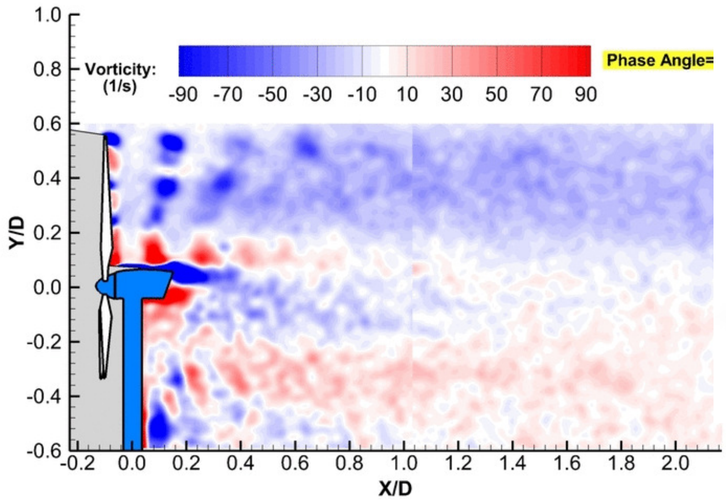

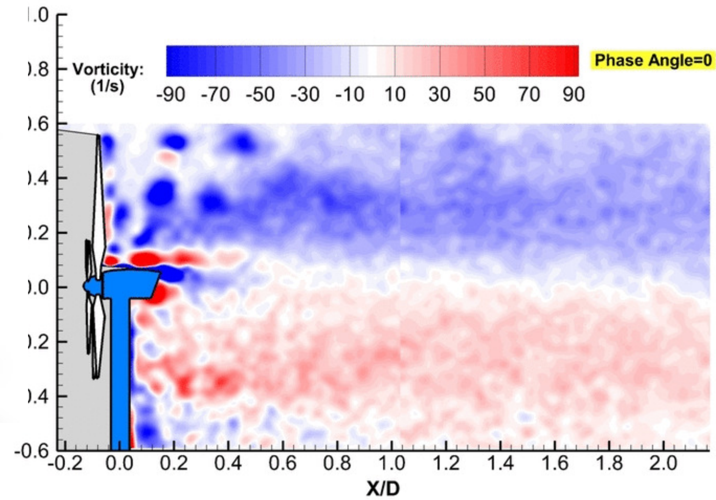

A Wind Tunnel Study on the Aeromechanics of a Novel Twin-Rotor Wind Turbine Model

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Iowa State University

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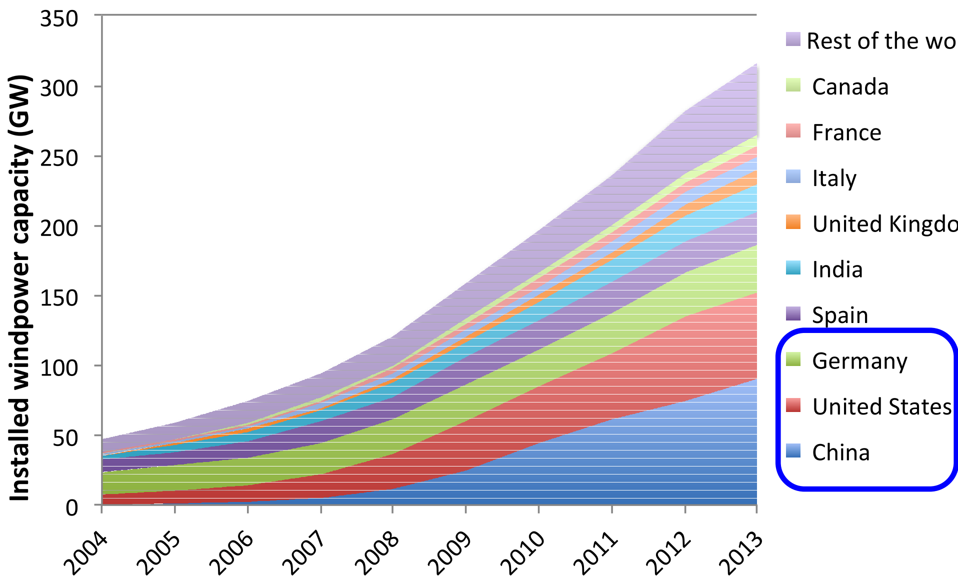
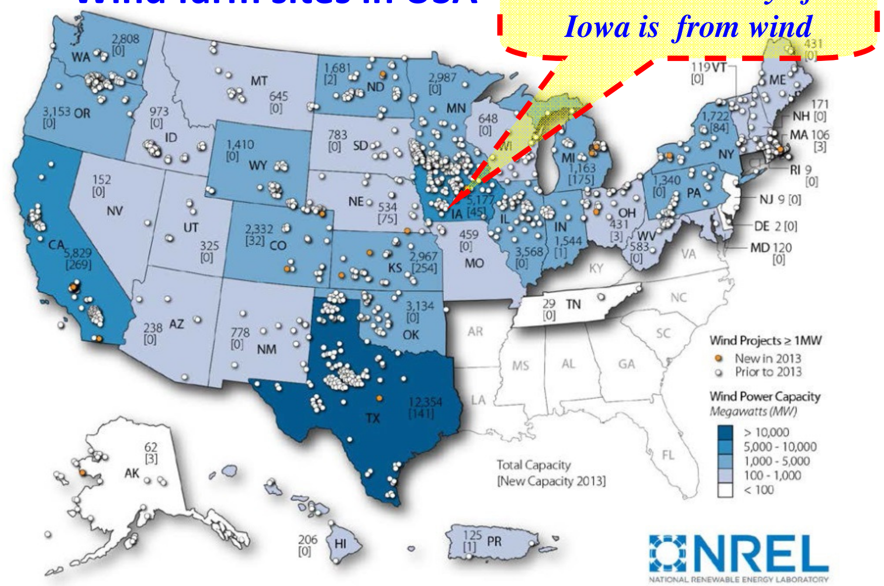
Wind Energy Production and Wind Turbine Installations in USA



