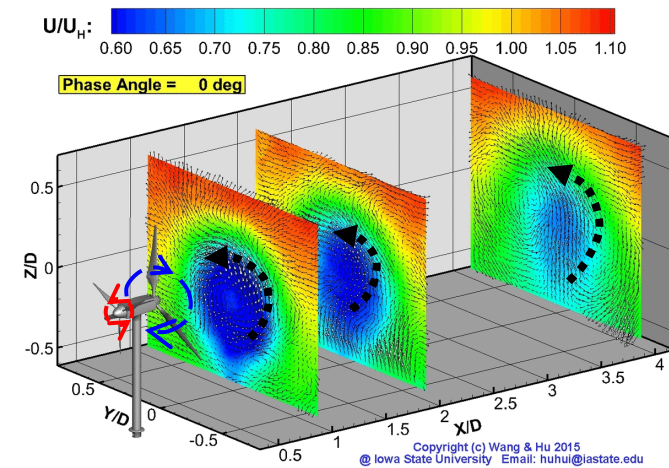
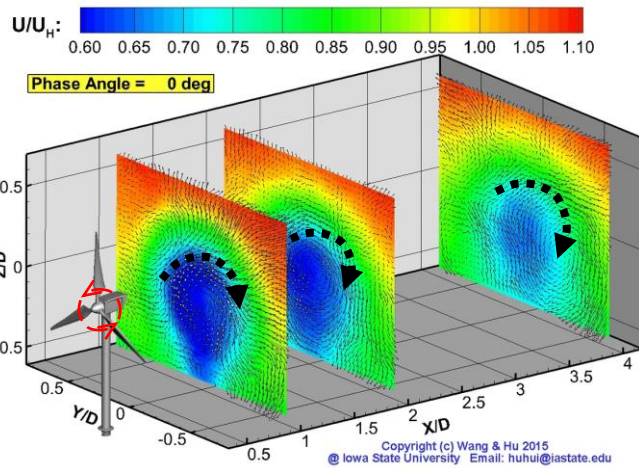




Overview of the Research on Wind Turbine Aeromechanics and Wind Farm Optimization at Iowa State University

Dr. Hui HU

Professor and Director

Advanced Flow Diagnostics and Experimental Aerodynamics Laboratory

Department of Aerospace Engineering, Iowa State University

2251 Howe Hall, Ames, IA 50011-2271

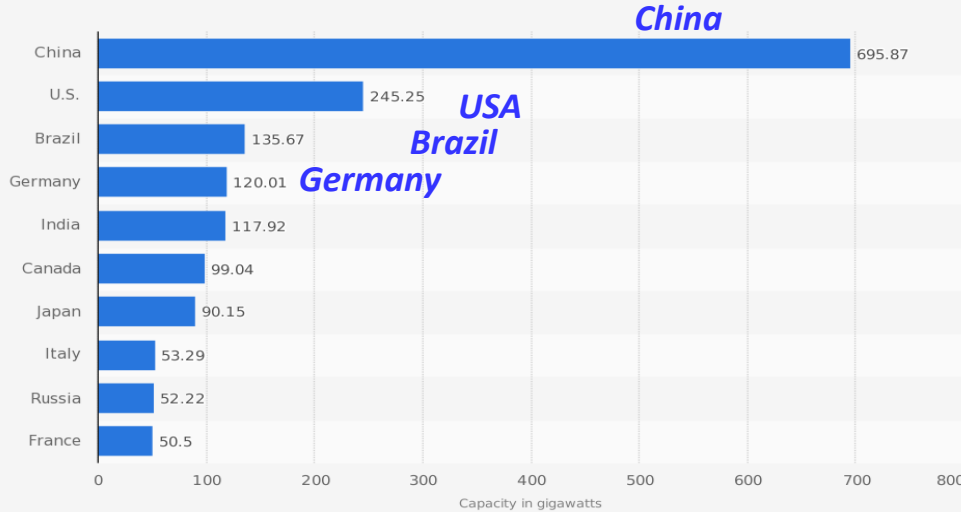
Email: huhui@iastate.edu



IOWA STATE UNIVERSITY

Wind Energy Production and Wind Turbine Installations in USA

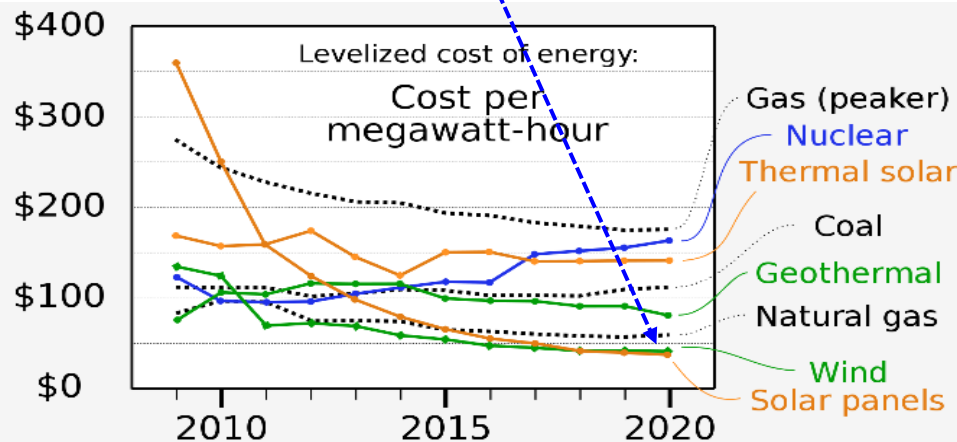
Leading countries in installed renewable energy capacity worldwide in 2018 (in gigawatts)



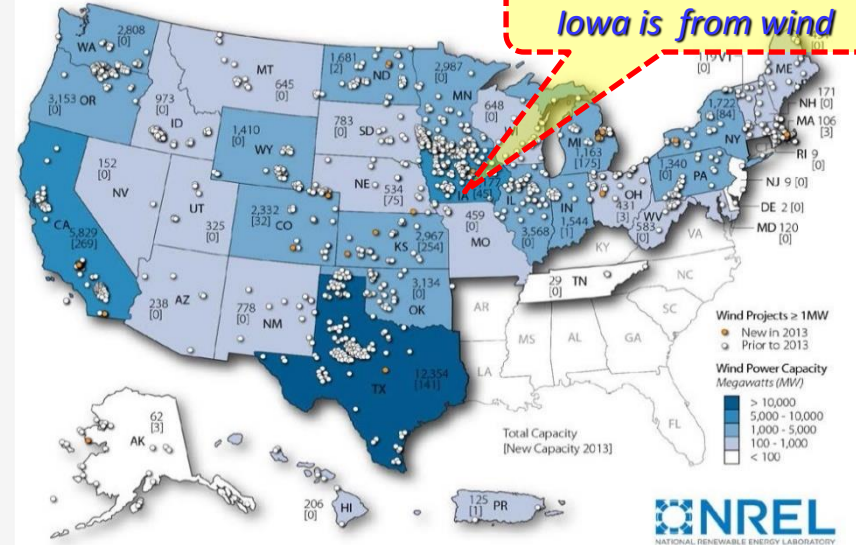
Source: IRENA, © Statista 2019

Additional Information: Worldwide; IRENA, 2018

- Wind power is the cheapest power



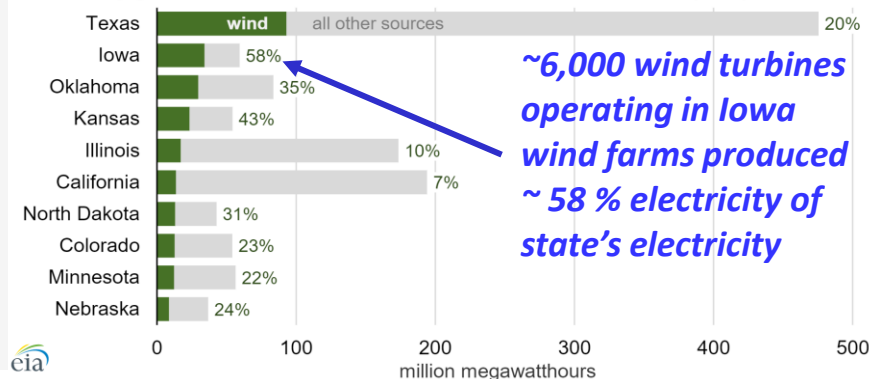
Wind farm sites in USA



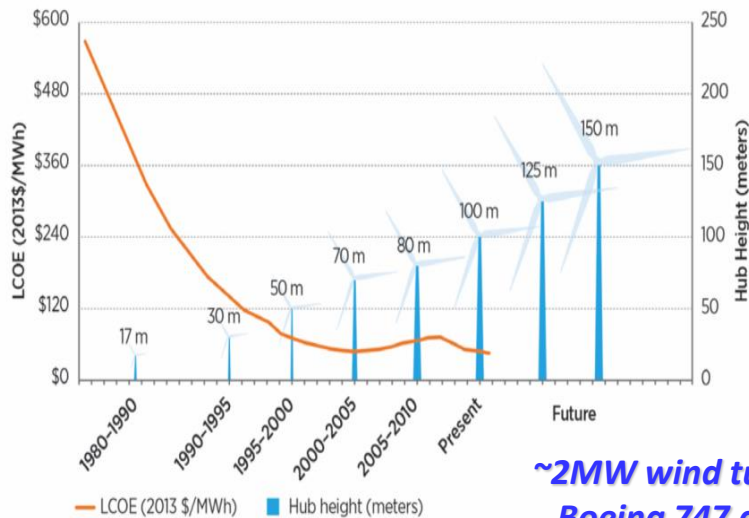
- US Department of Energy sets up the targets of **20% of US electricity from wind energy by 2030; and 35% by 2050 (~8.4% by 2020).**

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

Let electricity generation from wind and other sources in selected states (2020)

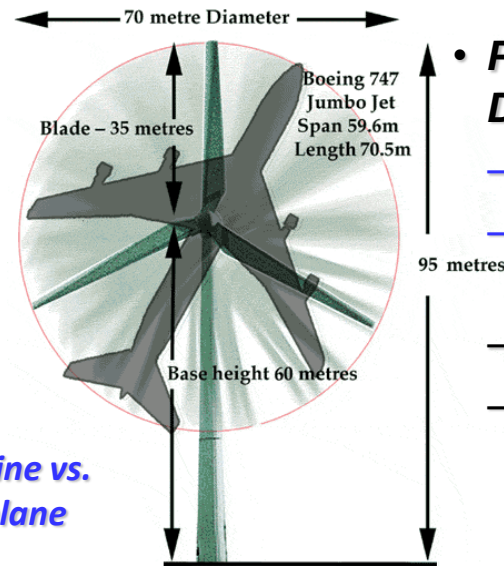


Technical Challenges Related to Wind Energy



**~2MW wind turbine vs.
Boeing 747 airplane**

Note: LCOE is estimated in good to excellent wind resource sites (typically those with average wind speeds of 7.5 m/s or higher), excluding the federal PTC. Hub heights reflect typical turbine model size for the time period.



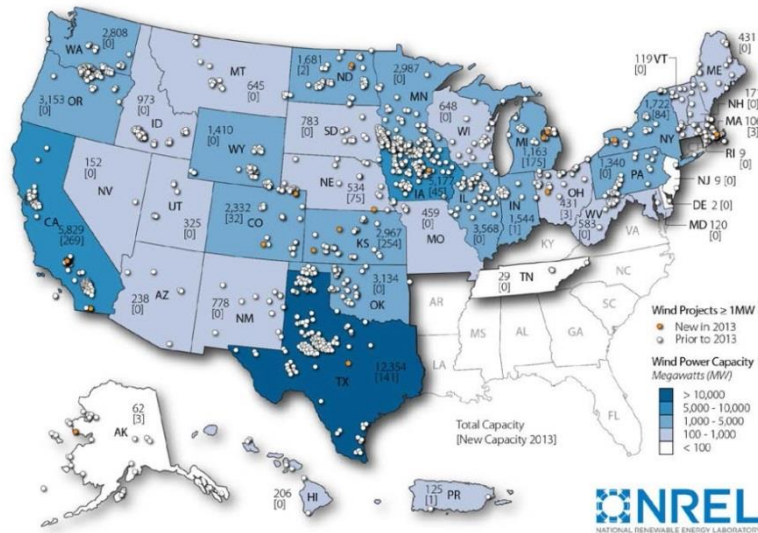
• **Four focus areas identified in DoE Wind Energy Report:**

- **Turbine Dynamics**
- **Micro-siting and Array Effects**
- **Mesoscale Processes**
- **Climate Effects**

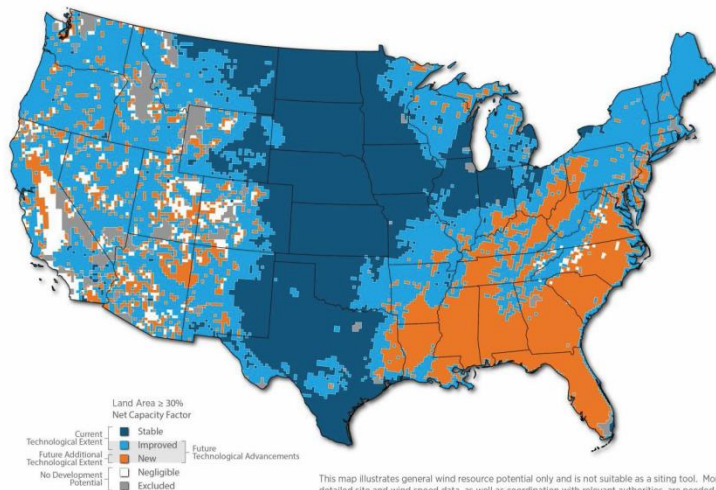


- **Schreck S, Lundquist J, and Shaw W (2008) U.S. Department of energy workshop report: research needs for wind resource characterization. Technical Report, NREL/TP-500-43521**

Wind Resources Map in USA



Current wind farms with 80m turbine hub height



This map illustrates general wind resource potential only and is not suitable as a siting tool. More detailed site and wind speed data, as well as coordination with relevant authorities, are needed to thoroughly evaluate appropriate wind energy development at any given location.
 Data sources: AWS Truepower, National Renewable Energy Laboratory

This map was produced by the
 National Renewable Energy Laboratory
 for the US Department of Energy
 March 2014

NREL
 NATIONAL RENEWABLE ENERGY LABORATORY

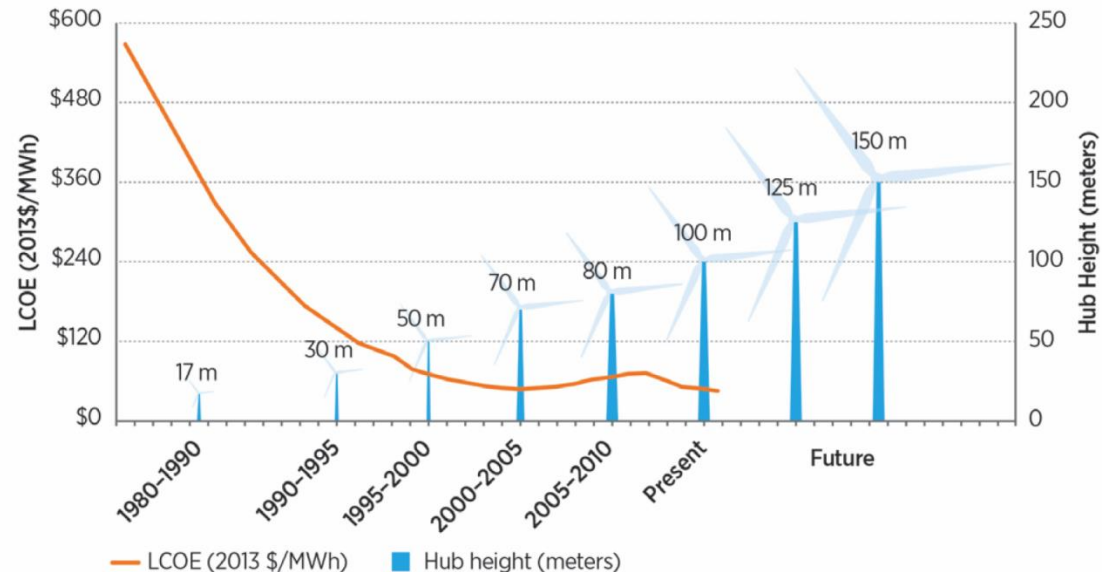
AWS Truepower

Wind resources with 140m hub height

Table 4-2. Land Area Relative to 2008 Technology

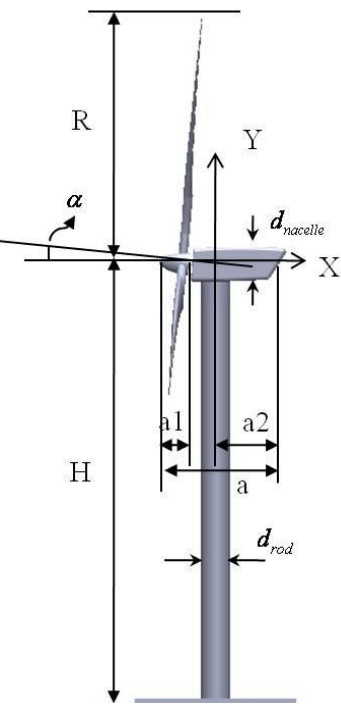
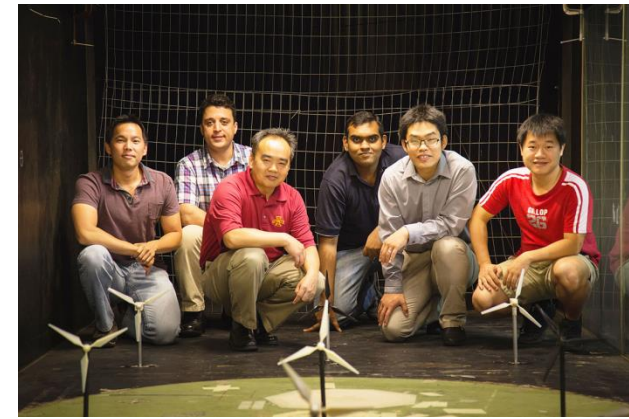
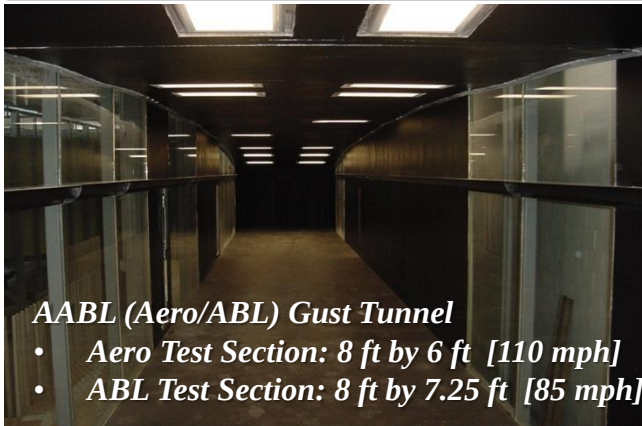
Hub Height	2008 Turbine Technology (km ²)	Current (2013) Turbine Technology (km ²)	% Change from 2008 @ 80 m	Near-Future Turbine Technology (km ²)	% Change from Current (2013) @ 80 m
80m	1,643,000	2,765,000	68%	3,518,000	27%
110m		3,420,000	108%	4,262,000	54%
140m		3,928,000	139%	4,629,000	67%

Sources: NREL Database, MAKE Consulting

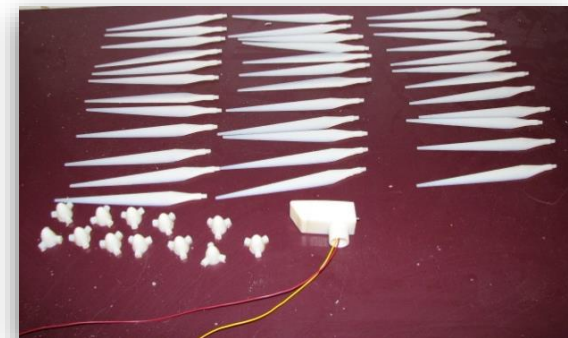
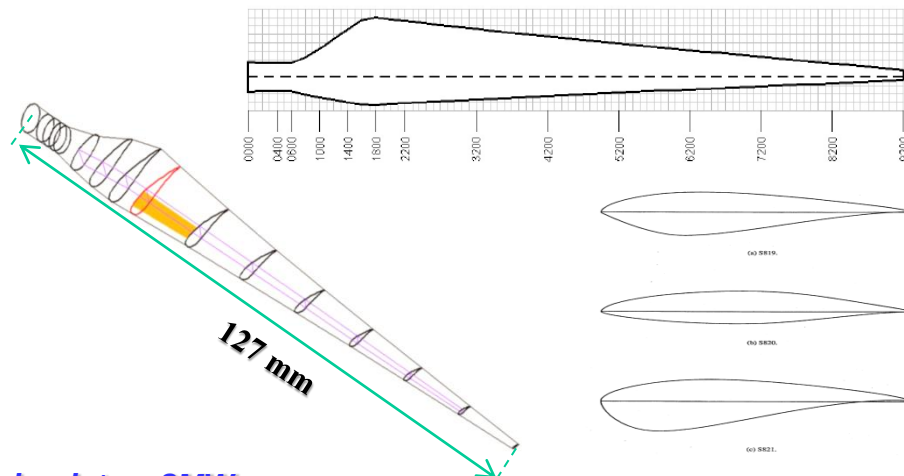


Note: LCOE is estimated in good to excellent wind resource sites (typically those with average wind speeds of 7.5 m/s or higher), excluding the federal PTC. Hub heights reflect typical turbine model size for the time period.

