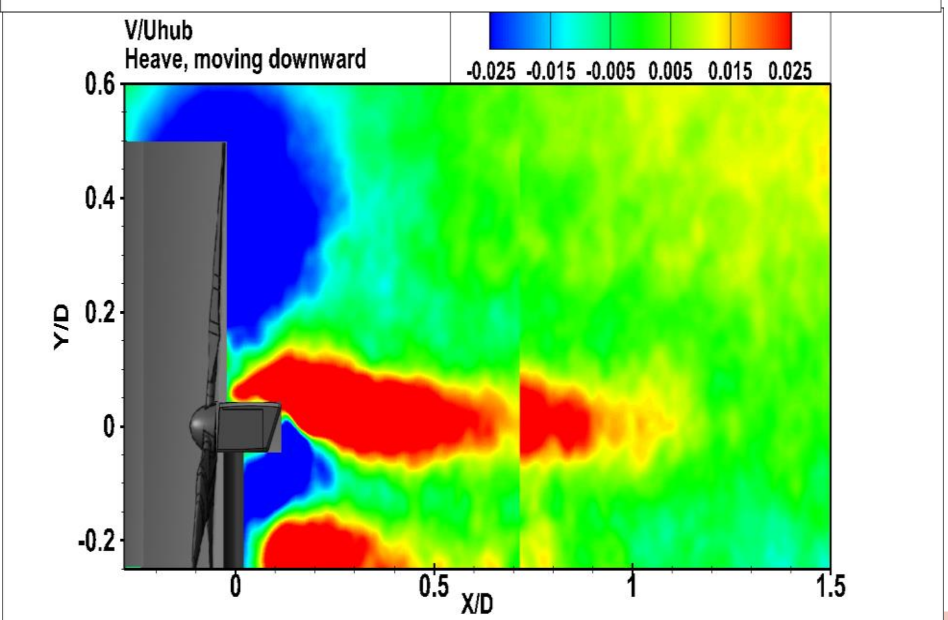


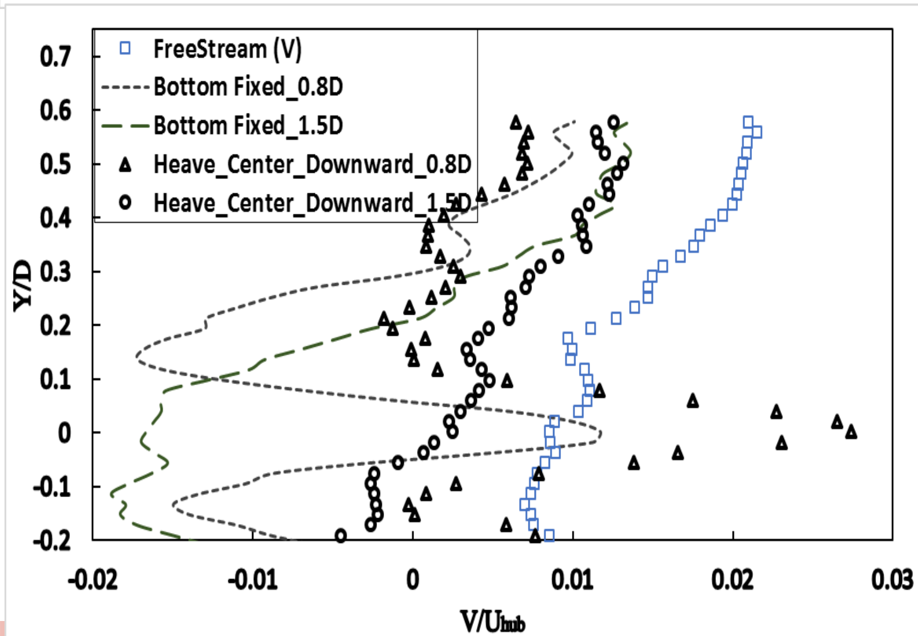
Bottom Fixed WT **WT in Heave Motion**

Effects of Heave Motion on the Wake Characteristics

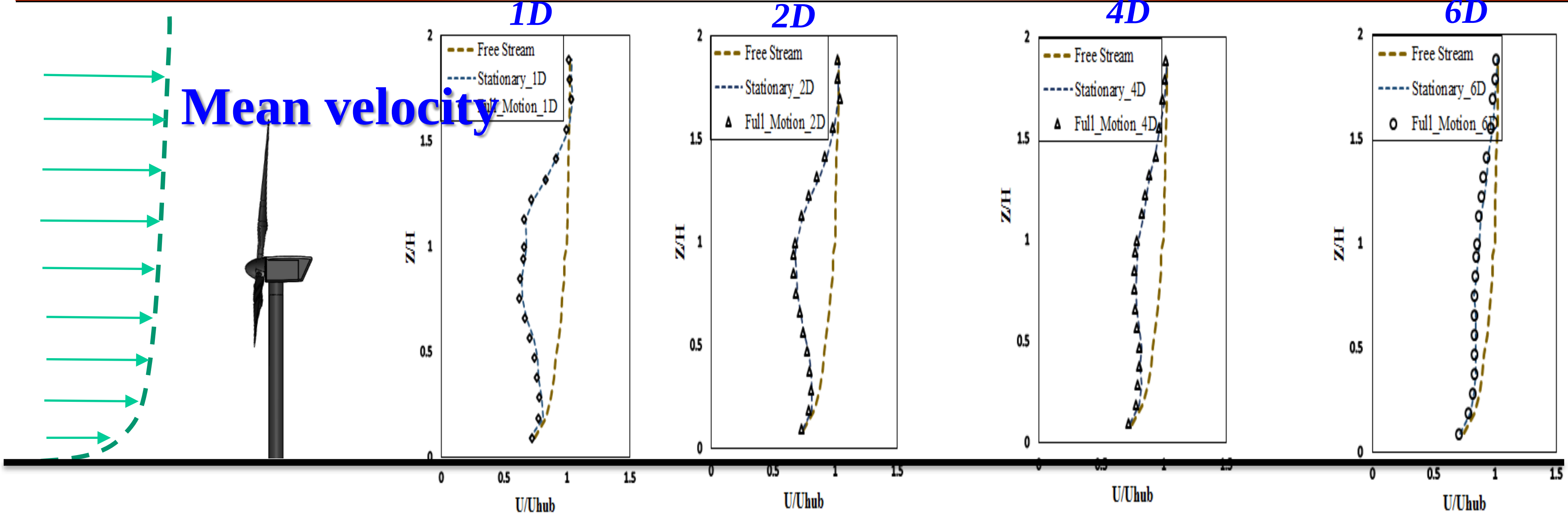


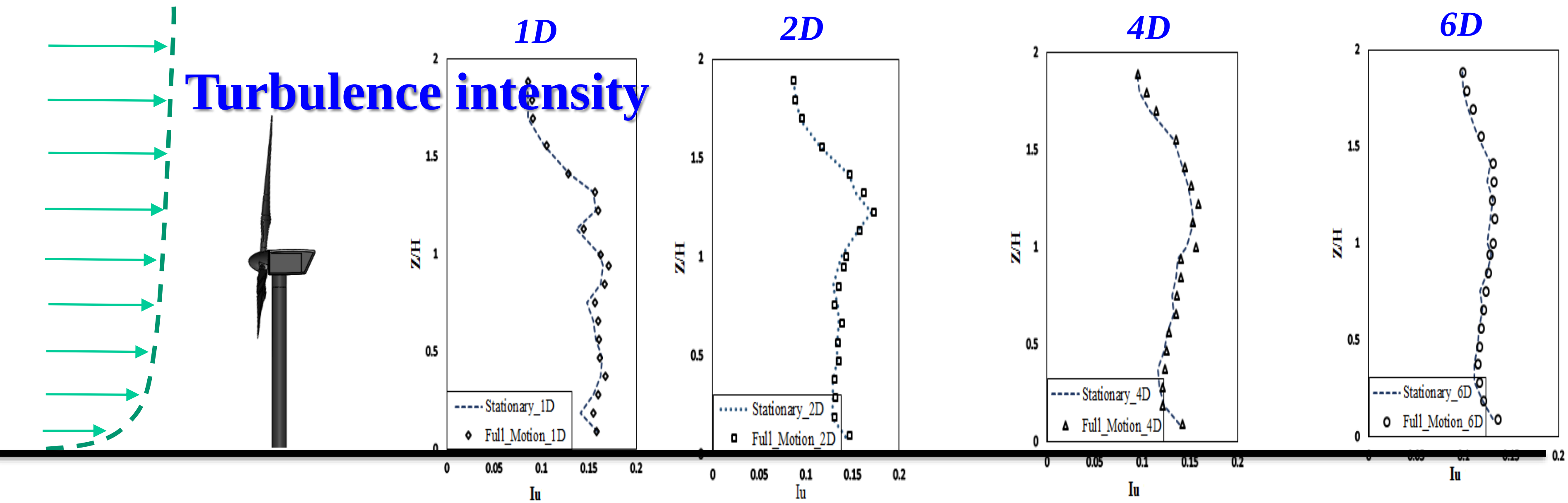




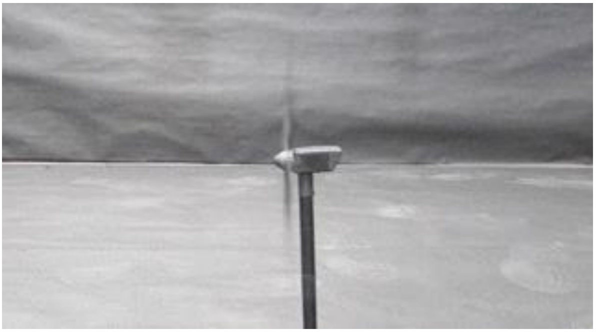