Wind farm sites in USA

27.4% electricity of Iowa is from wind



- ***A target of 20% of US electricity from wind energy by 2030 has been set up by the U.S. Department of Energy (DOE).***
- ***Iowa is the 3rd in the nation in installed wind energy capacity and it has the highest density of wind power generation capacity with 29.9 kW/km²***
- ***According to 2013 DoE wind Technologies Mark Report, Iowa has reached the milestone of 27.4% of the state's electricity in 2013, while the national average rate is about 4.1% in 2013.***

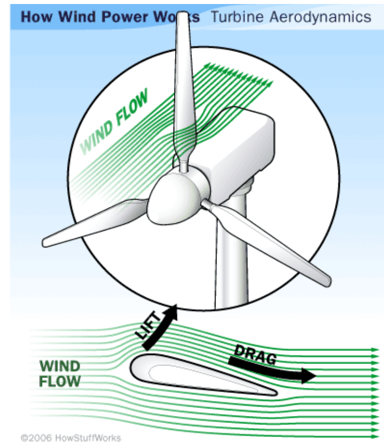
Top Wind Energy Production States:

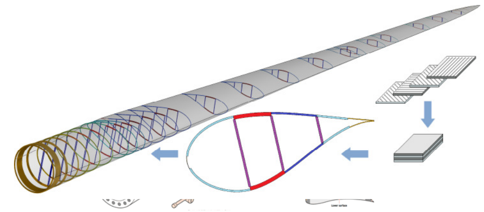
- ***Texas:*** ***12,354 MW(8.3%)***
- ***California:*** ***5,829 MW (6.6%)***
- ***Iowa:*** ***5,177 MW (27.4%)***
- ***Illinois:*** ***3,568 MW (4.7%)***
- ***Oregon:*** ***3,153 MW (12.4%)***
- ***Oklahoma:*** ***3,134 MW (14.8%)***
- ***Minnesota:*** ***2,987 MW (15.7%)***

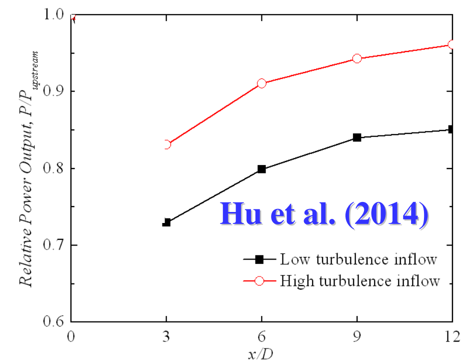
(2014 DoE Wind Technologies Market Report)