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	5°	78	15	50

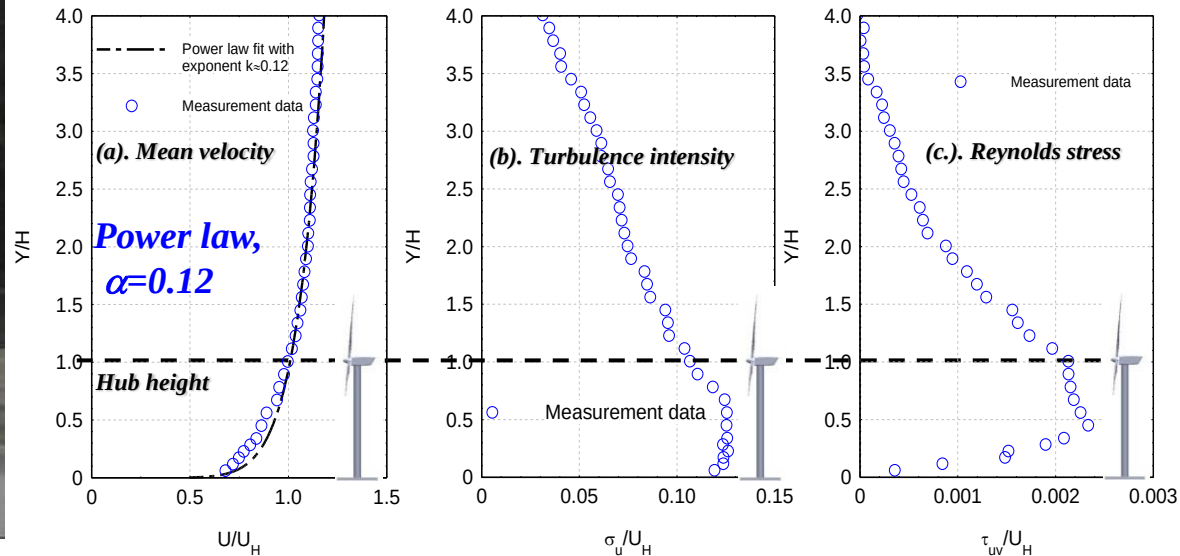


1:320 scaled model to simulate a 2MW wind turbine with 90m rotor blades

ERS-100 turbine blade design by TPI

IOWA STATE UNIVERSITY

Experimental Setup to Study Wind Turbine Aeromechanics

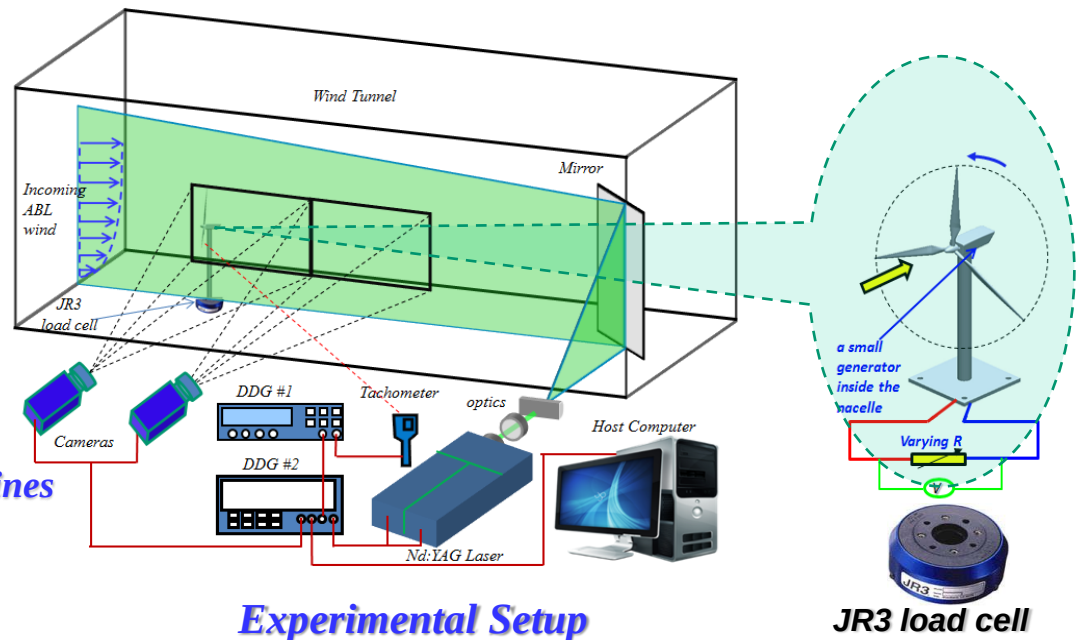


Test flow conditions:

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

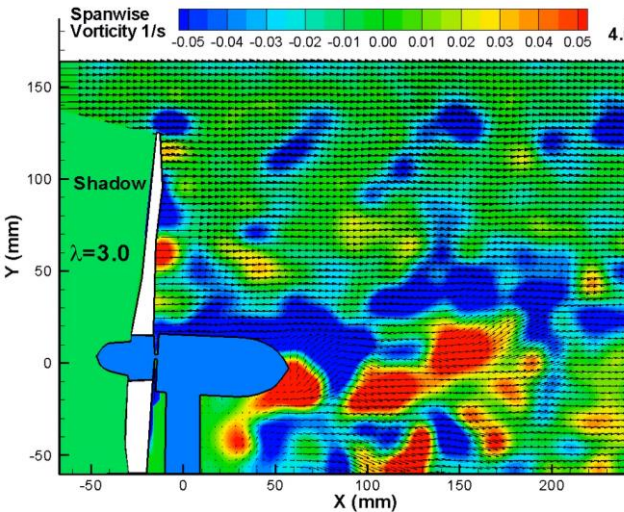
Measured parameters:

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

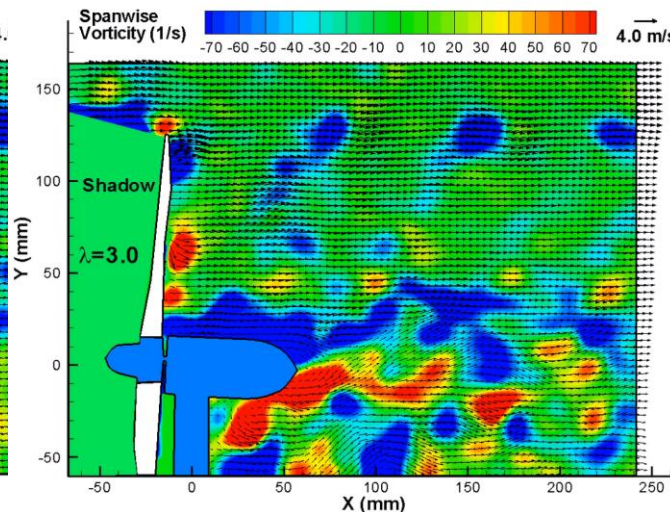


Experimental Setup

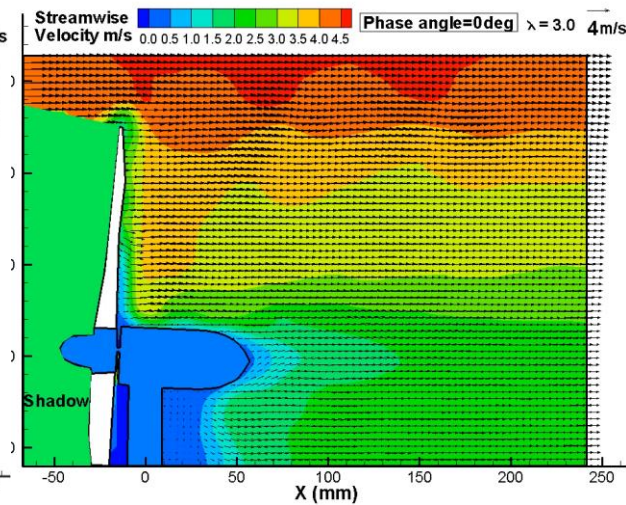
Near Wake Measurement Results at Tip-Speed Ratio, $\lambda=3.0$



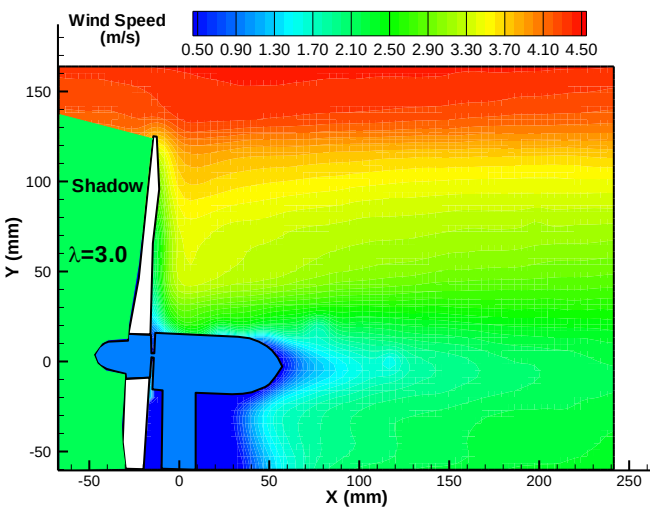
Instantaneous PIV results



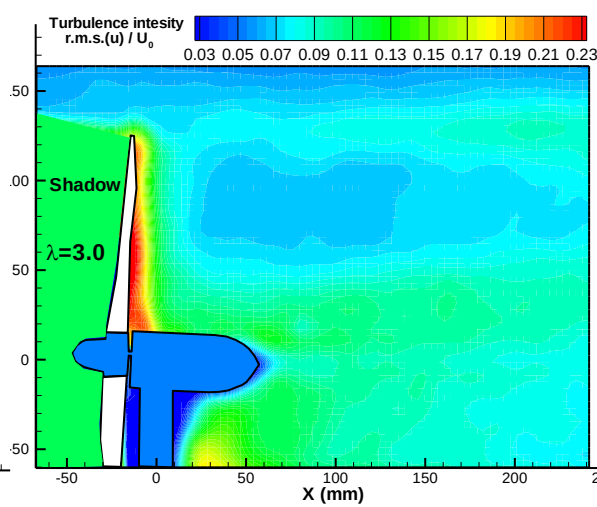
Phase-locked PIV measurement results



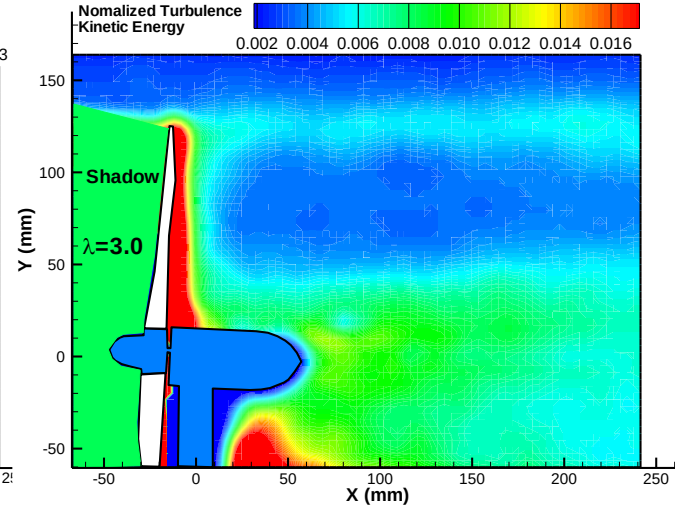
Phase-locked PIV measurement results



Time-averaged velocity distribution

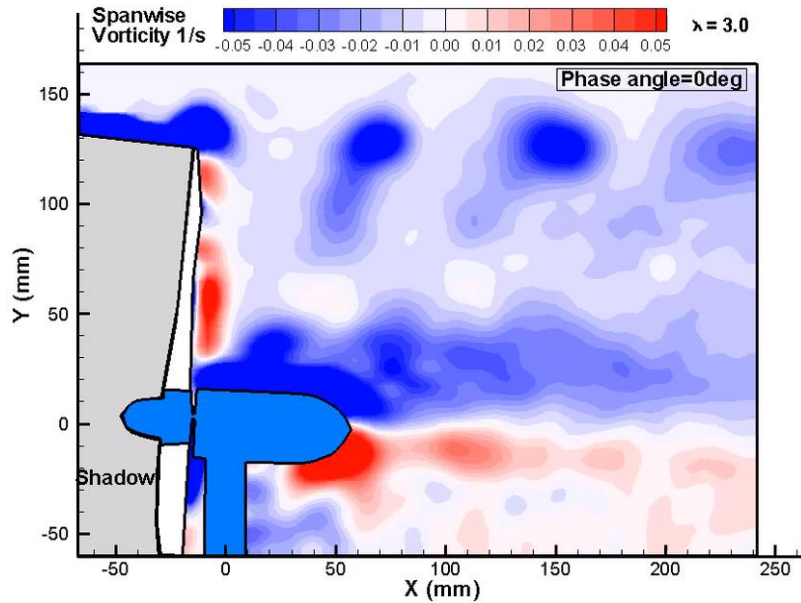


Turbulence intensity r.m.s (u)/ U_0

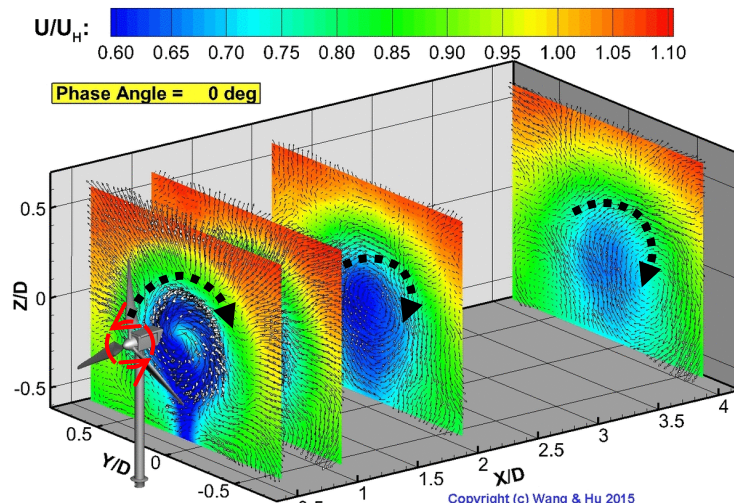
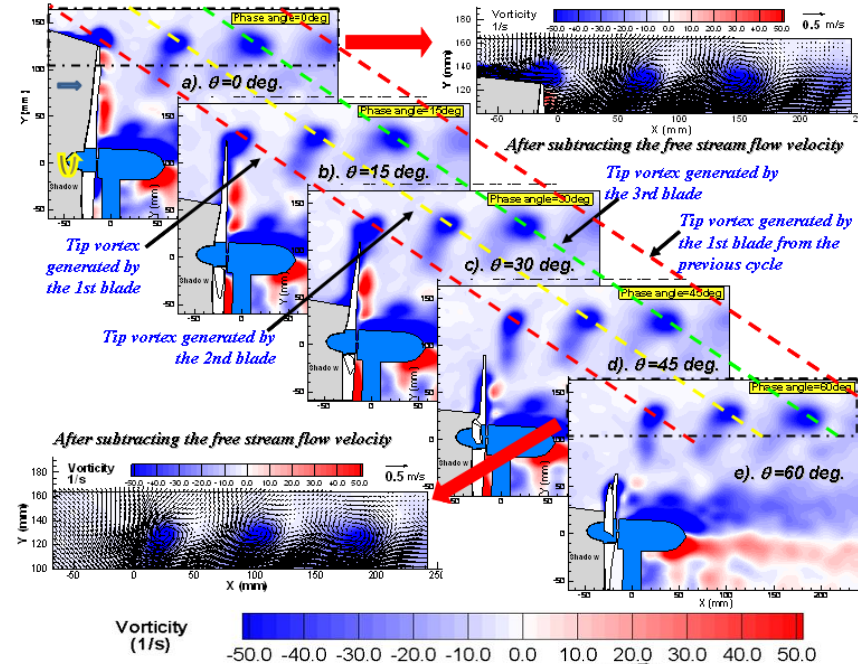


Normalized Turbulence $\frac{(u'u' + v'v')}{2U_0^2}$
kinetic energy

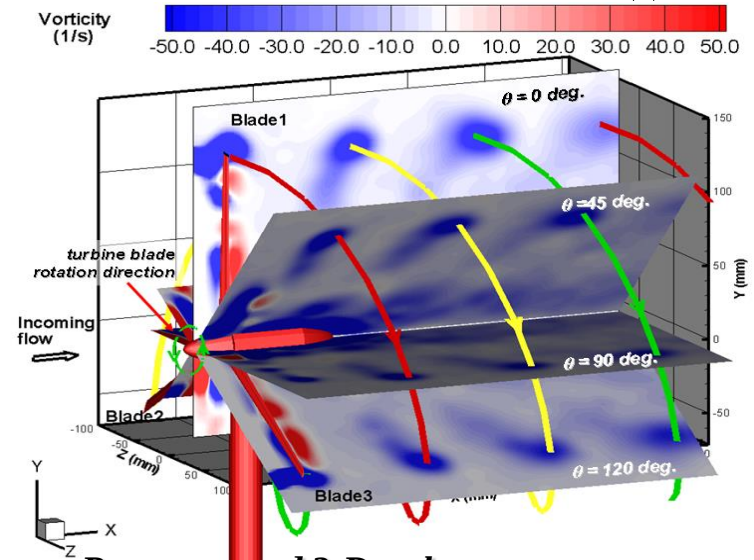
Phase-Locked PIV Measurement Results at Tip-Speed Ratio, $\lambda=3.0$



wake vortex structures at different phase angles

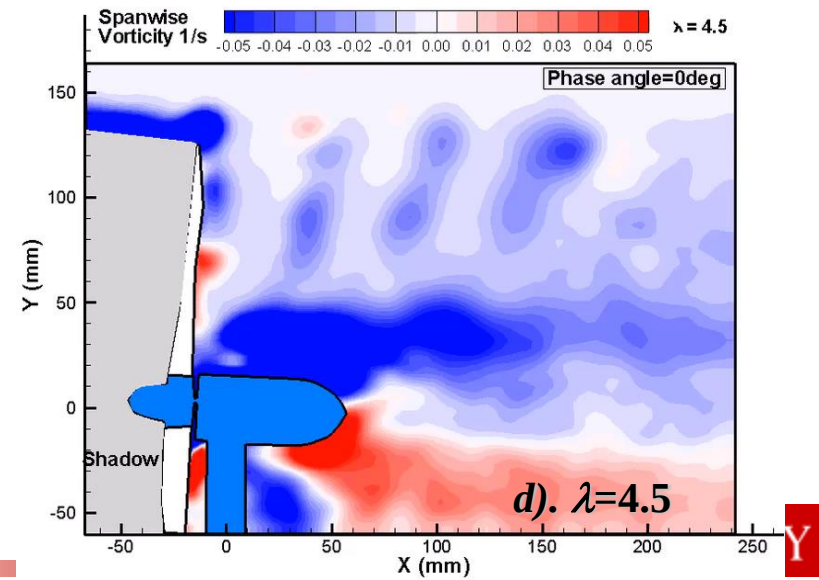
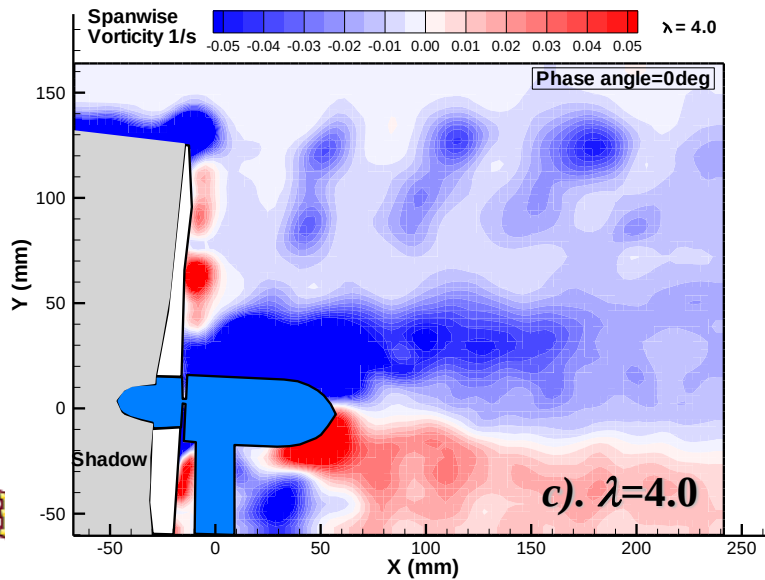
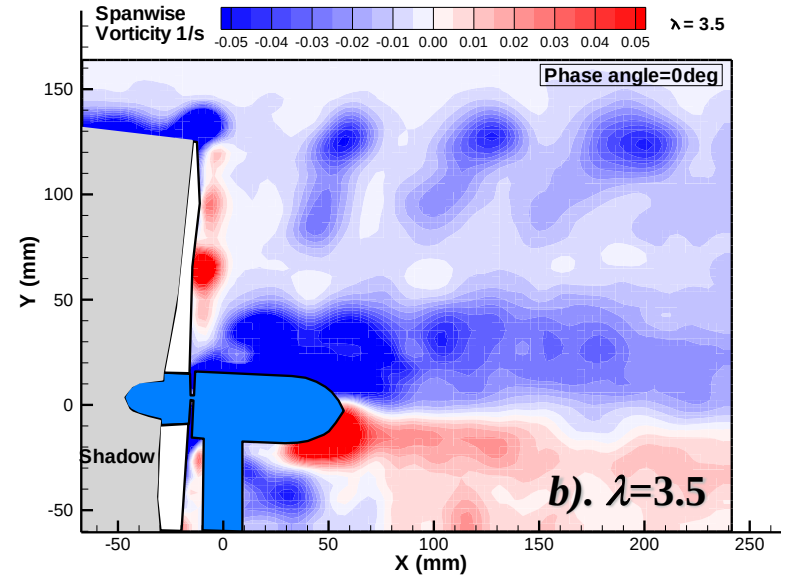
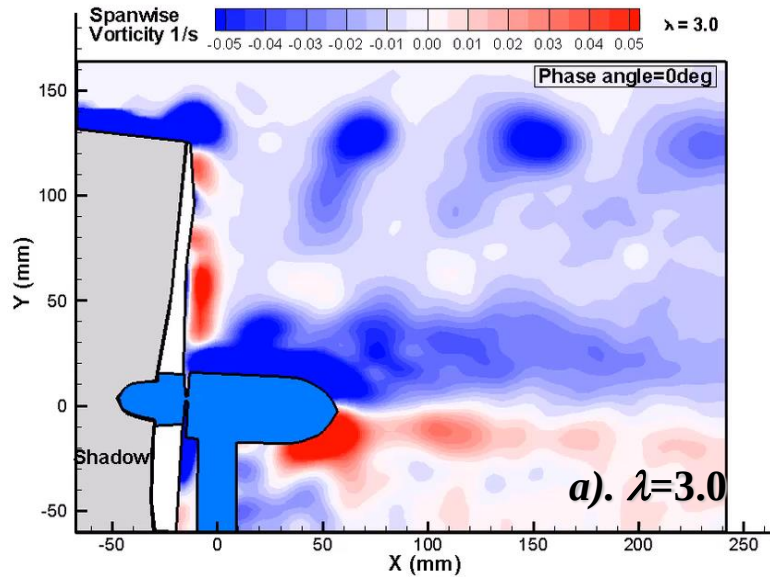


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@ Iowa State University Email: huhu@iastate.edu



Reconstructed 3-D wake vortex structures
(Hu et al. Experiments in Fluids, 2012, DOI: 10.1007/s00348-011-1253-5)