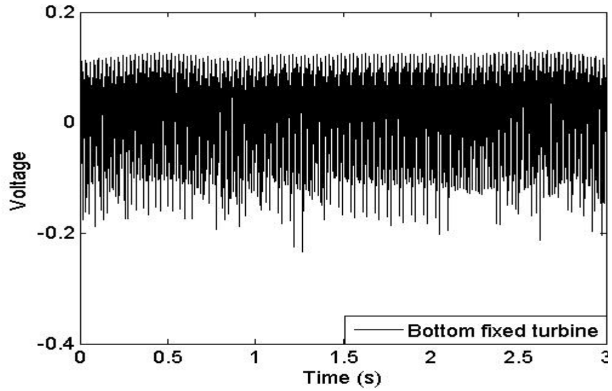
r Wake Characteristics of the Wind Turbine in Combined Motion

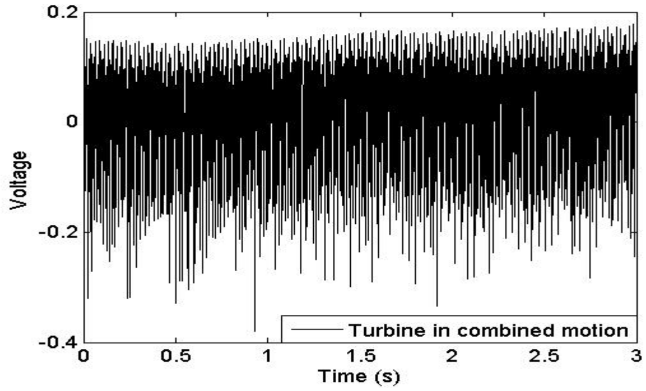




Bottom Fixed WT vs. the WT in Combined Motion

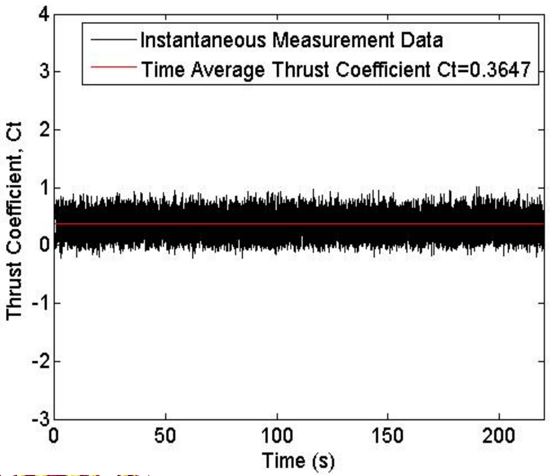


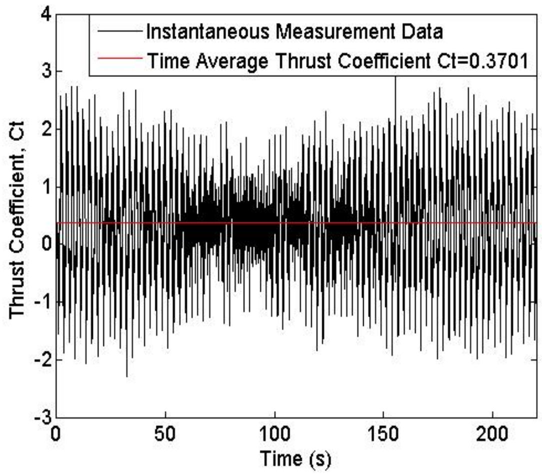


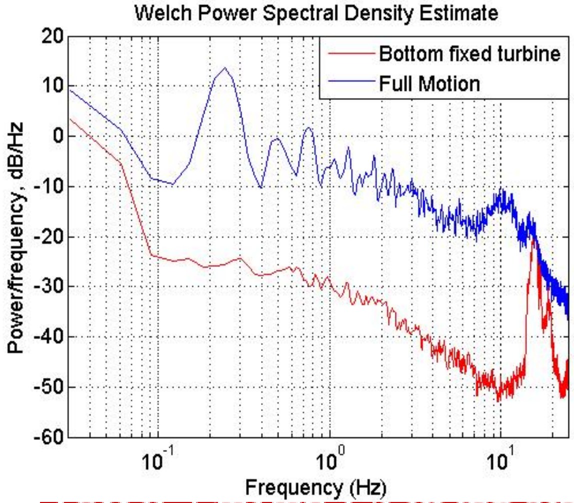


- *Combined motion*

	Base Fixed Wind Turbine	Turbine in combined motions
Mean loading	0.36	0.47
Fatigue loading	0.14	0.96







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Hu Lab's Summer BBQ Party on 08/24/2015

Thank You Very Much for Your Time!

Questions?