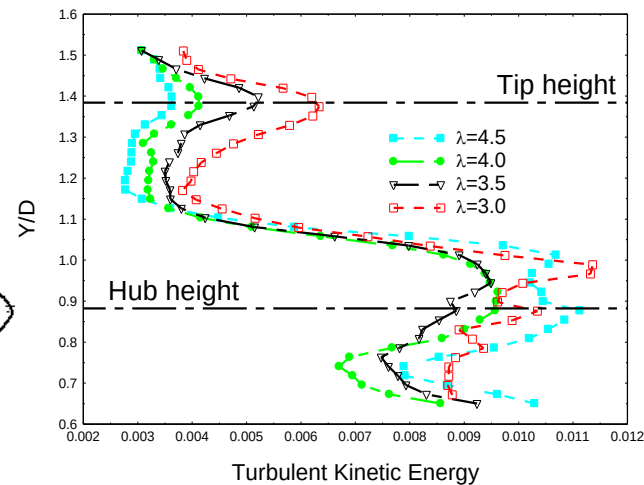
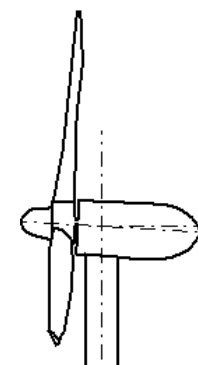
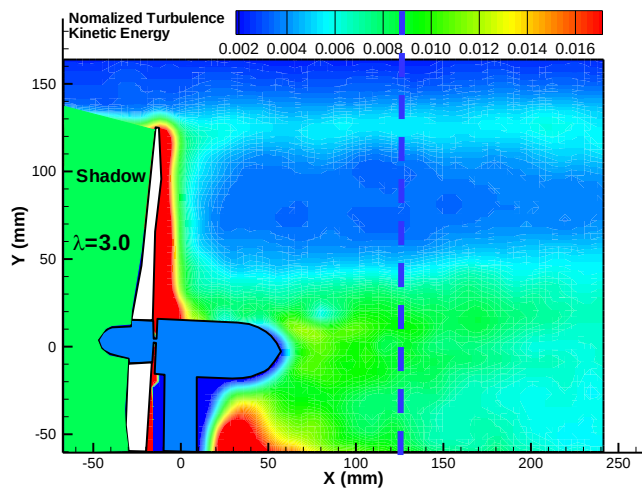
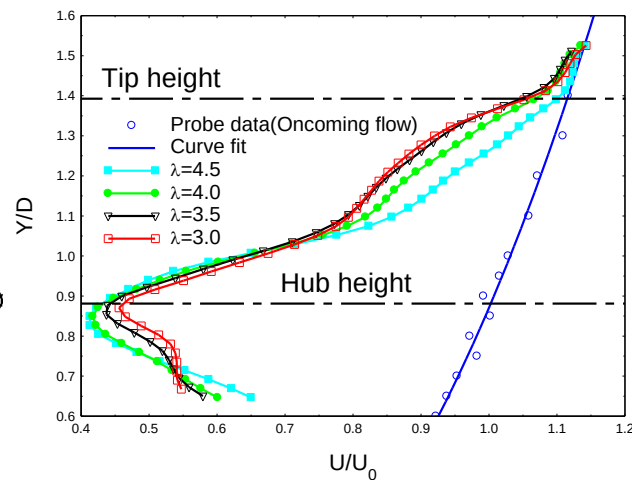
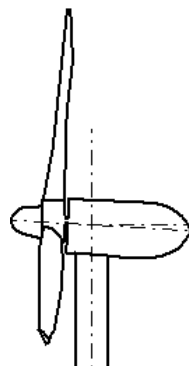
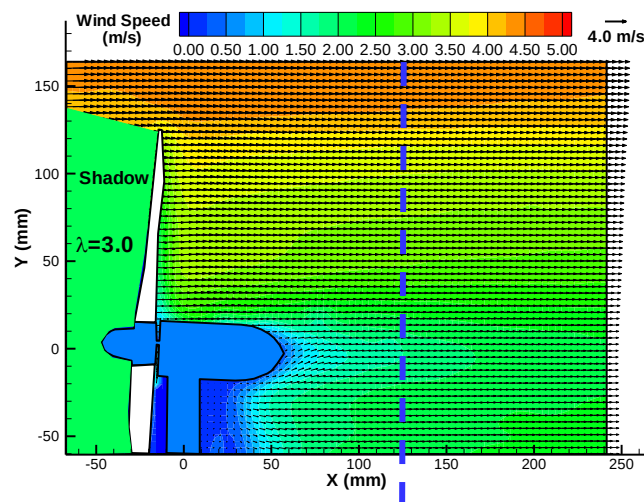
Effects of Tip-speed Ratio on the Wake Vortex Structures



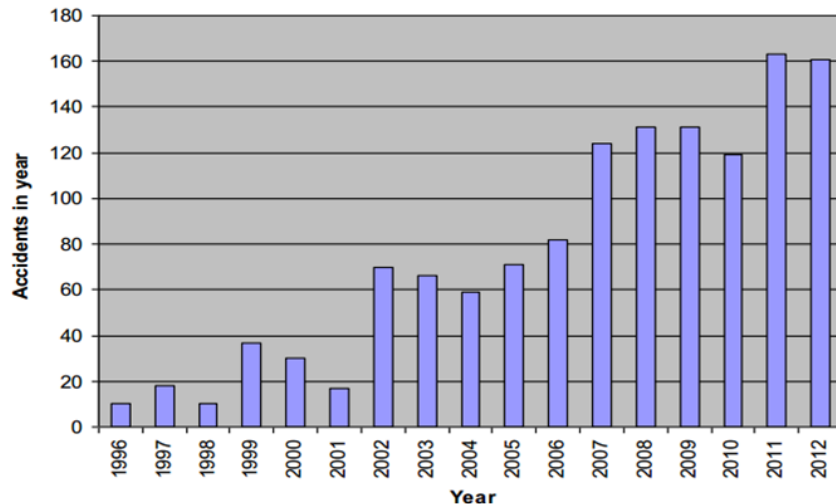
Wake Profiles at X/D=0.5 Downstream of the Wind Turbine Model

$$\text{Wind Energy} \propto \frac{1}{2} A \rho V^3$$

$$\text{Aerodynamic Force} \propto \frac{1}{2} A \rho V^2$$



Wind Turbine Failures



Caithness Wind Farm, UK

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

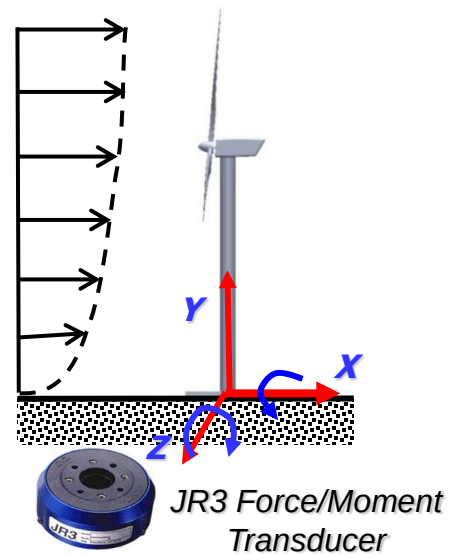
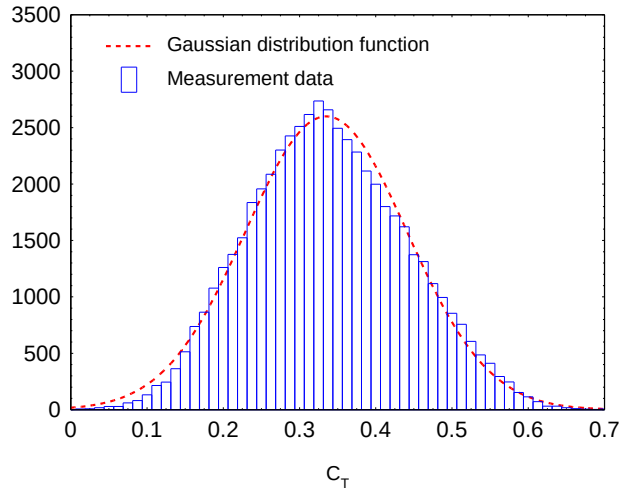
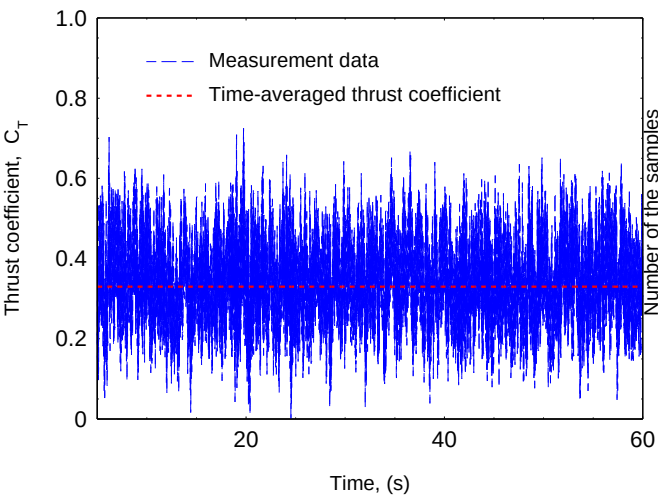
(202 WT in operation + 198 in construction)

Total number of accidents: 1405

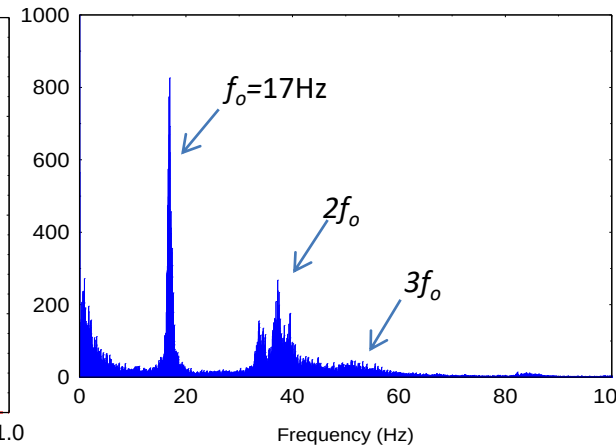
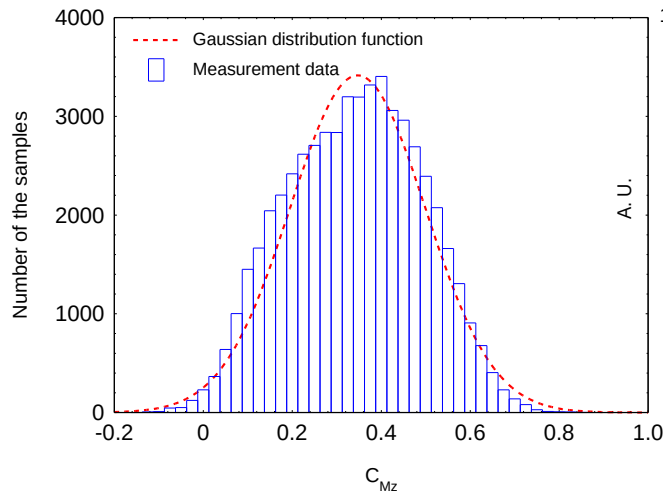
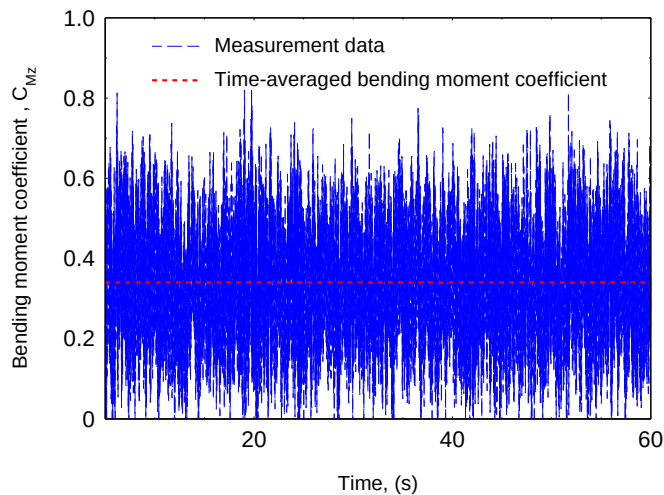
- **Human fatalities & injuries:** 136+145
- **Blade failure:** 265
- **Fire:** 202
- **Structural failure:** 138
- **Ice throw:** 34
- **Transport:** 113
- **Environmental (bird death):** 128
- **Others:** 282



Dynamic Wind Loads Acting on Wind Turbines



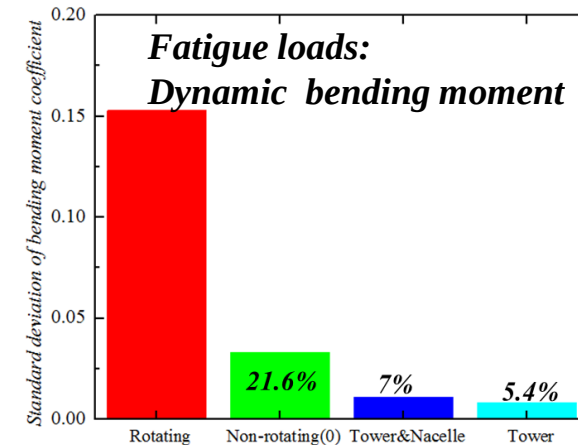
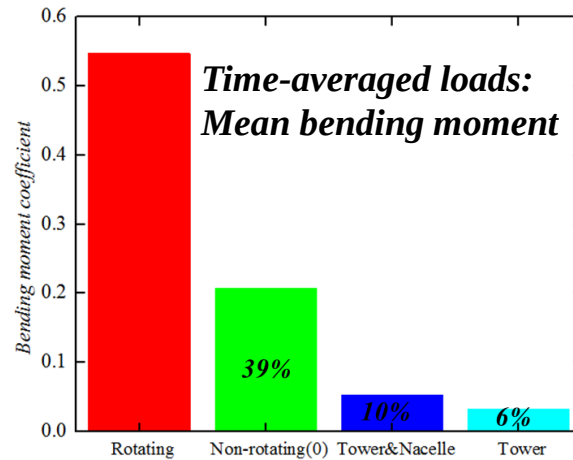
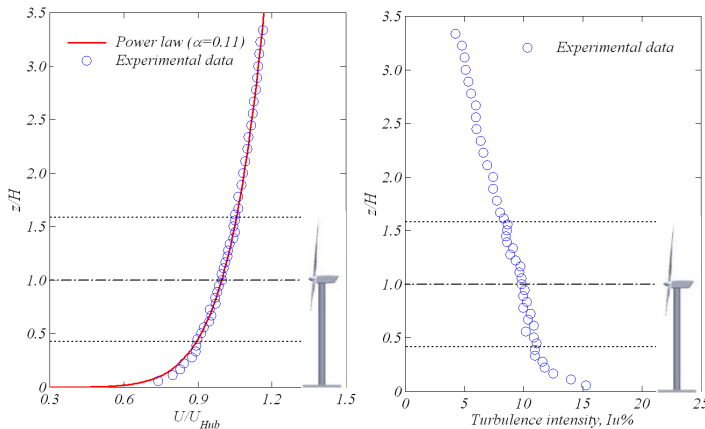
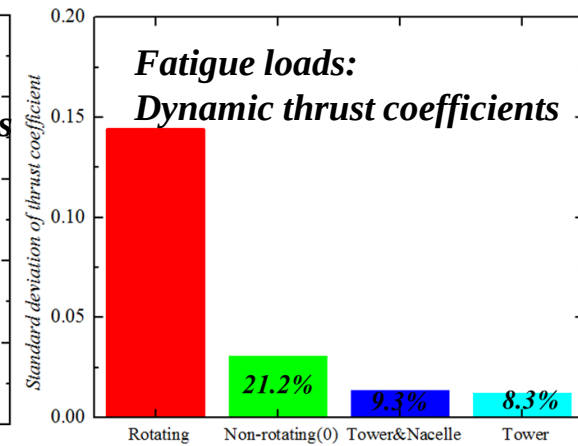
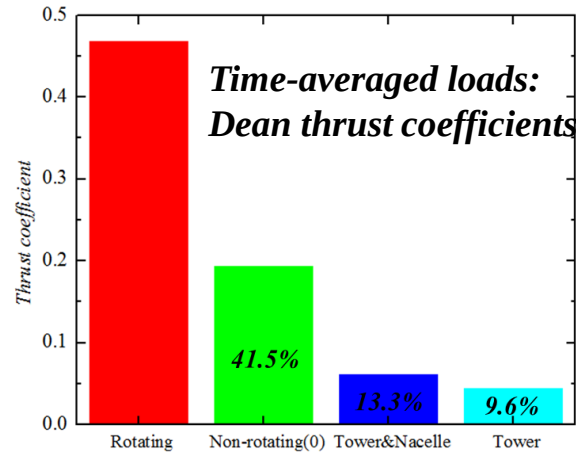
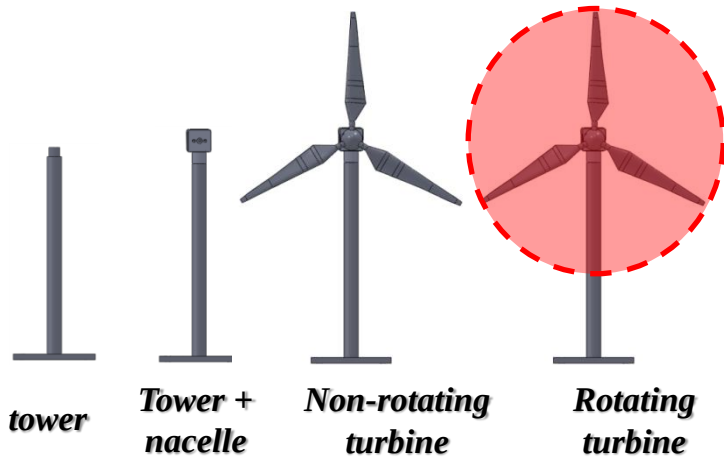
(a). Measured thrust coefficient data



(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

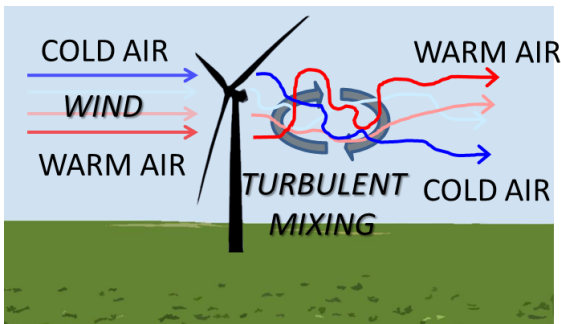


Test conditions:

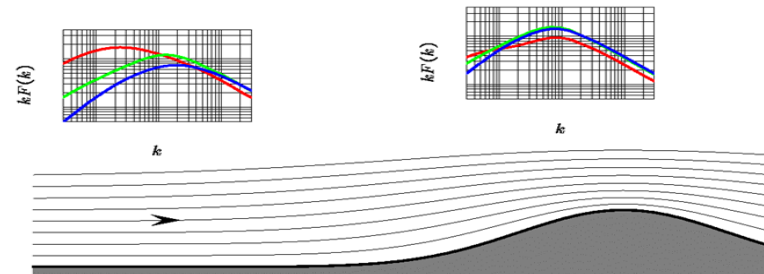
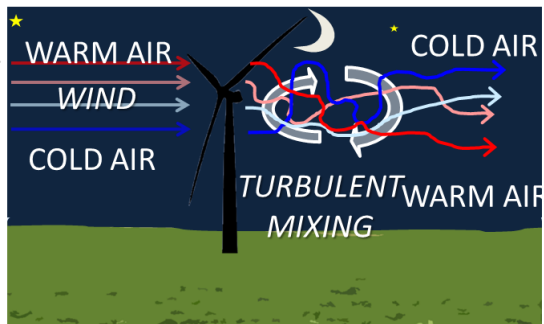
- Oncoiming ABL wind
- Velocity at hub height $U_{Hub} = 4.8$ m/s
- Chord Reynolds number, $Re \approx 7,200$
- Tip-speed-ratio, $\lambda = 4.6$

Wind Farm Aerodynamics: Wake Interferences of Multiple Wind Turbines

DAYTIME

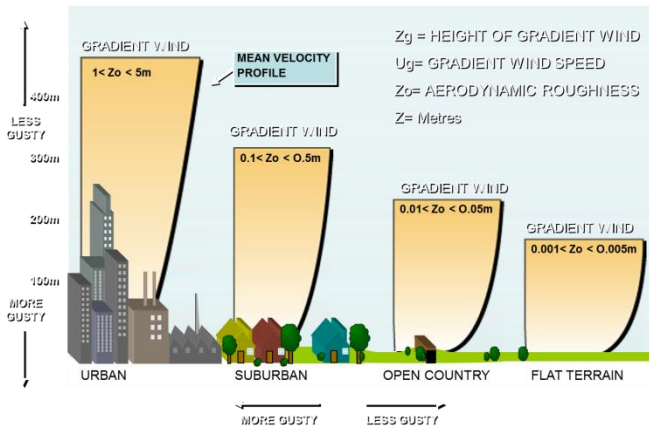


NIGHTTIME



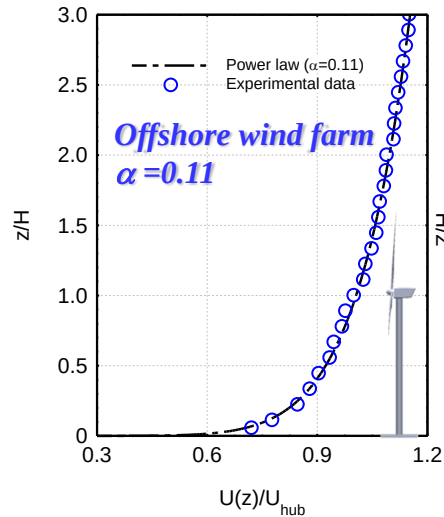
- **Offshore wind farms:**
 - Wind turbine sitting on flat ocean surface.
 - High wind speed with relatively low ambient turbulence.
 - Near neutral atmospheric boundary layer winds.
- **Onshore wind farms:**
 - Atmospheric stability is rarely close to near-neutral, varying significantly between highly 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

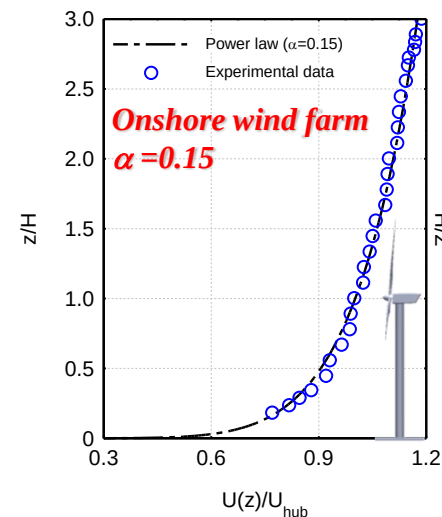
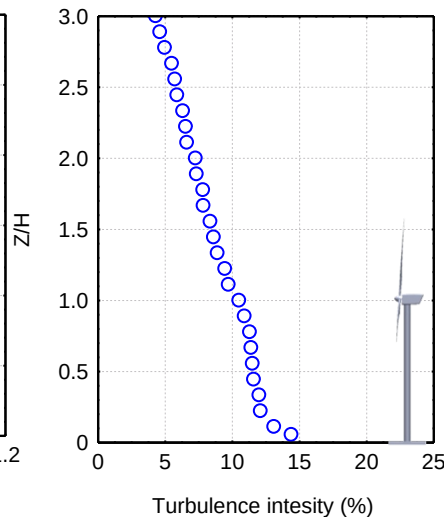


Terrain Category	Terrain description	Gradient height, Z_G (m)	Roughness length, Z_o (m)	Wind Speed exponent, α
1	Open sea, ice, tundra desert	250	0.001	0.11
2	Open country with low scrub or scattered trees	300	0.03	0.15
3	Suburban area, small towns, wooded areas	400	0.3	0.25
4	Tall buildings, city centers,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

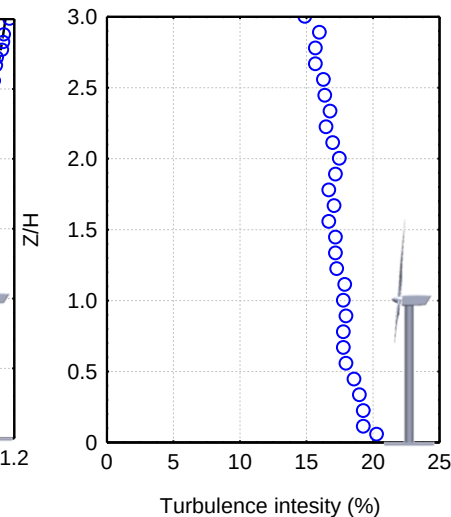
$$U(z) = U_{Z_G} \left(\frac{Z}{Z_G} \right)^\alpha$$



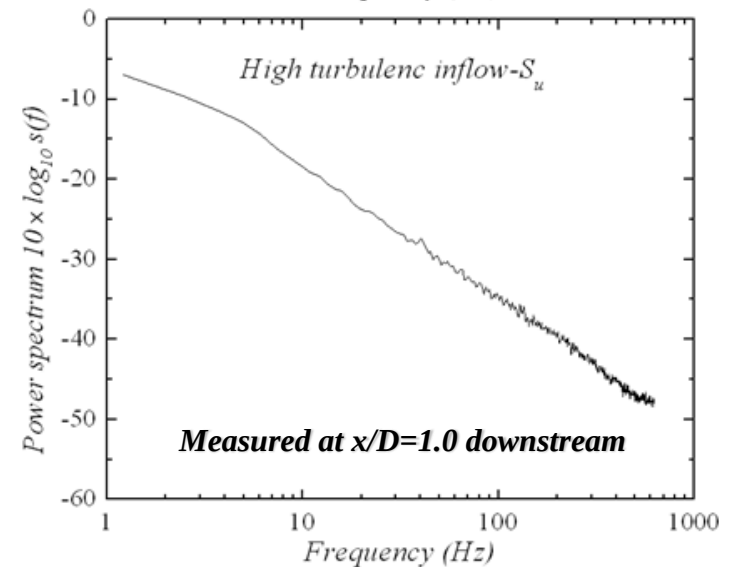
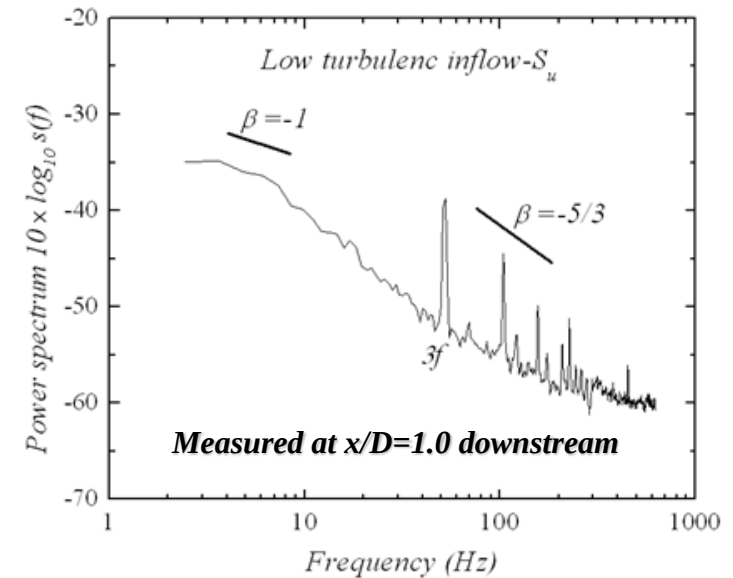
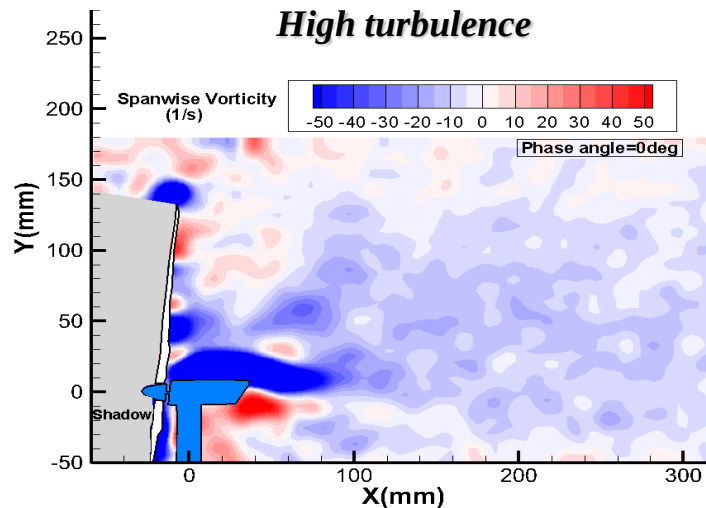
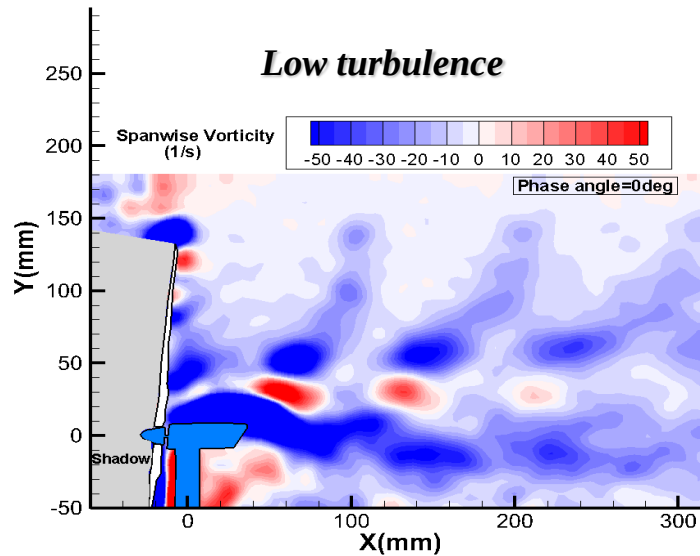
**Low turbulence intensity case
(10% at hub height)**



**High turbulence intensity case
(18% at hub height)**



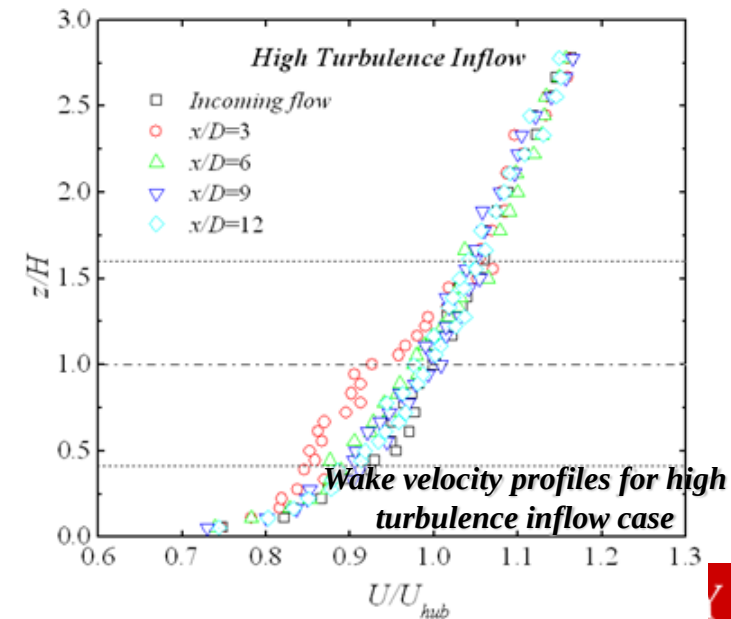
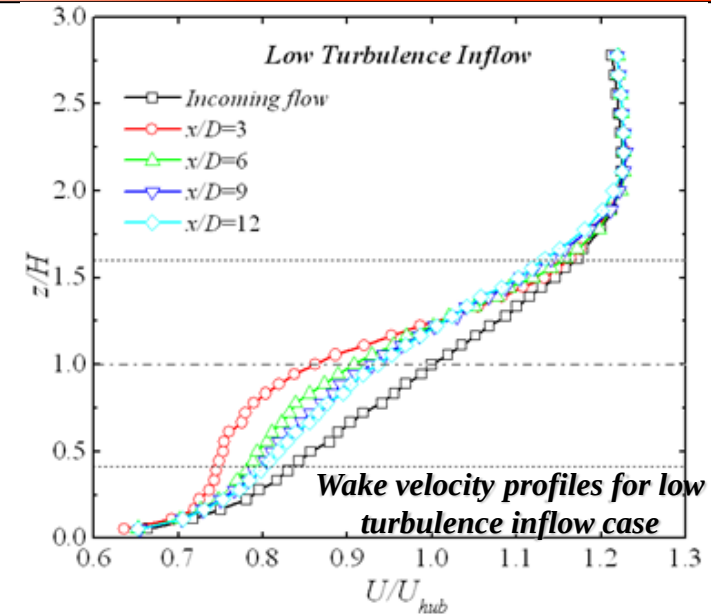
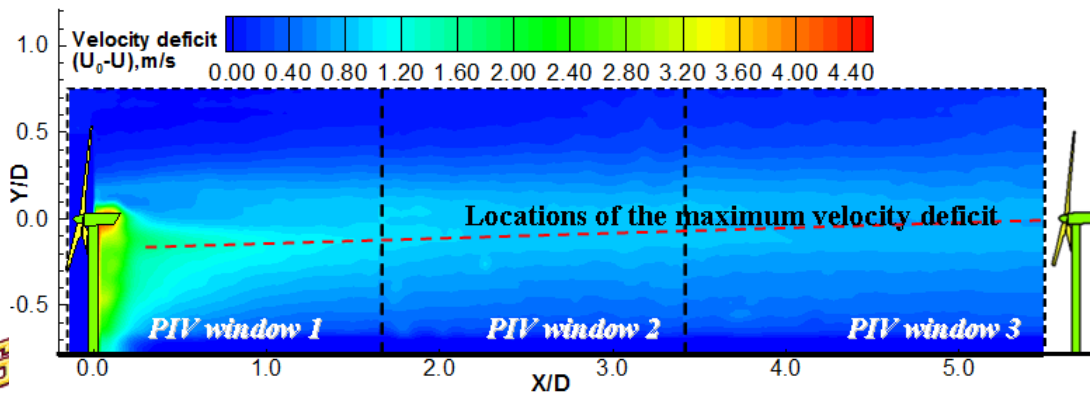
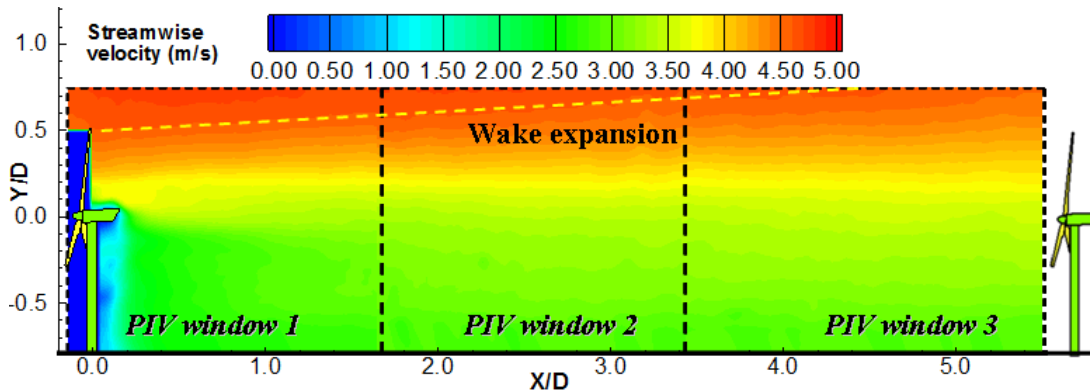
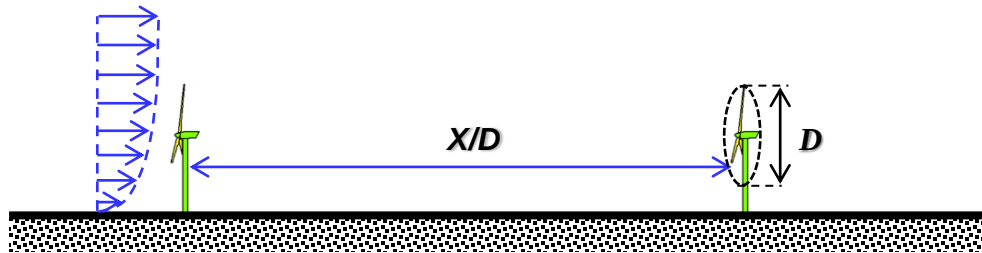
The Effects of ABL Turbulence Level on the Wake Vortex Dissipation



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

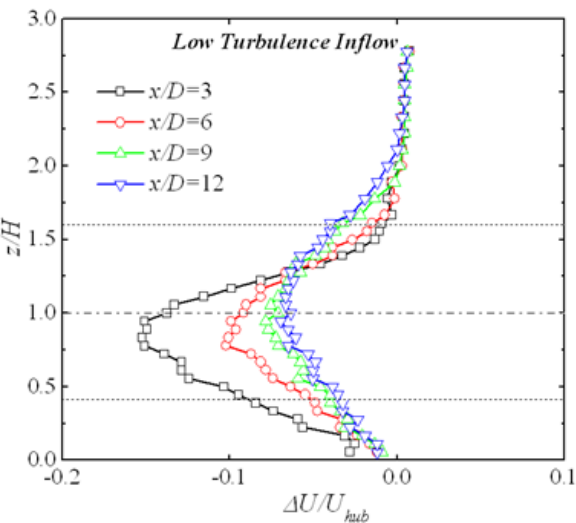
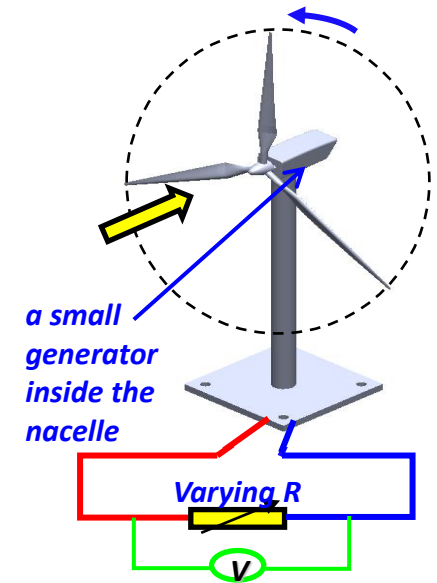
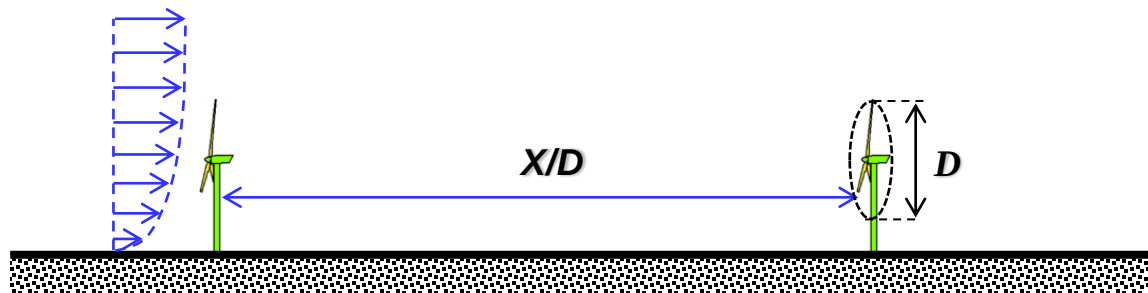
The Effects of ABL Turbulence Level on the Wake Characteristics

Atmospheric boundary layer wind

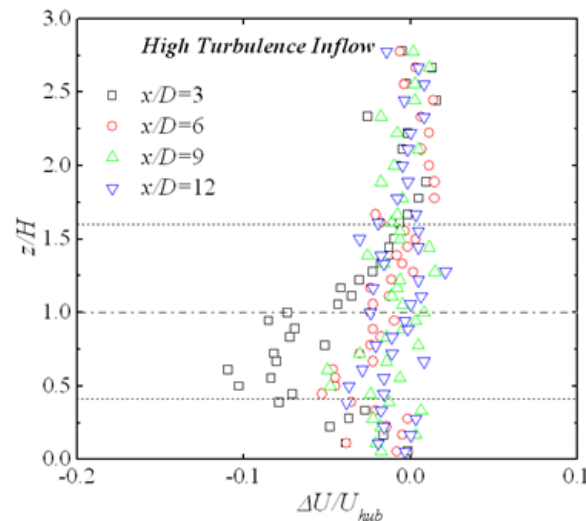


The Effects of ABL Turbulence Level on the Wake Characteristics

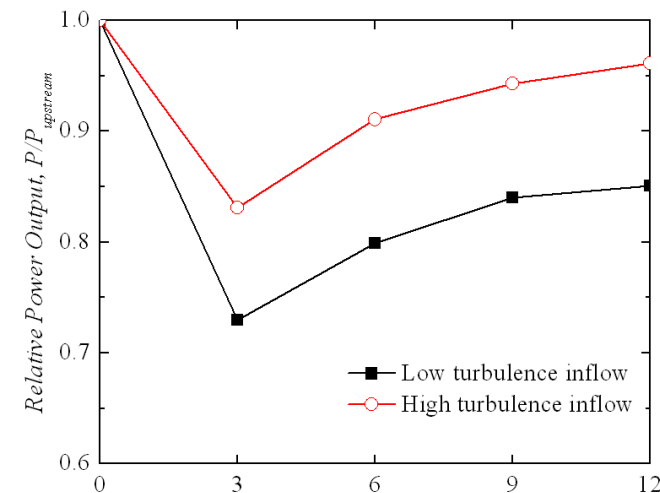
Atmospheric
boundary layer wind



Wake velocity deficit profiles for
low turbulence inflow case

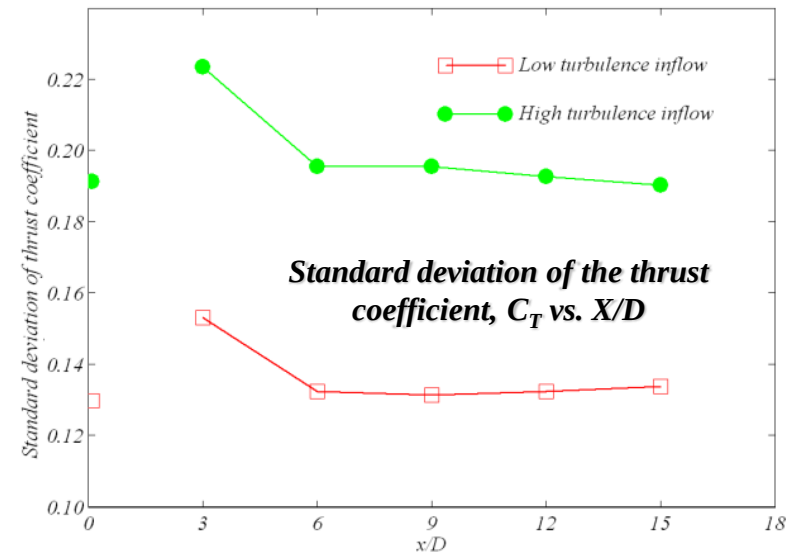
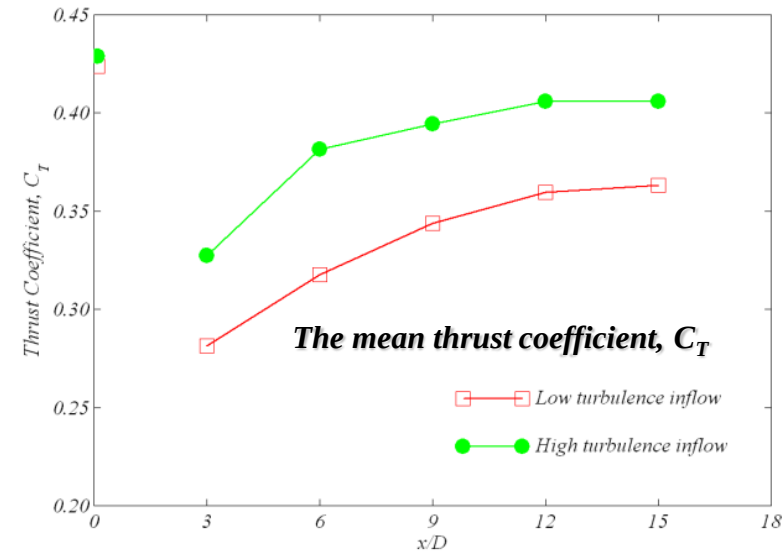
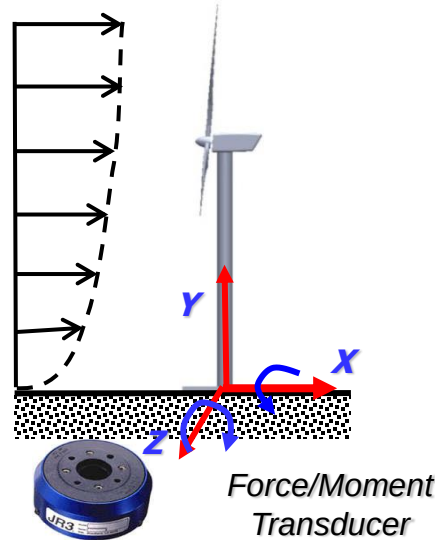
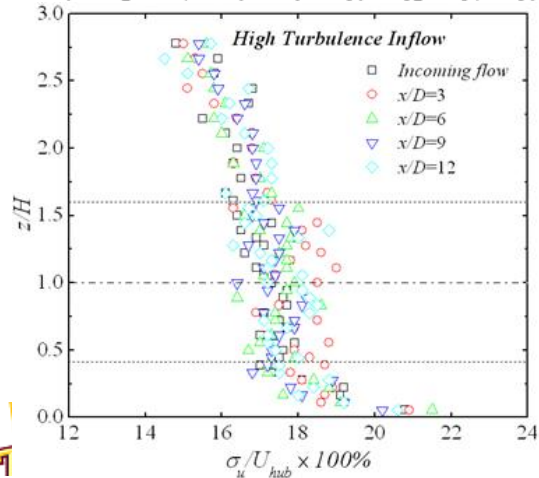
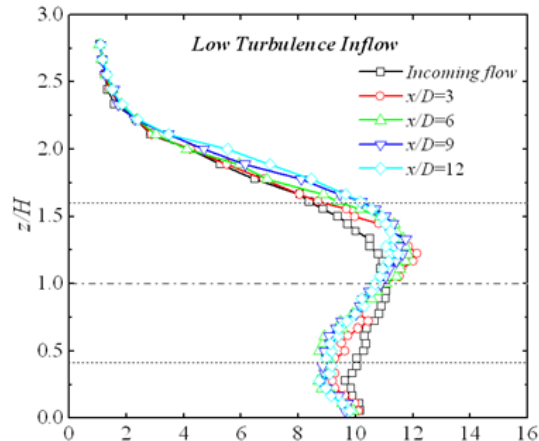
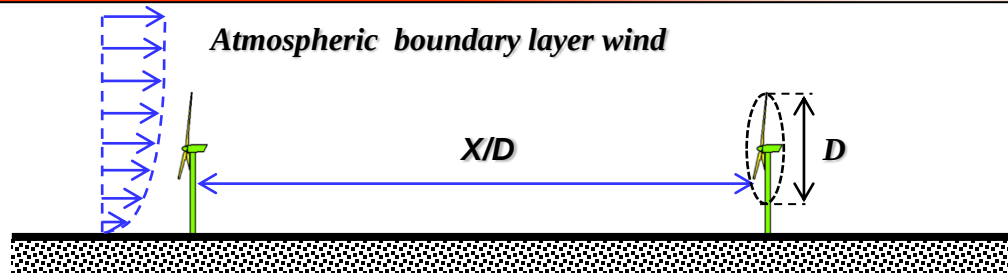


Wake velocity deficit profiles for
high turbulence inflow case



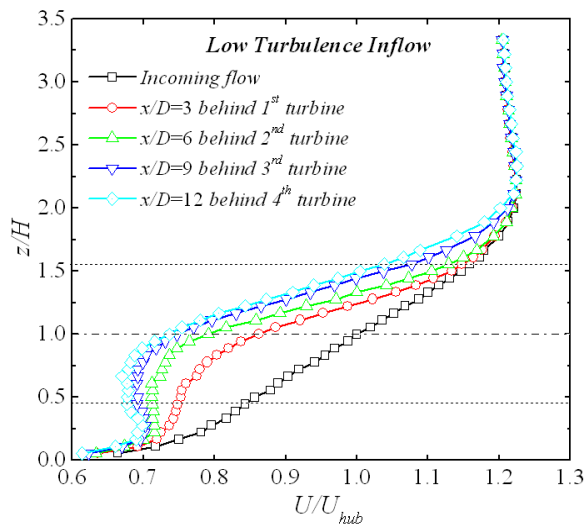
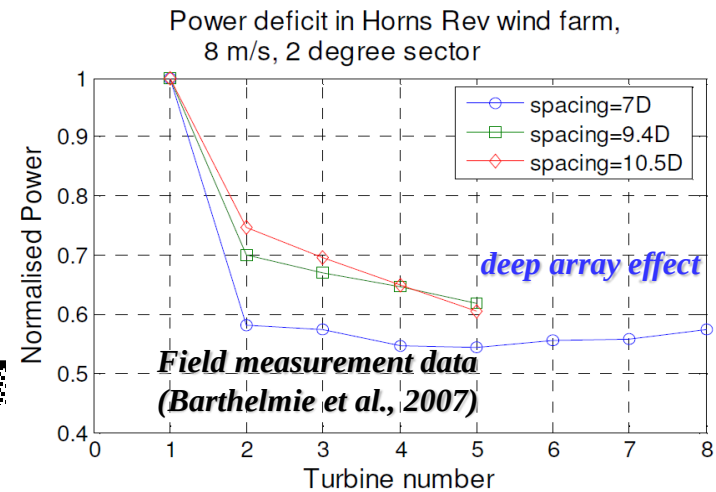
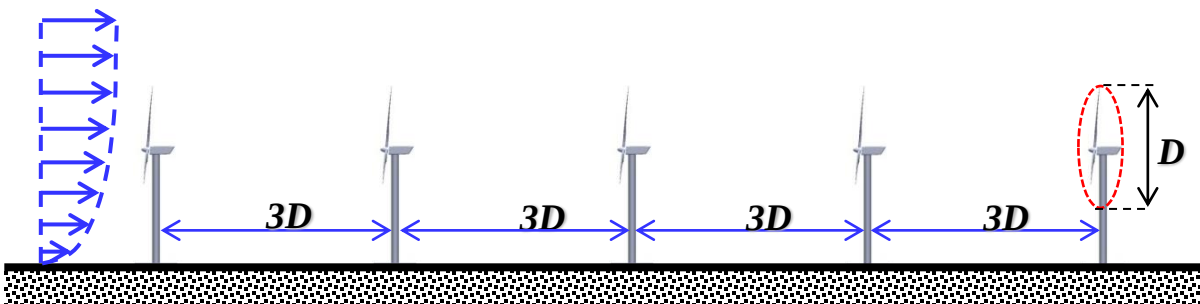
Power output of the downstream
wind turbine vs. X/D

The Effects of Oncoming Turbulence Level on the Wake Characteristics

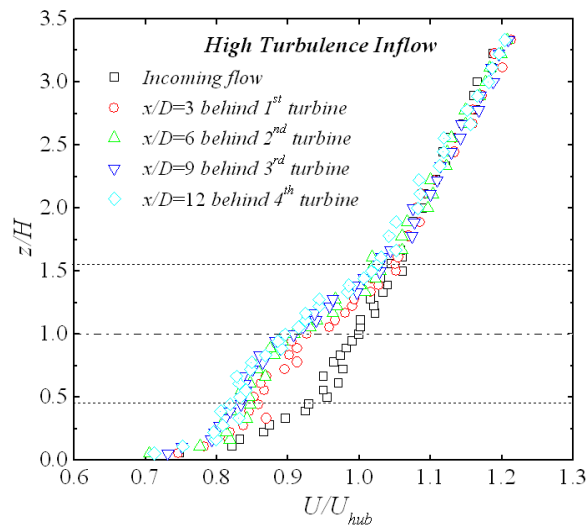


Turbulence shear stress in the wakes

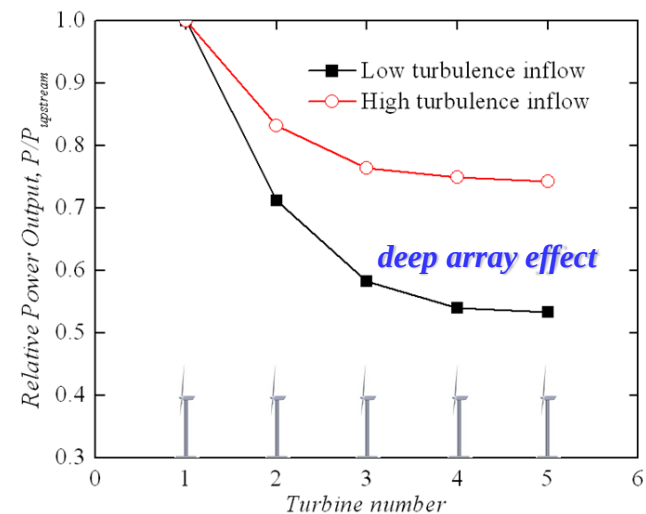
Wake Interferences among Multiple Wind Turbines



Velocity profiles in the wake for low turbulence inflow case



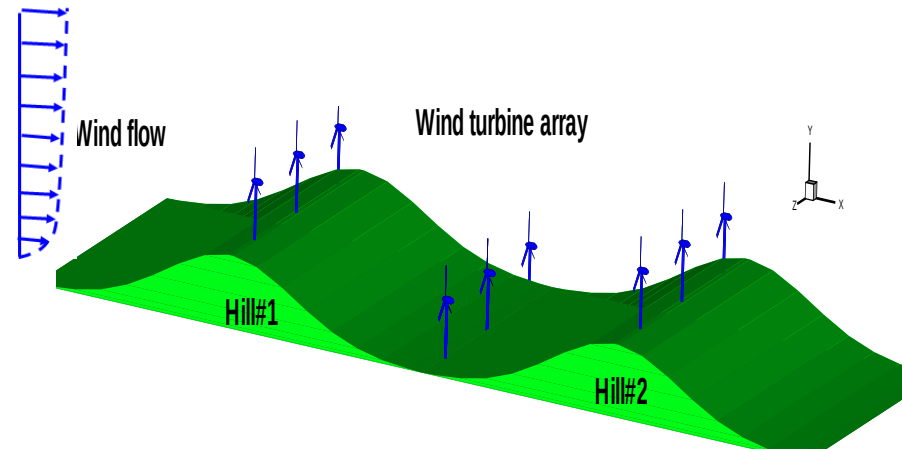
Velocity profiles in the wake for high turbulence inflow case



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

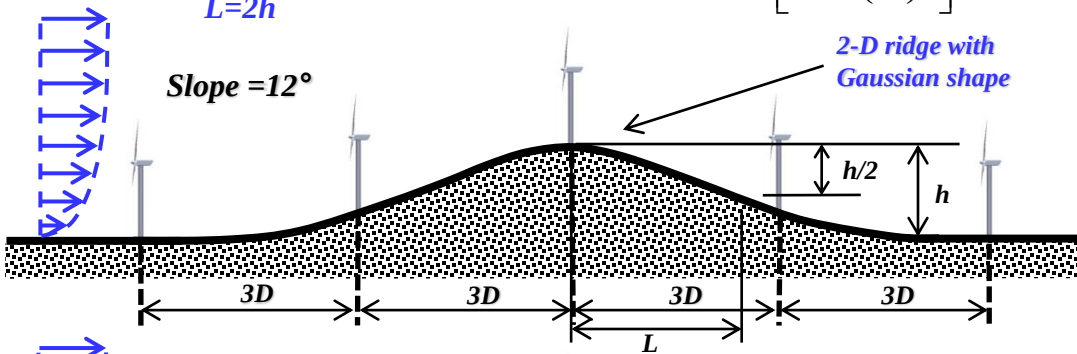


Effects of Complex Terrains on the Wind Turbine Performance

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

Slope = 12°

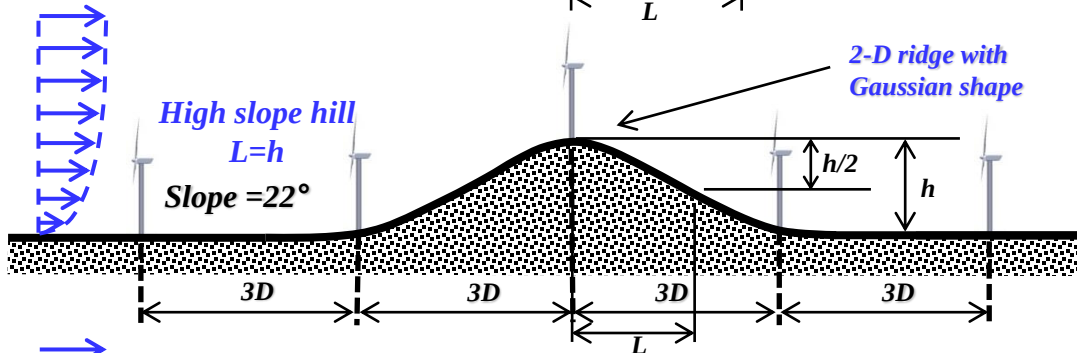
2-D ridge with Gaussian shape



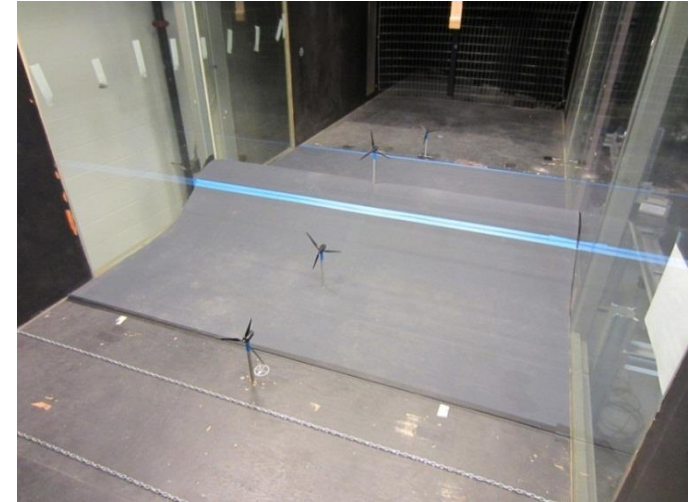
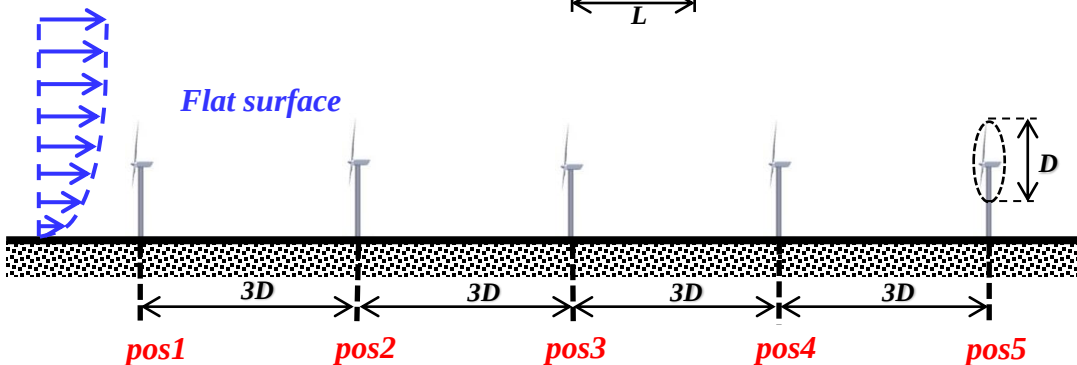
High slope hill $L=h$

Slope = 22°

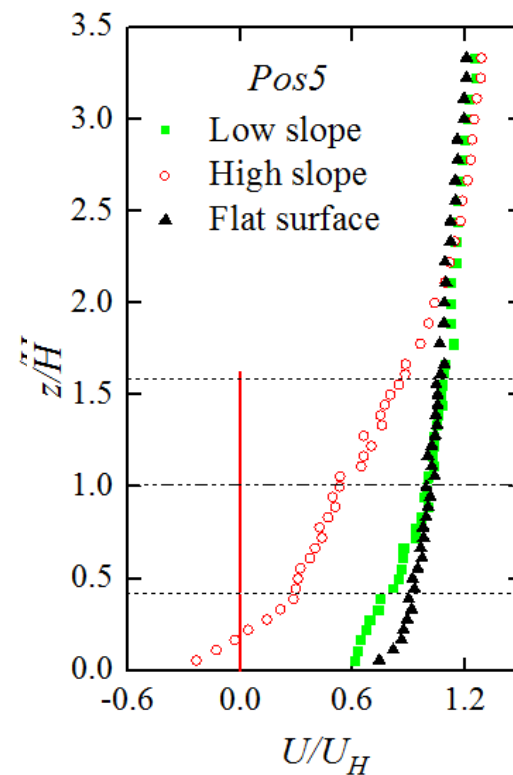
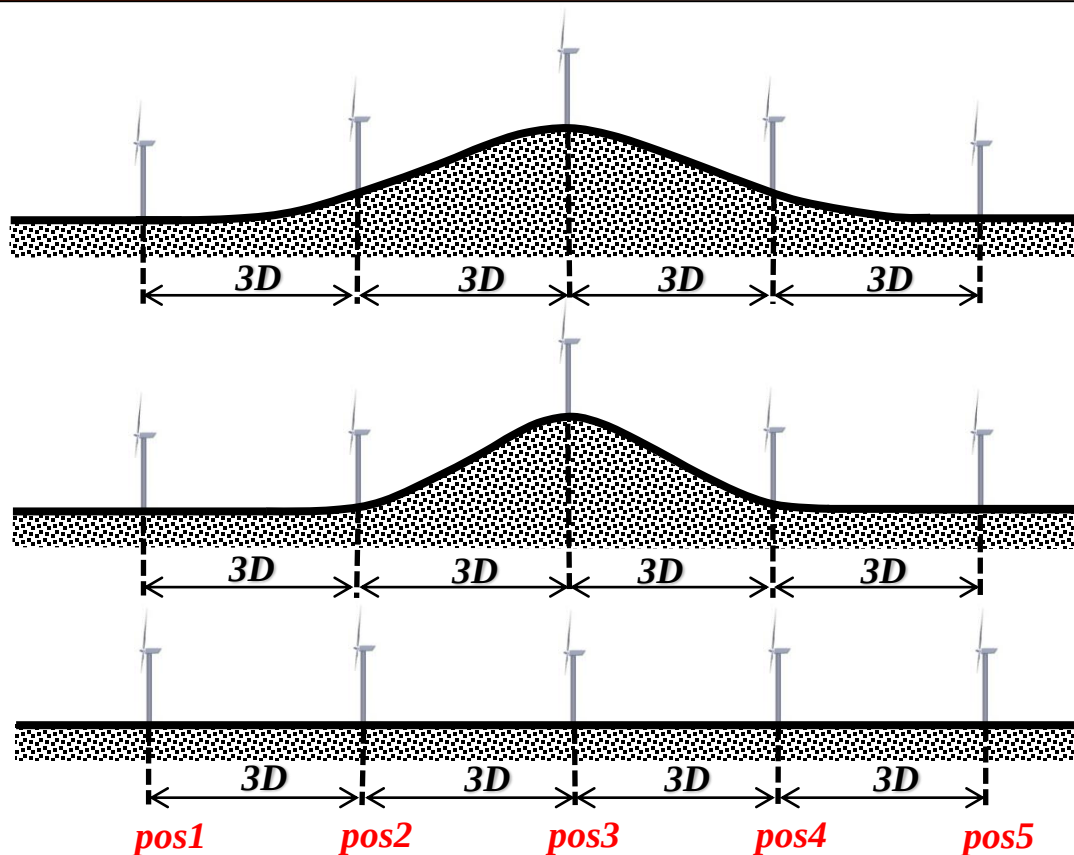
2-D ridge with Gaussian shape



Flat surface

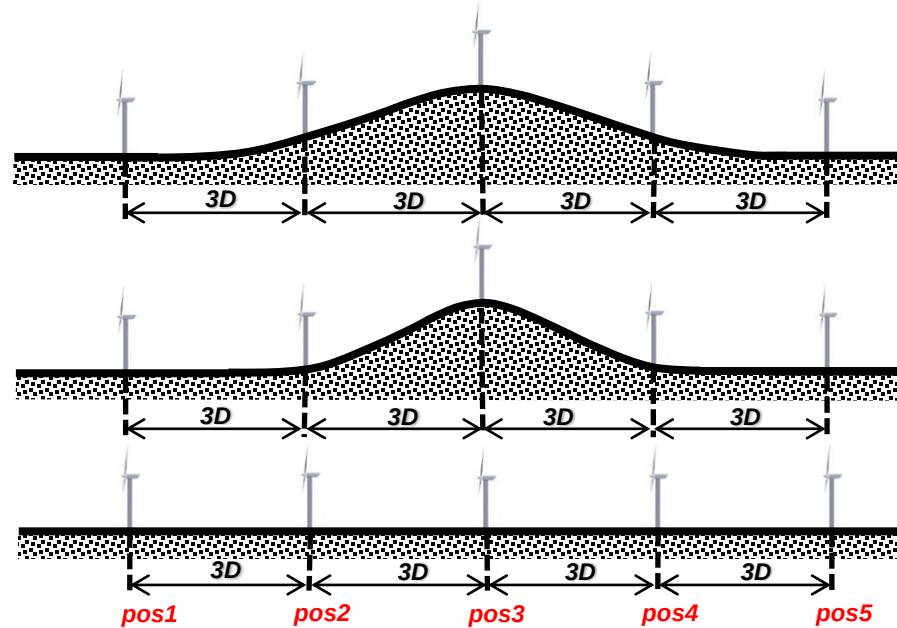


Performances of Single Wind Turbine Sited over Complex Terrains



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

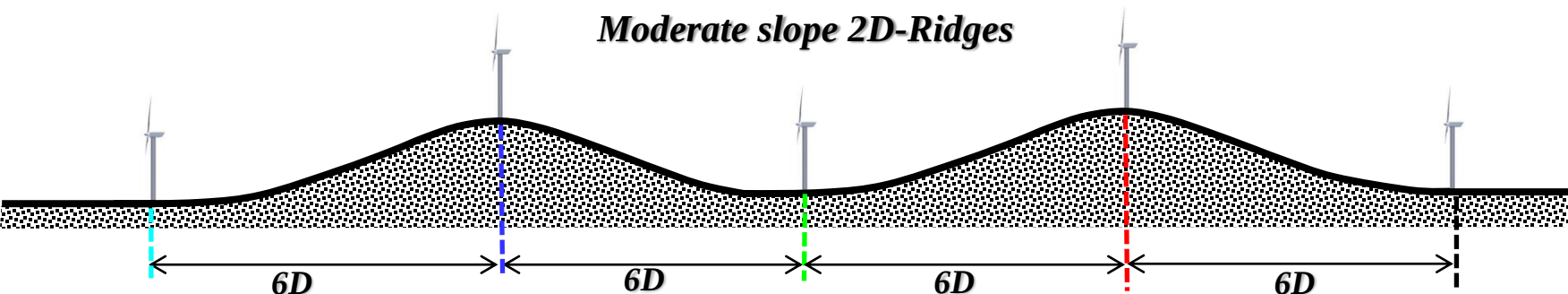
Power Outputs of Wind Turbines over Flat Surface vs. Complex Terrains



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

Moderate slope 2D-Ridges



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

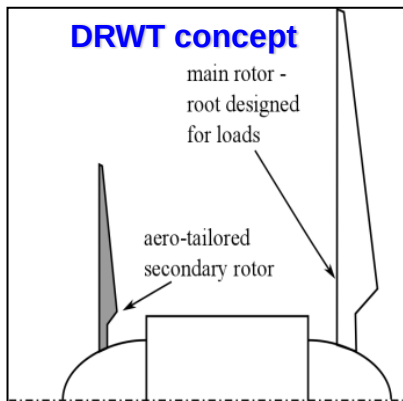
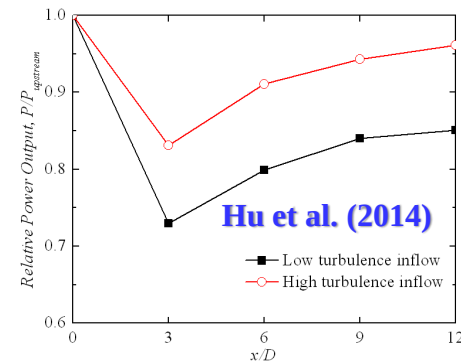
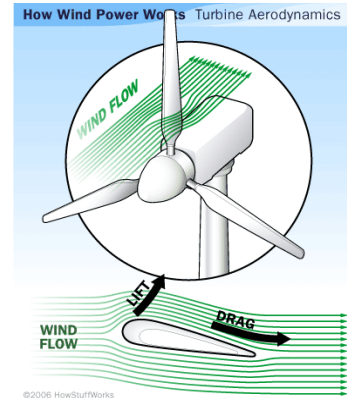
Root Loss and Wake Loss of Wind Turbines

• 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.

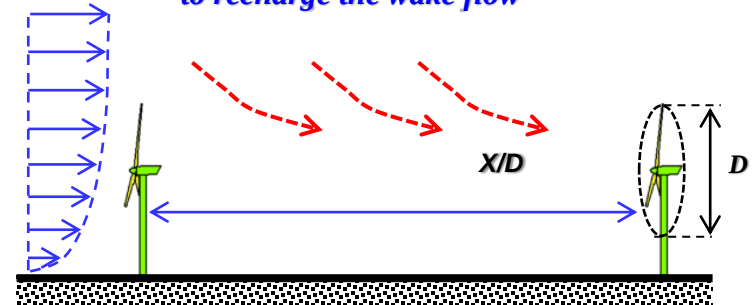
• Wake Loss (up to 40%):

- Aerodynamic interaction between wind turbines will result 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.



ABL wind

Entrainment of high-speed airflow from above to recharge the wake flow



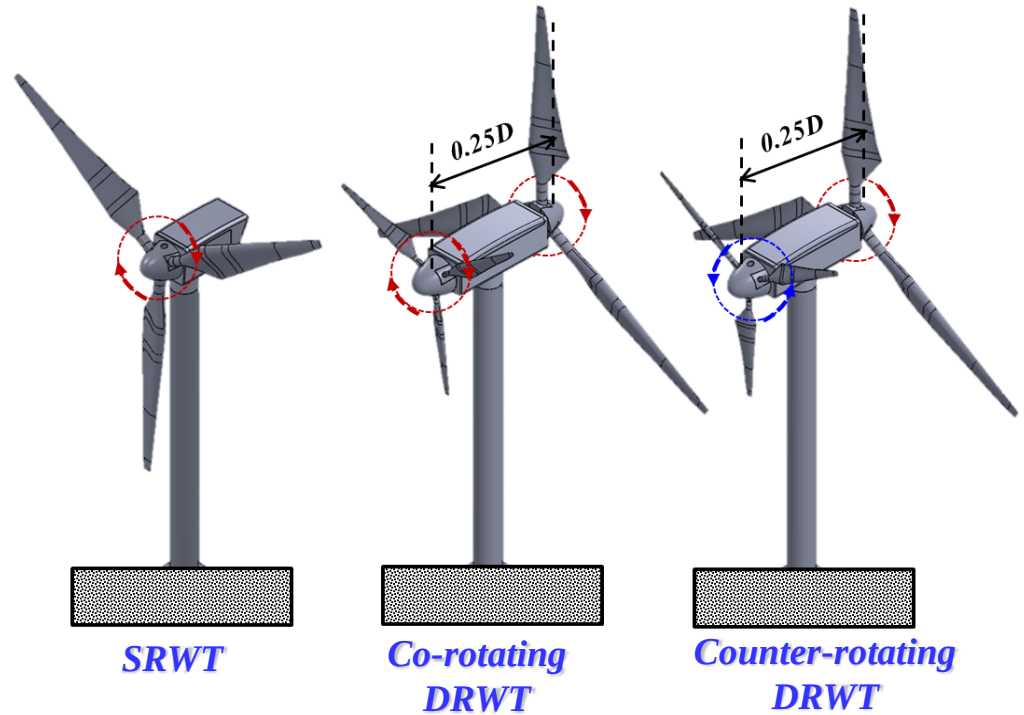
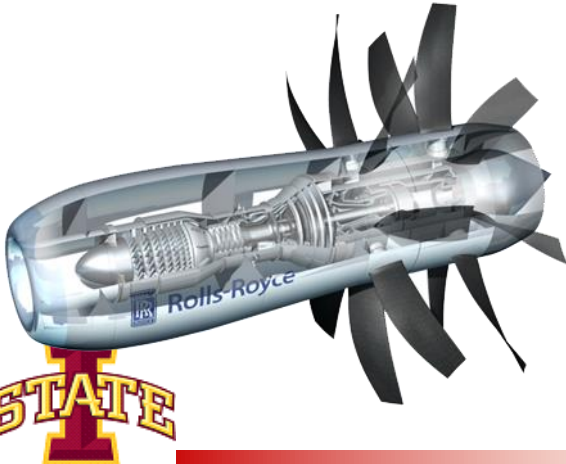
Dual-Rotor Wind Turbine Models and Counter-Rotating Rotor Concept



Soviet Ka-2 helicopter with counter-rotating rotors

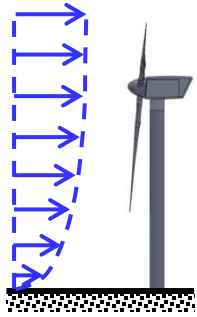


Contra-rotating propeller

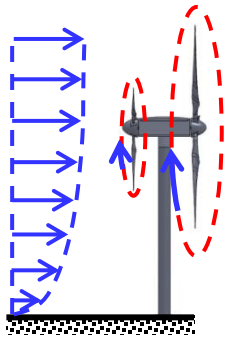
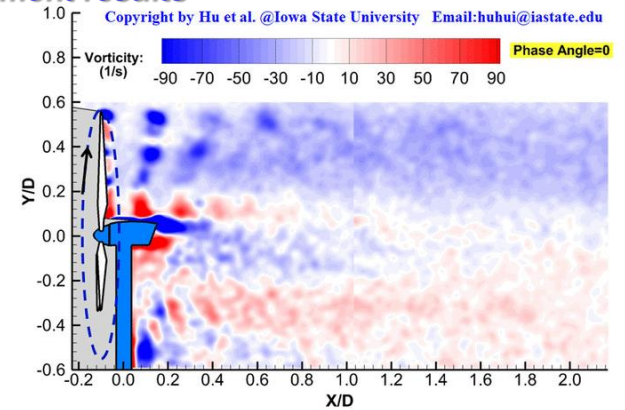
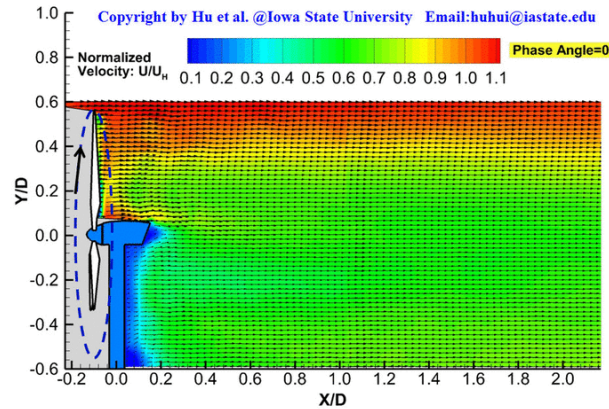


SRWT vs. Co-Rotating DRWT vs. Counter-rotating DRWT

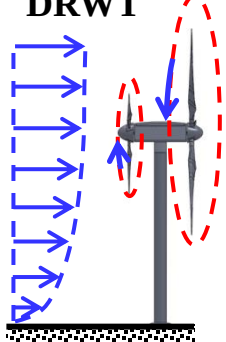
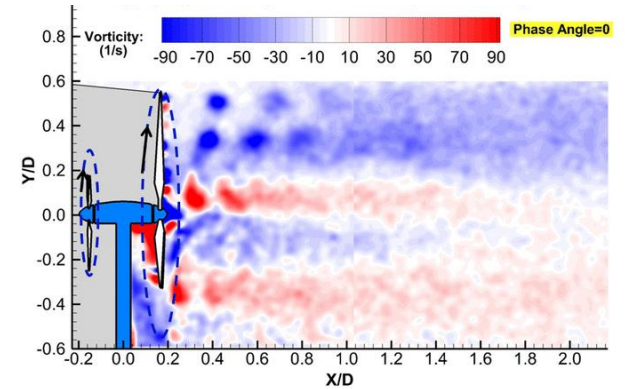
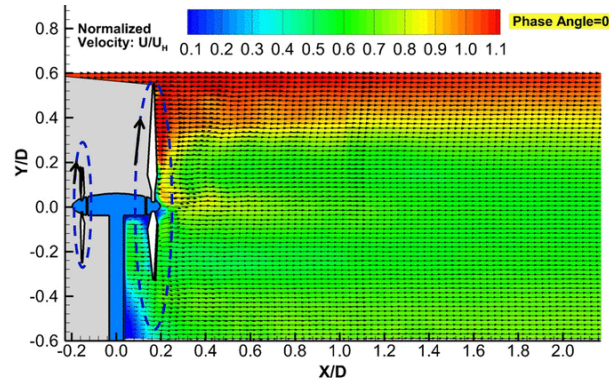
Phase-locked PIV measurement results



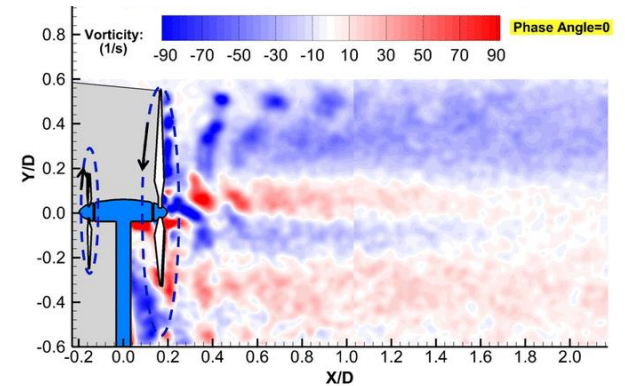
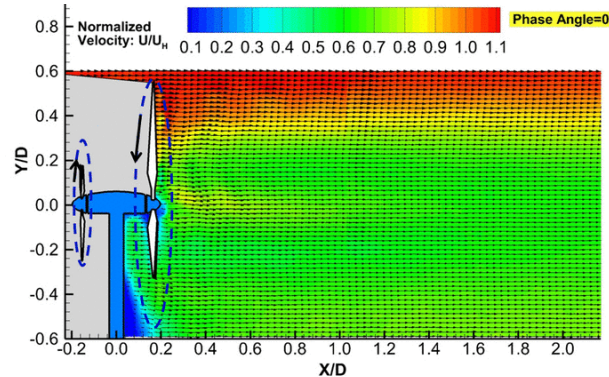
SRWT



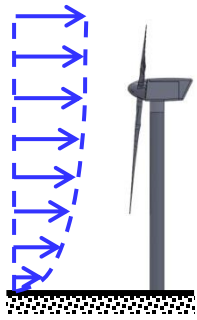
Co-rotating
DRWT



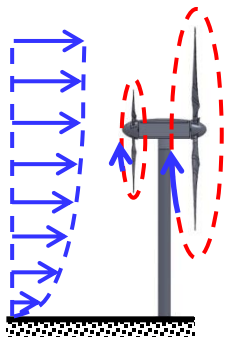
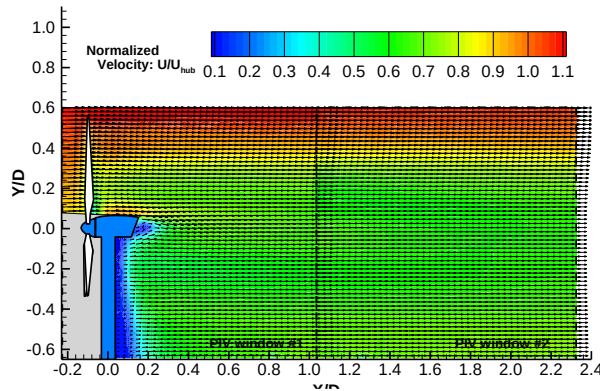
Counter-rotating
DRWT



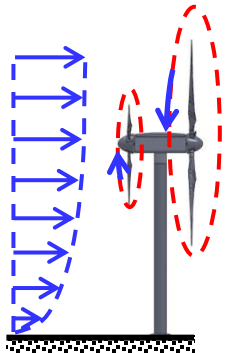
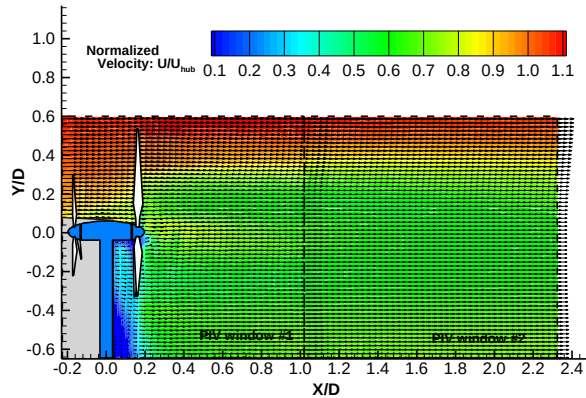
SRWT vs. Co-Rotating DRWT vs. Counter-rotating DRWT



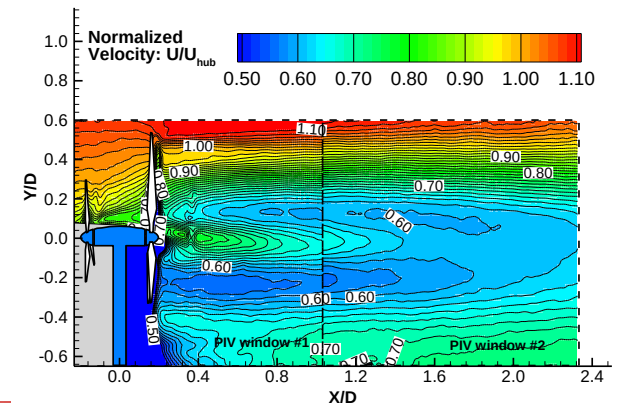
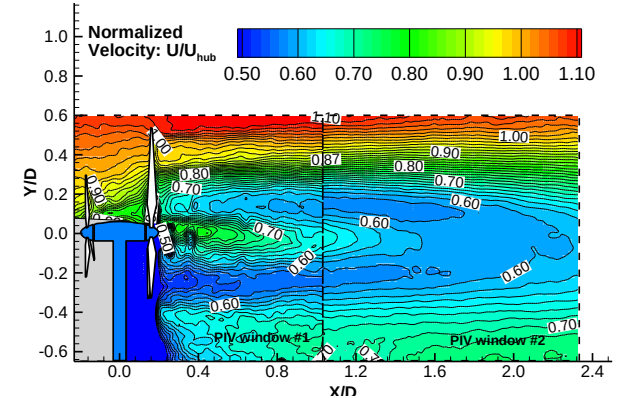
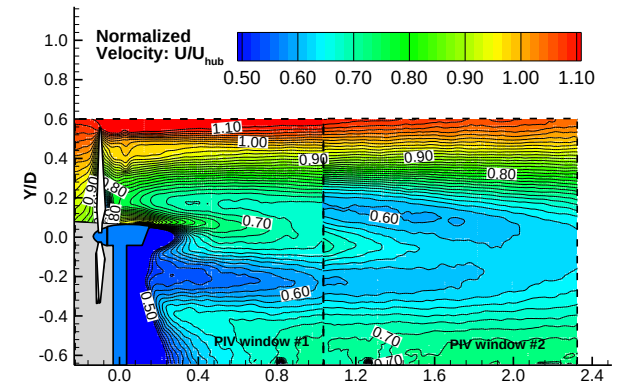
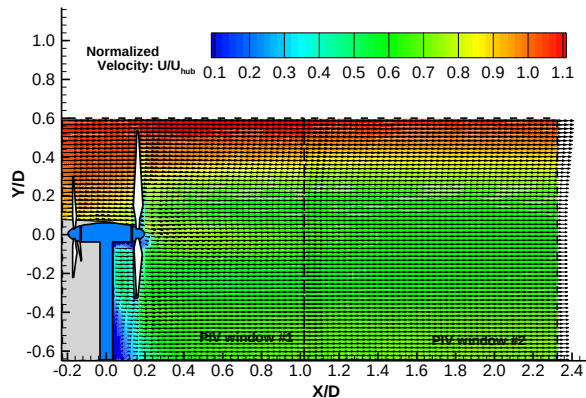
SRWT



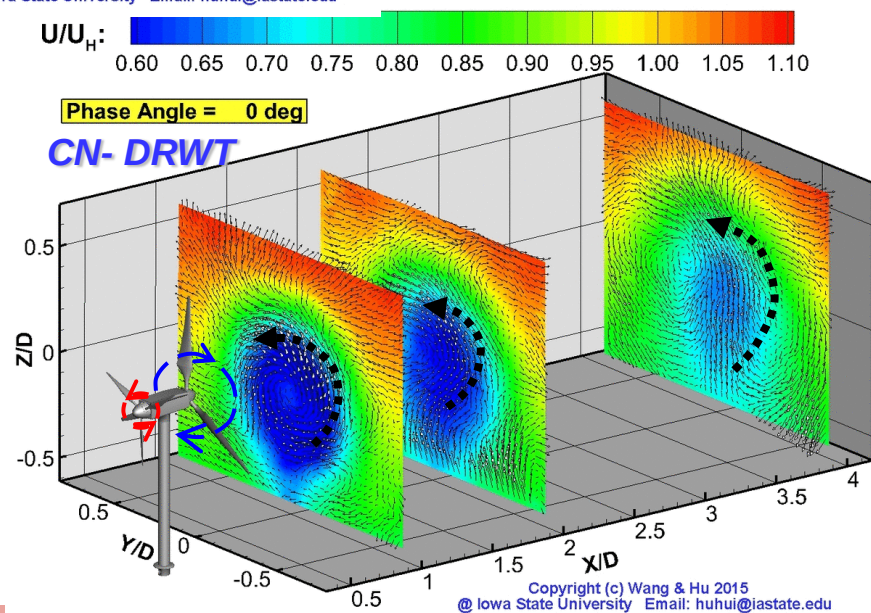
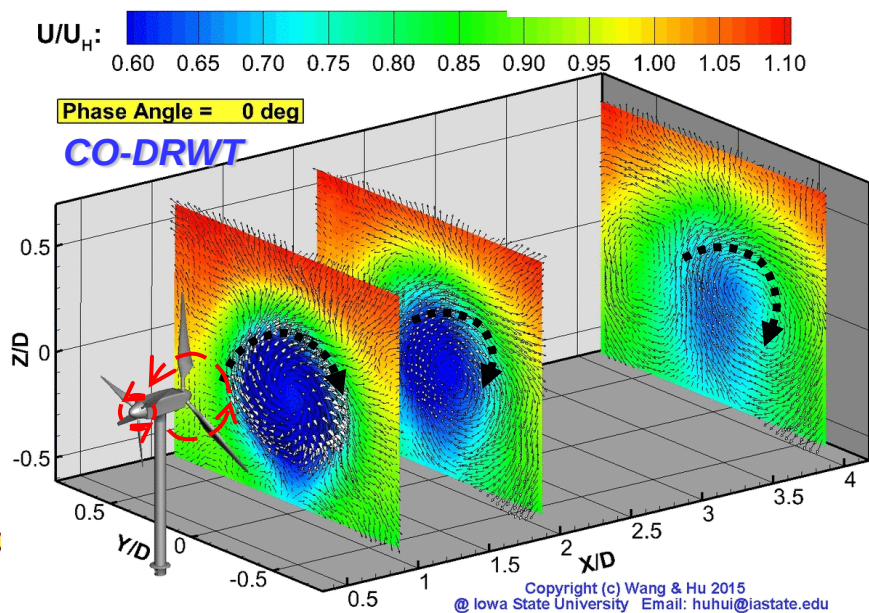
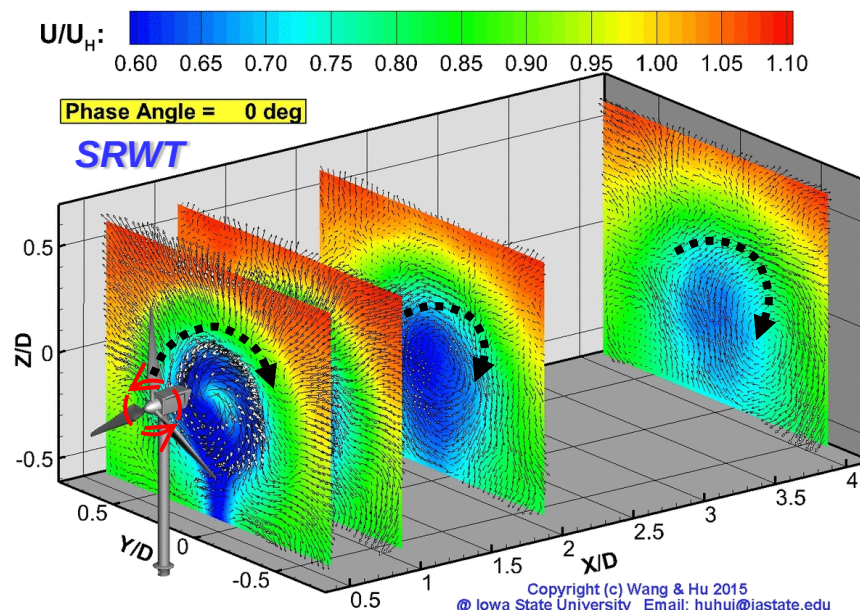
Co-rotating DRWT



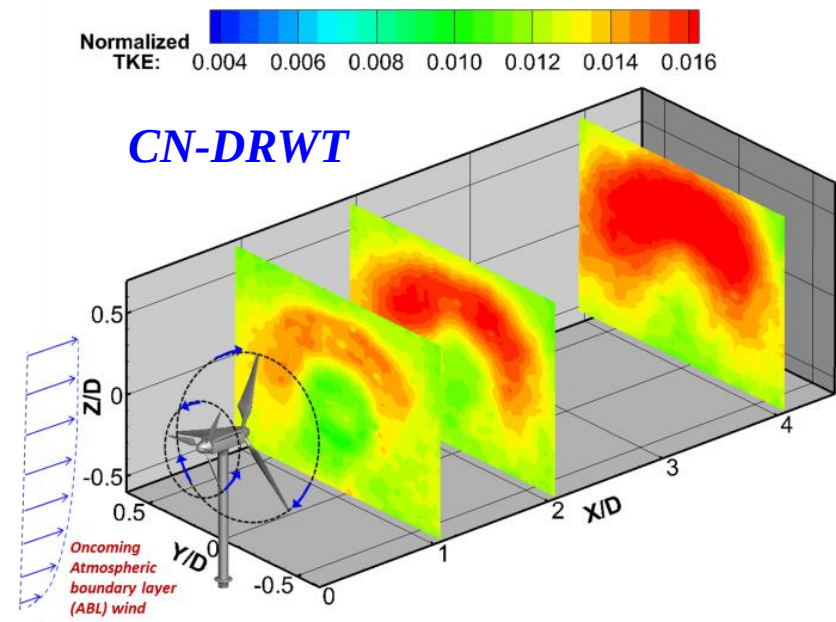
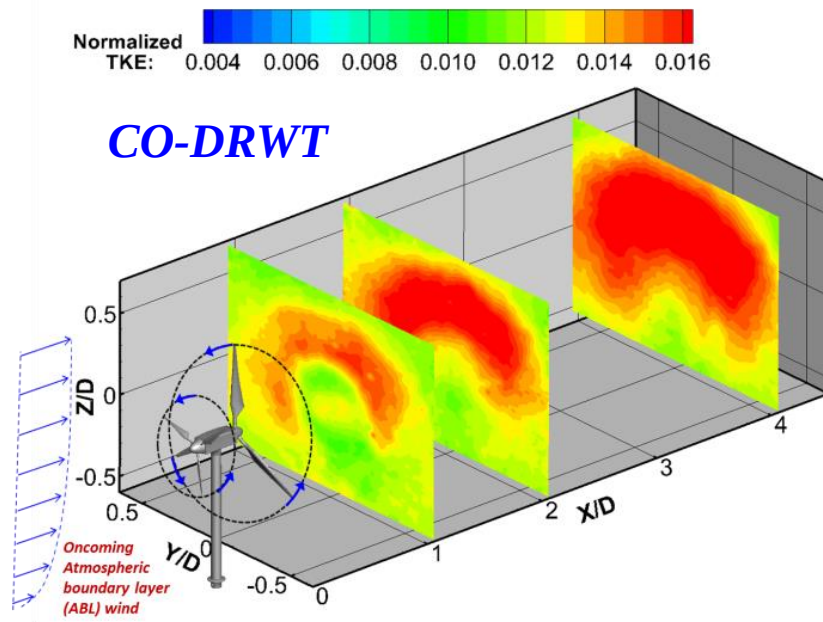
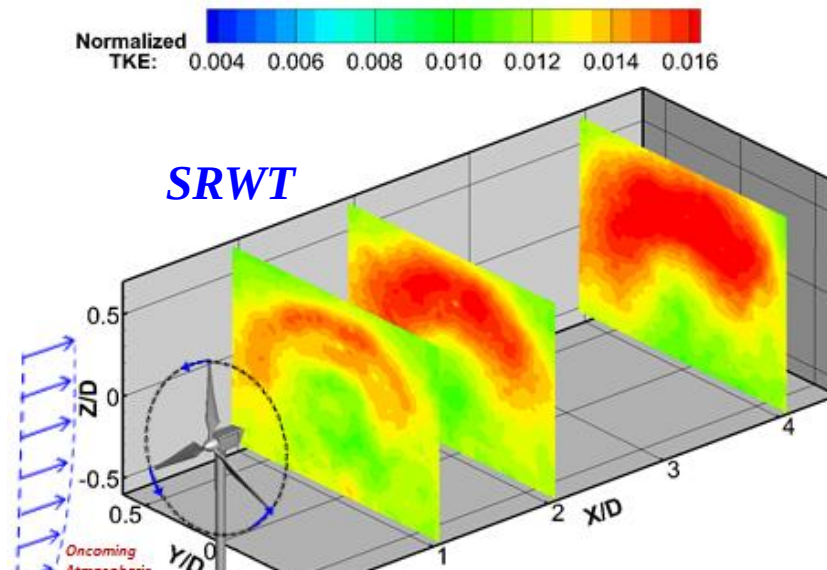
Counter-rotating DRWT



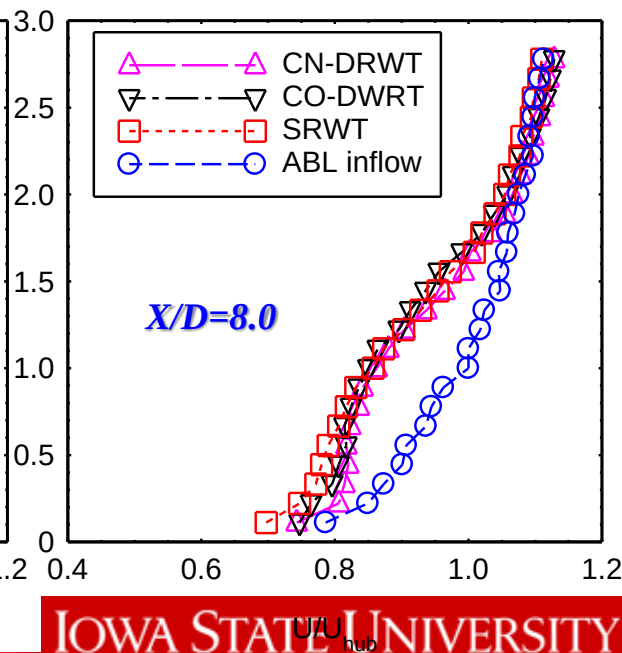
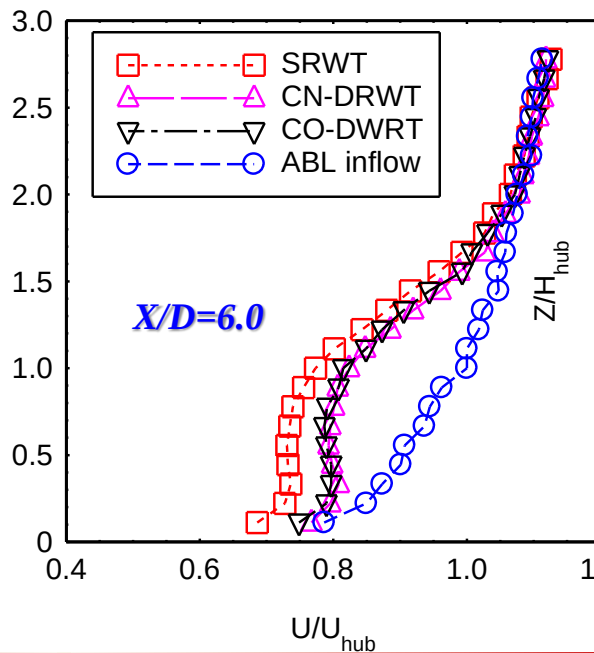
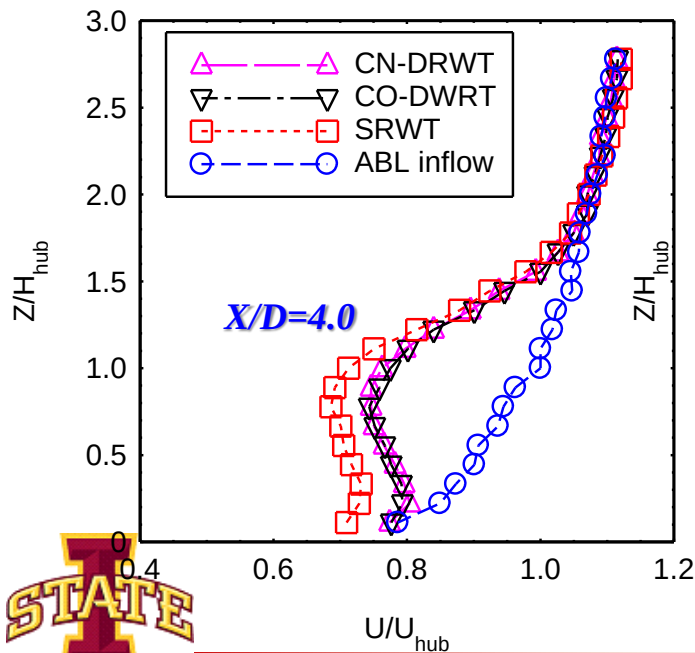
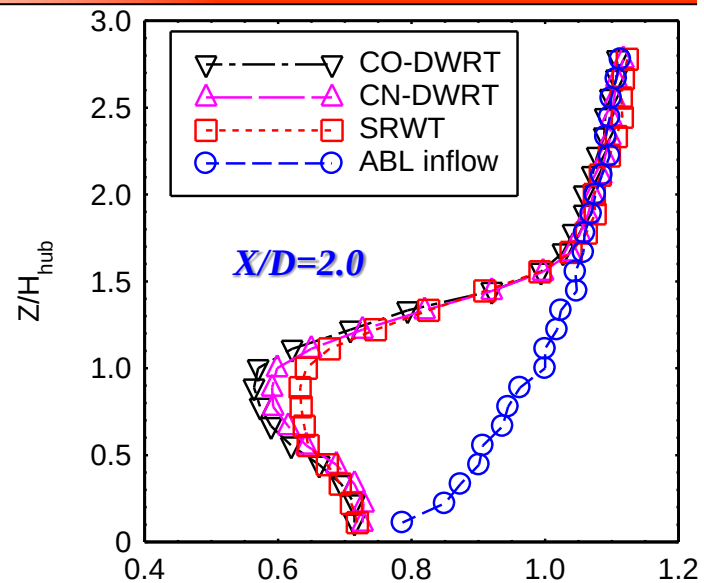
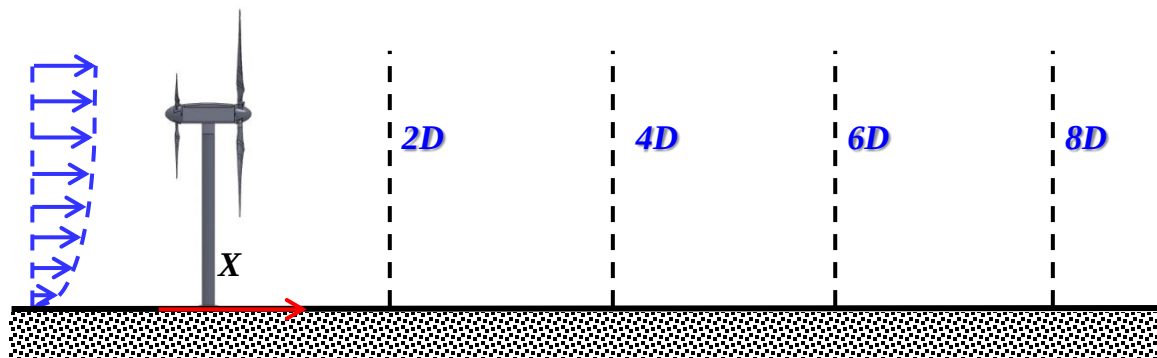
Stereo-PIV measurement Results: SRWT and DRWTs



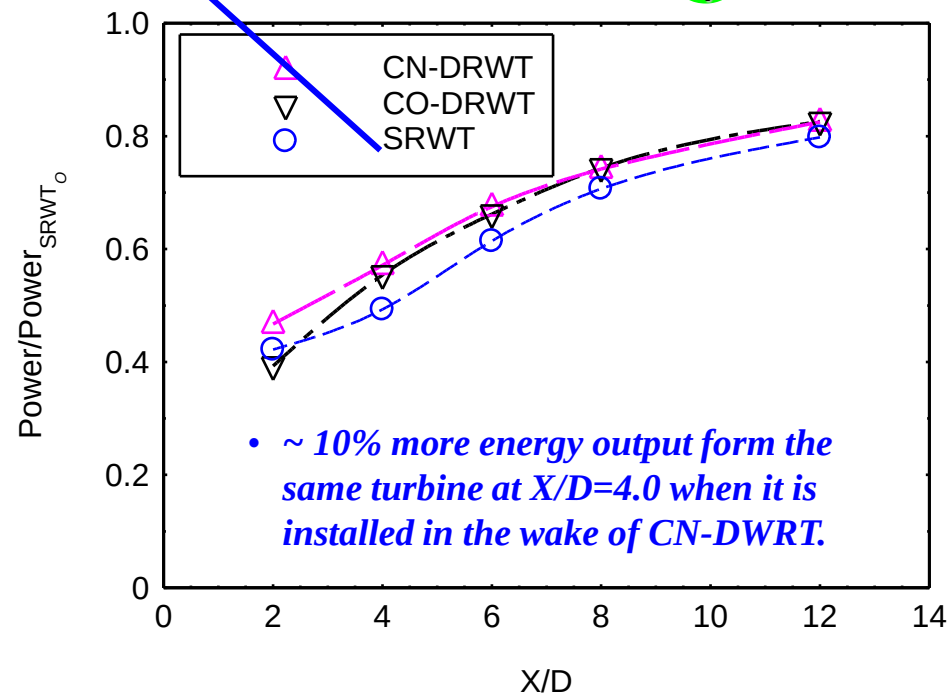
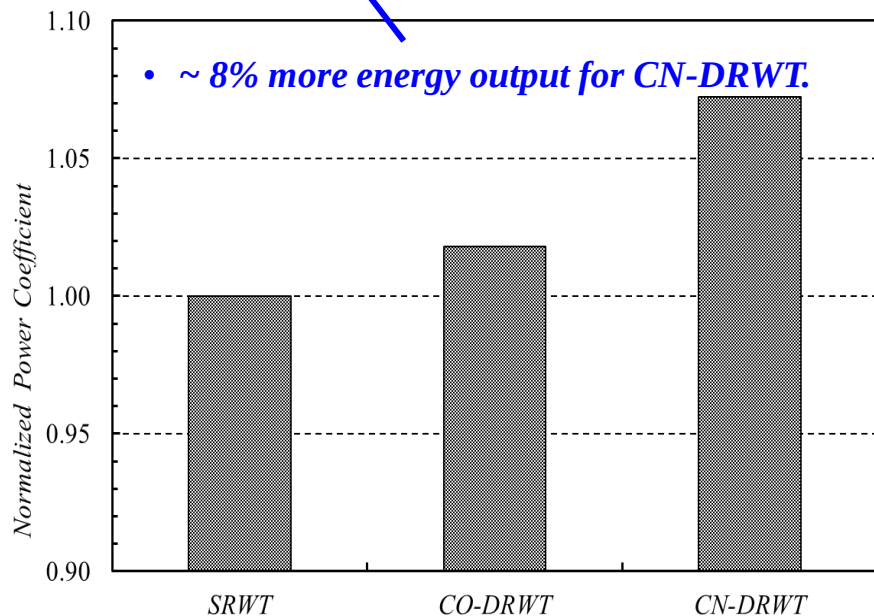
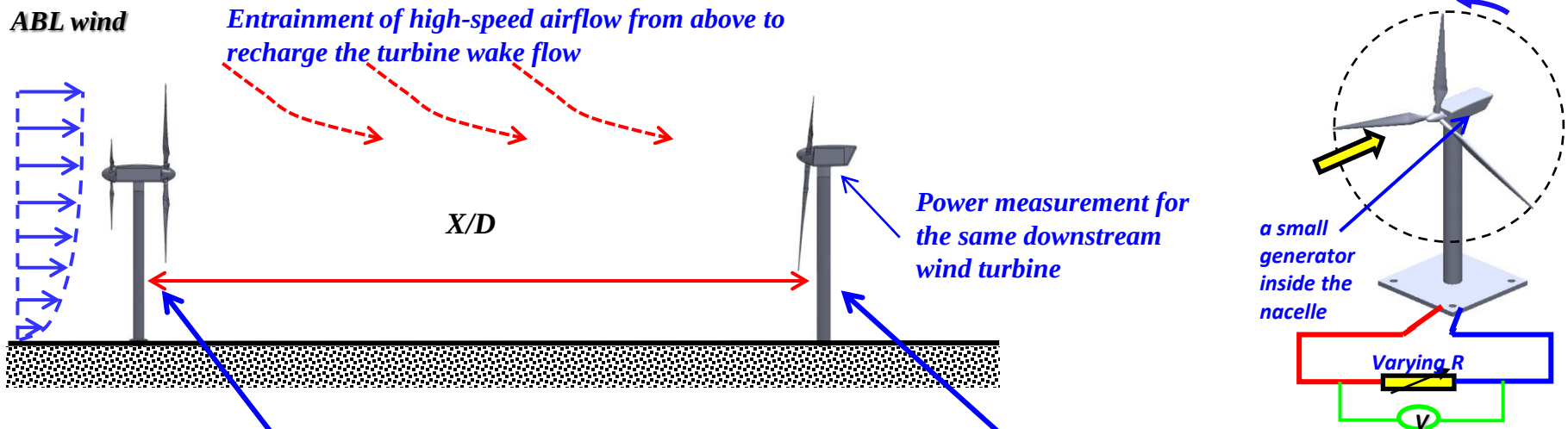
Stereo-PIV measurement Results: SRWT and DRWTs



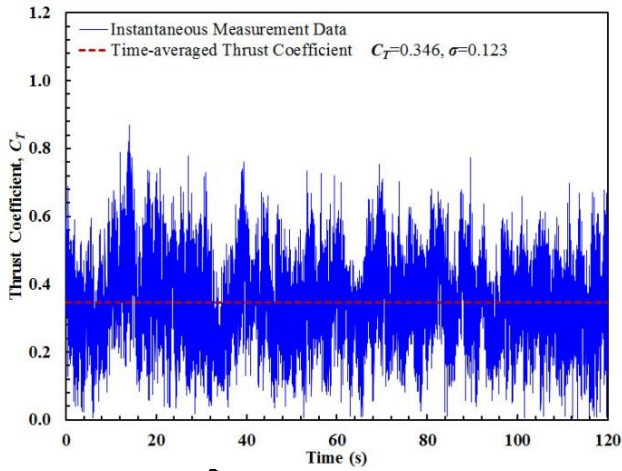
SRWT vs. Co-Rotating DRWT vs. Counter-rotating DRWT



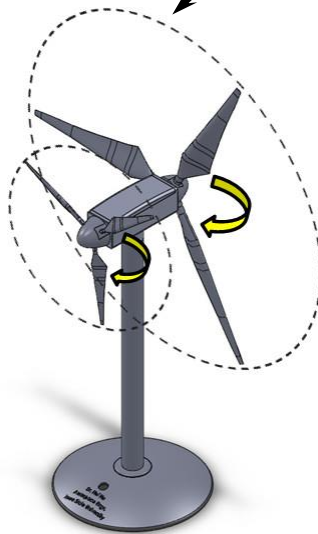
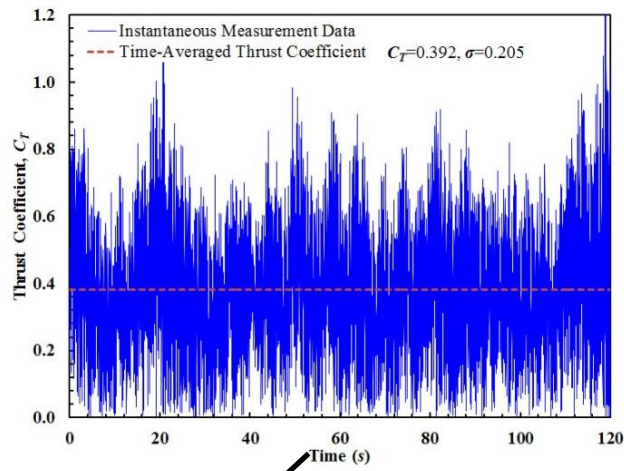
SRWT vs. Co-rotating DRWT vs. Counter-rotating DRWT



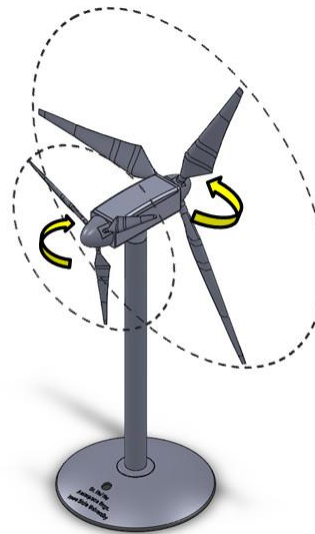
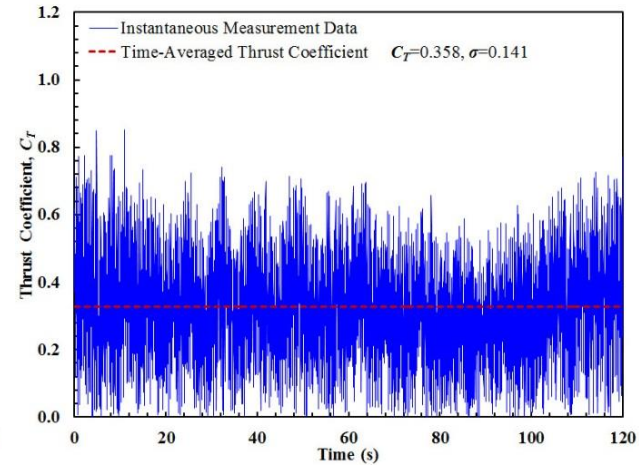
Dynamic wind loads for SRWT and DRWTs



SRWT

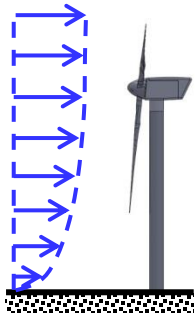


CO-DRWT

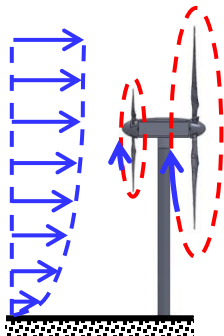


CN-DRWT

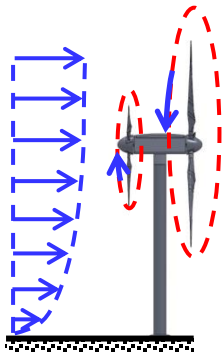
Comparison of SRWT and DRWT: Thrust Force and Bending Moment



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**

- RMS 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

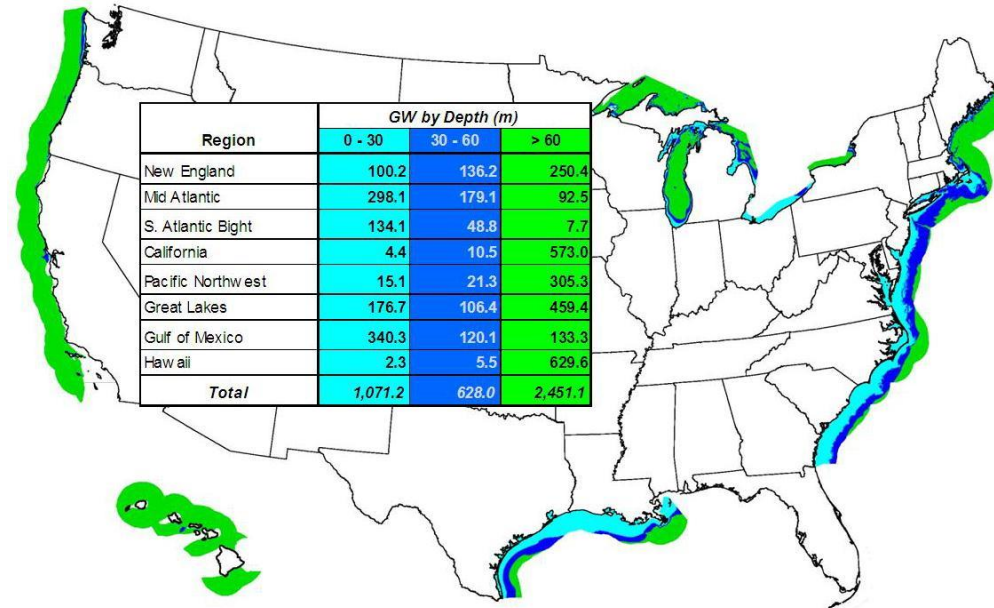
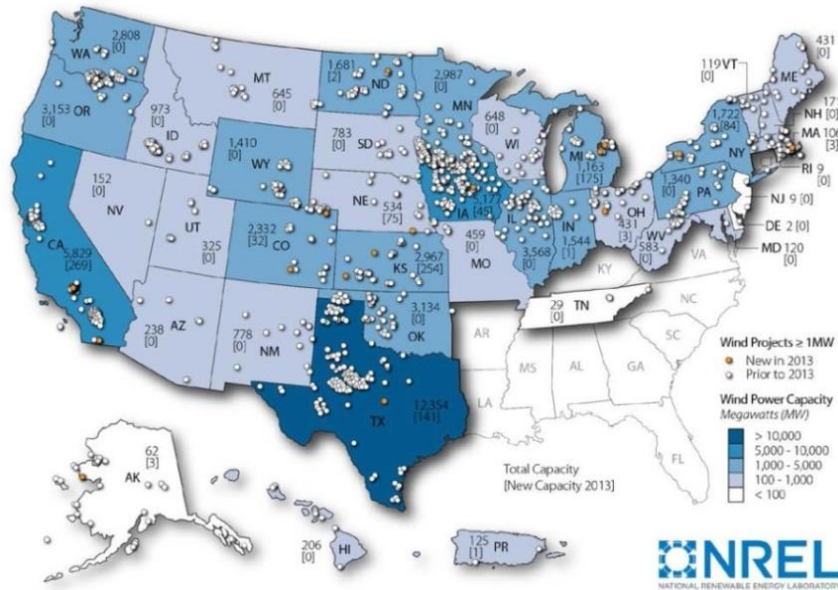
- 10%~30% higher wind load fluctuations for DRWTs**

Dual-Rotor Wind Turbine Designs

- ❑ Dr. Hui Hu and Dr. Anupam Sharma received **2014 Renewable Energy Impact Award** of Iowa Energy Center (IEC) due to their research on "Innovative Dual-Rotor Wind Turbine (DRWT) Designs for Improved Turbine Performance and Wind-Farm Efficiency".



Onshore and Offshore Wind Energy in USA



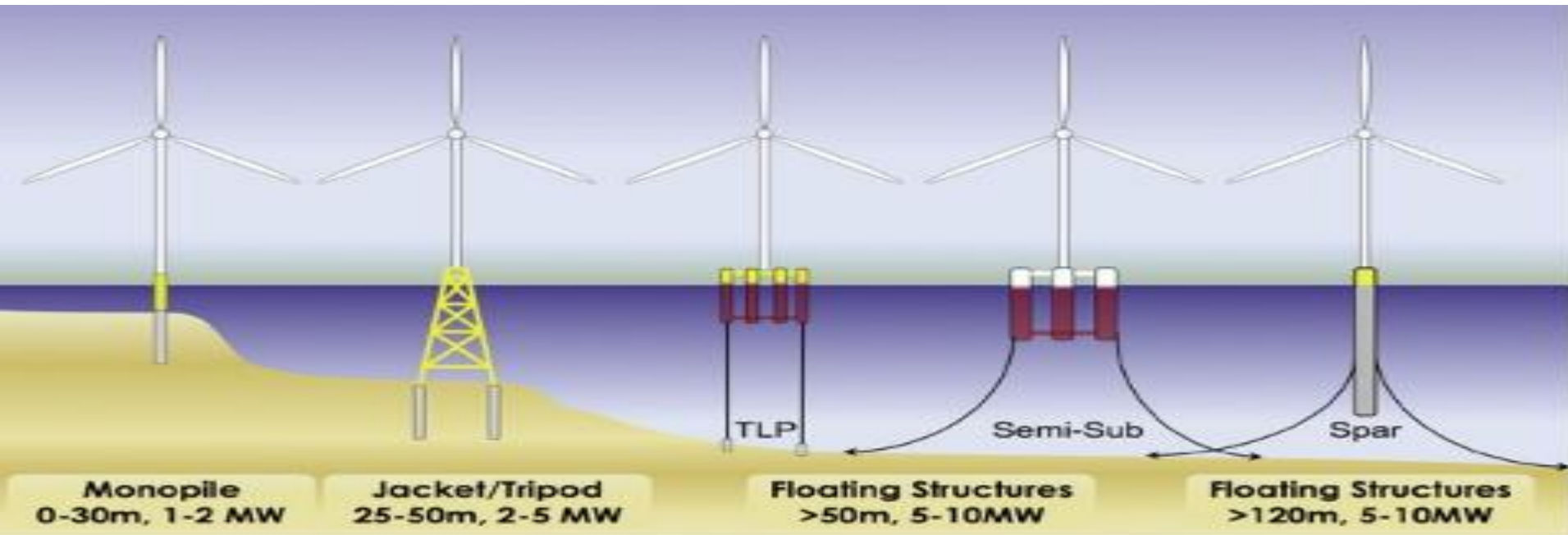
<http://www.nrel.gov/gis/wind.html>

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

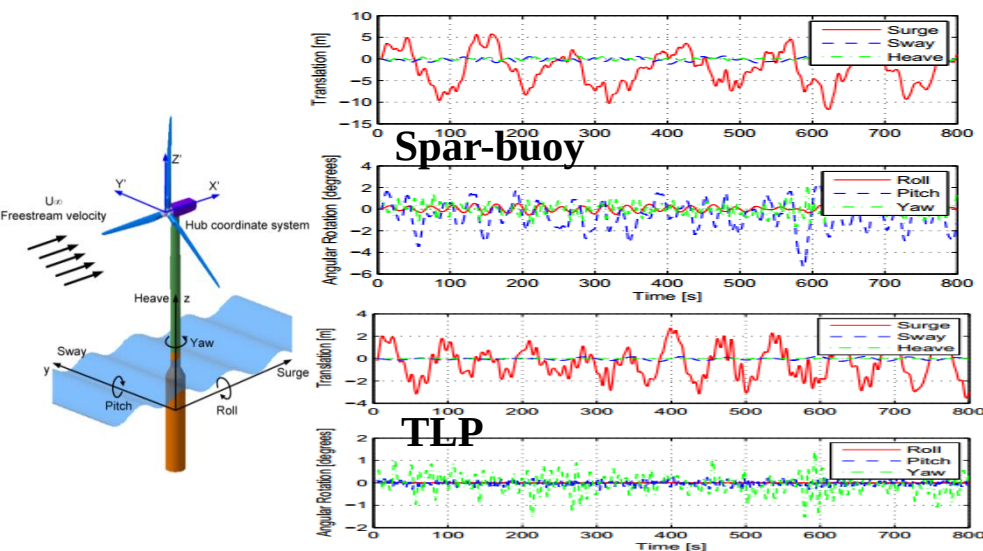
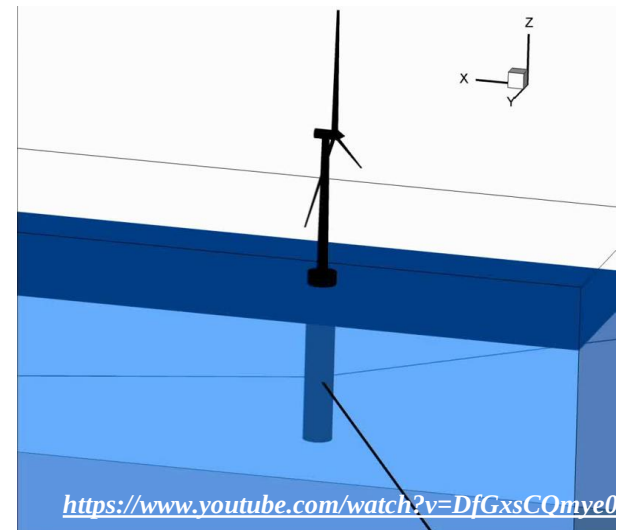
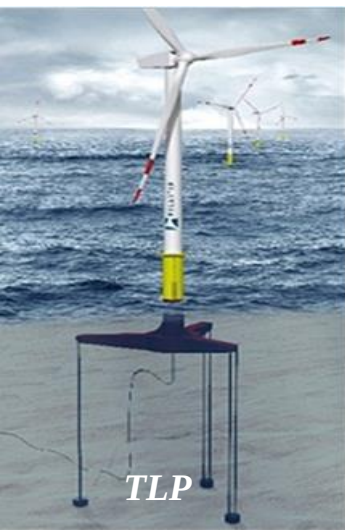


Offshore Wind Turbines

- *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

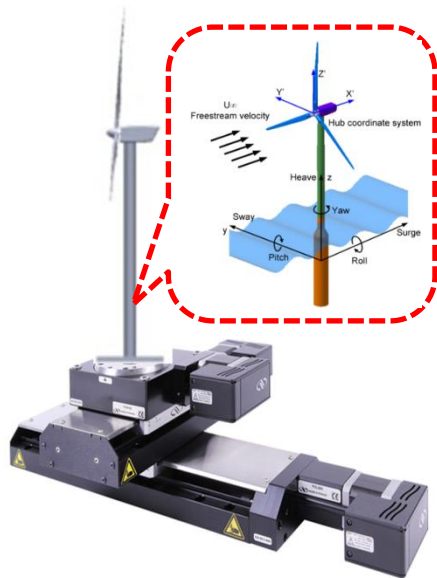


Aeromechanics of Offshore Wind Turbines

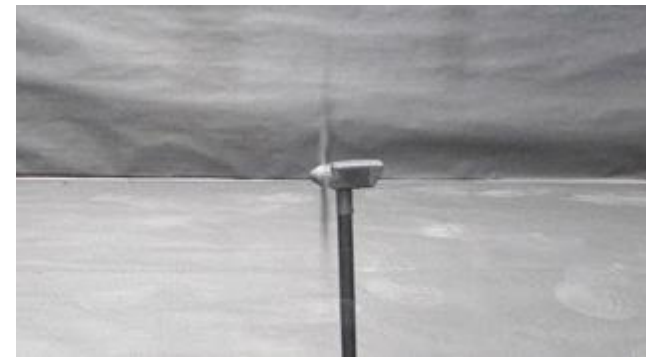
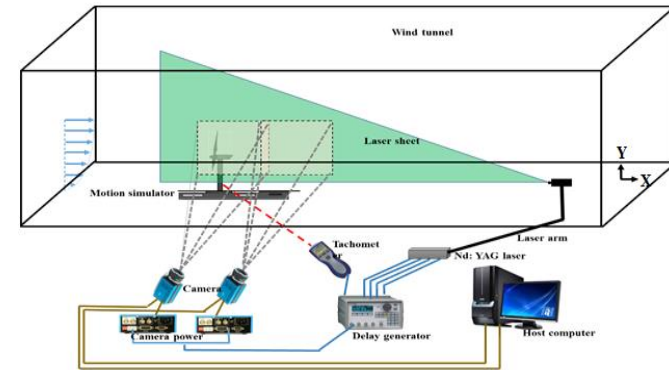
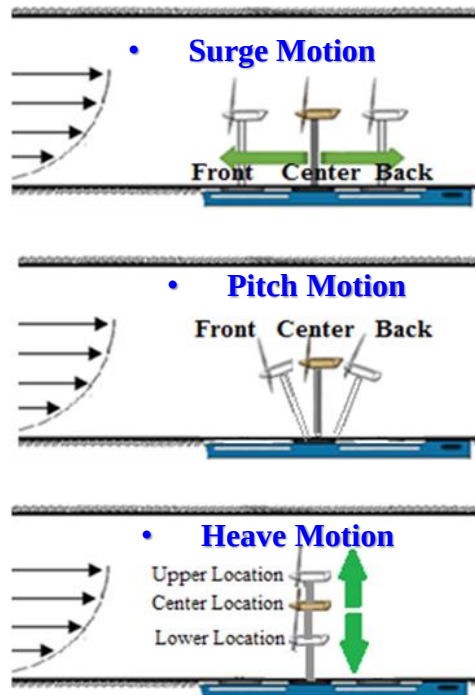


- Sebastian & Lackner (2013), "Characterization of the unsteady aerodynamics of offshore floating wind turbines," *Wind Energy*, 16(3), pp. 339–352.

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 wind turbine



• **Combined motion**



• **Surge motion**

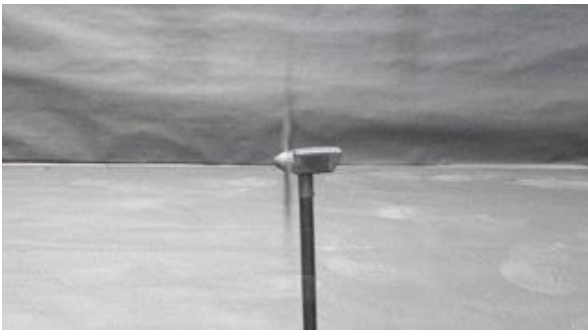


• **Pitch motion**

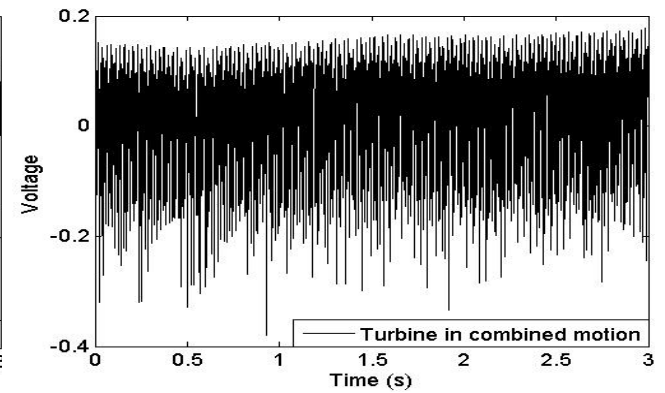
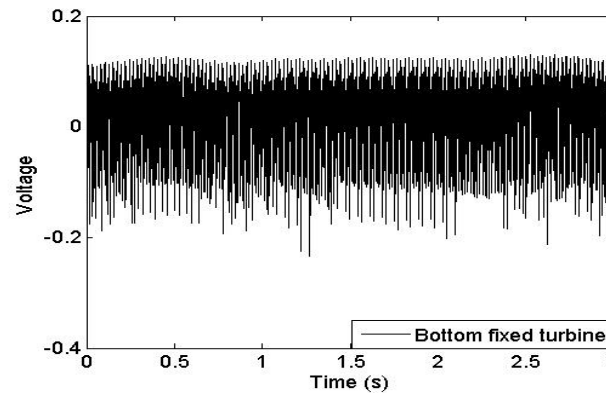


• **Heave motion**

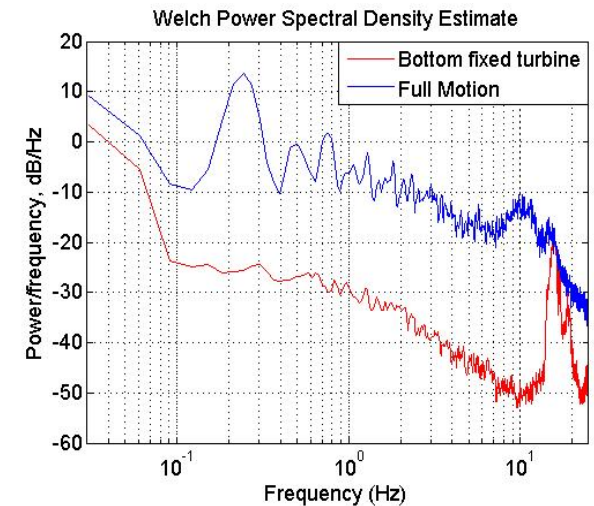
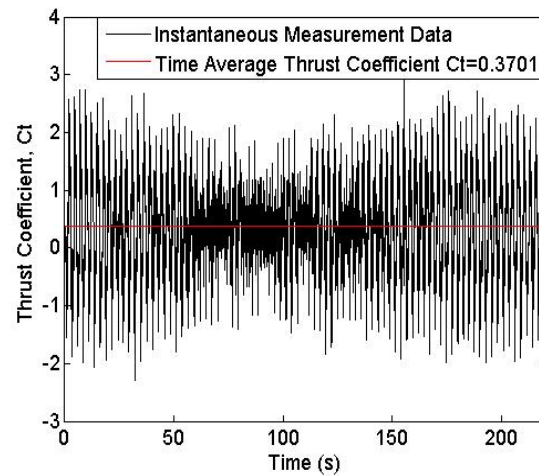
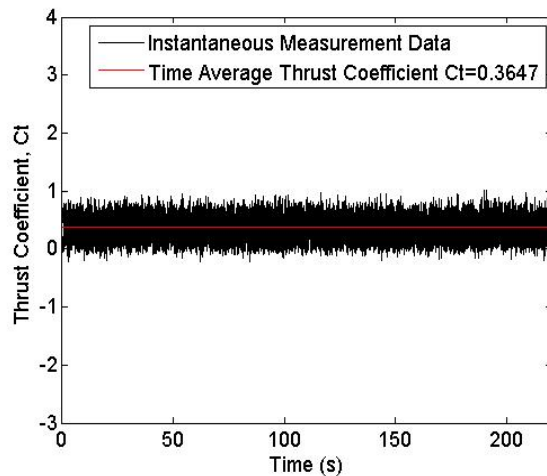
Bottom Fixed WT vs. the WT in Combined Motion



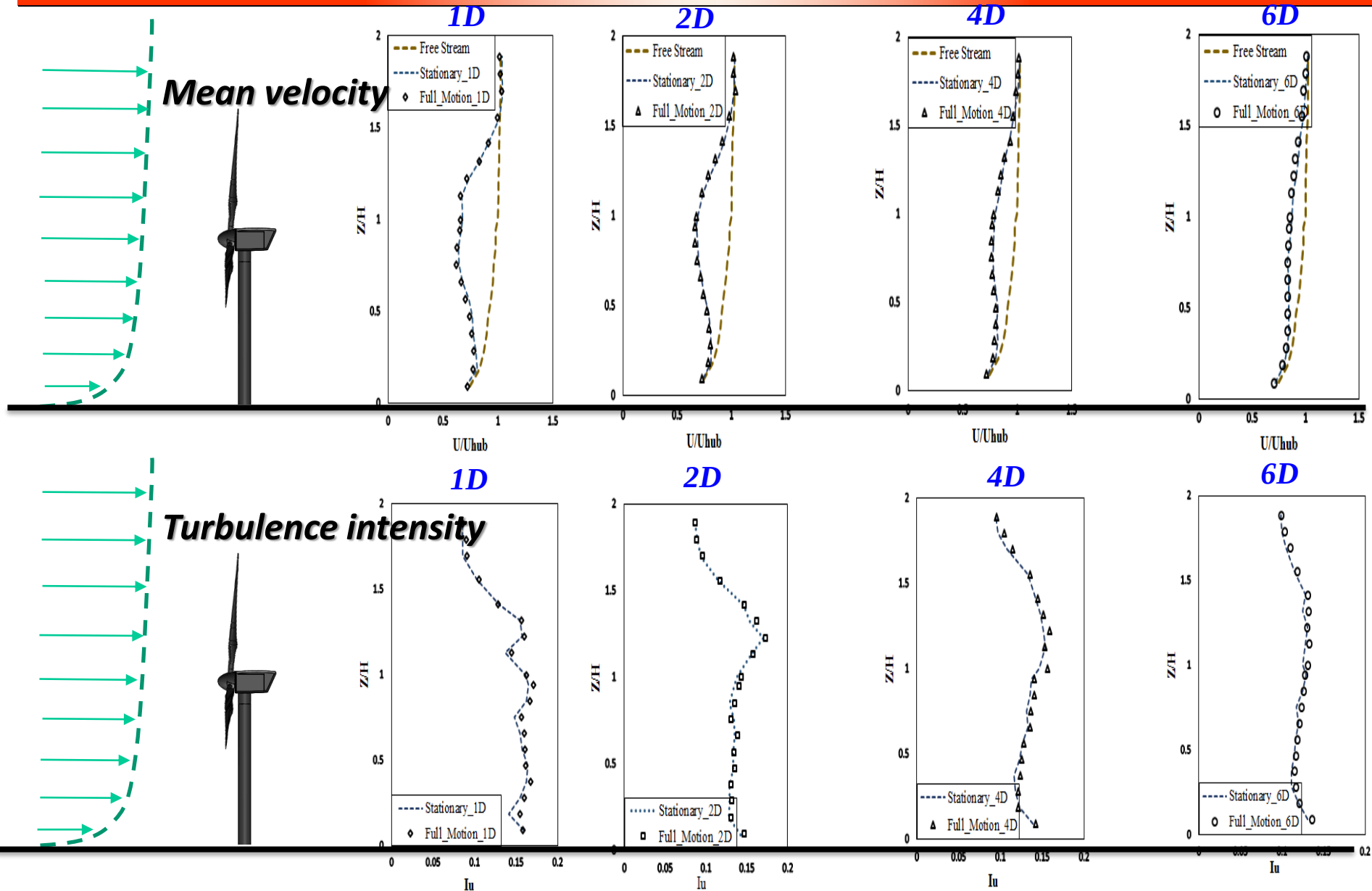
- Combined motion



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



Wake Characteristics of the Wind Turbine in Combined Motion



OFFSHORE WIND ENERGY IN USA?

https://www.youtube.com/watch?v=Toh_7XpyNo0

CBS news on Apr 22, 2021



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Hu Lab's Summer BBQ Party on 07/25/2021

THANK YOU VERY MUCH FOR YOUR TIME!
QUESTIONS?

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