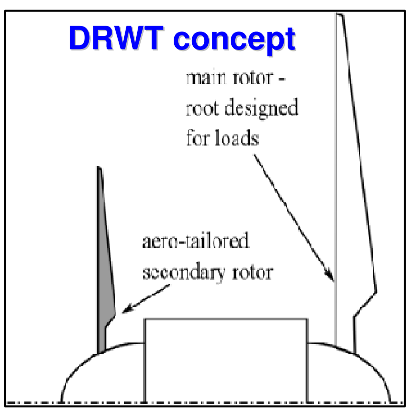
Root Loss and Wake Loss of Wind Turbines

- *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.*



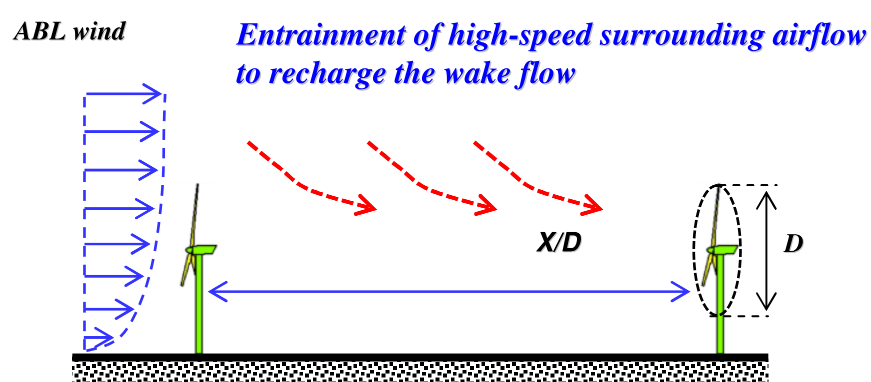




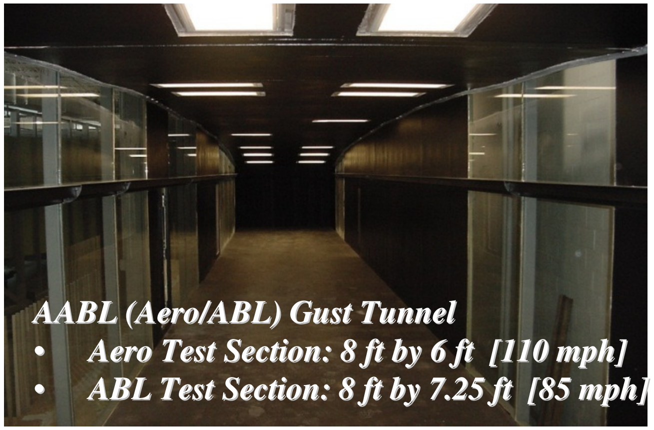


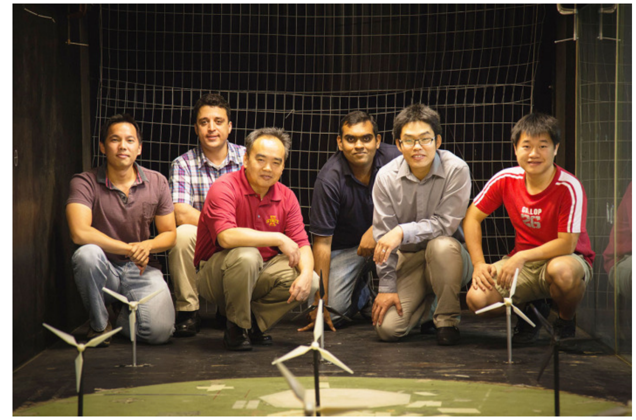
SRWT

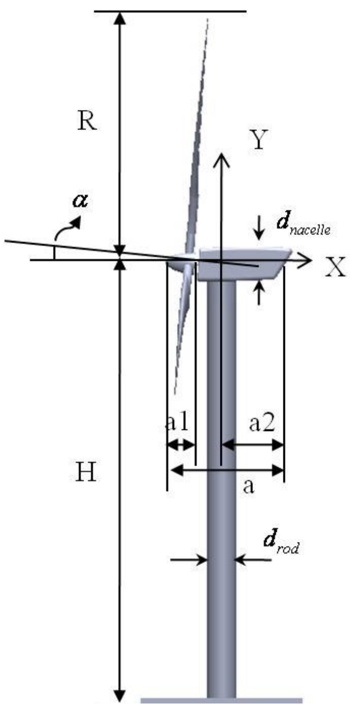
TRWT



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

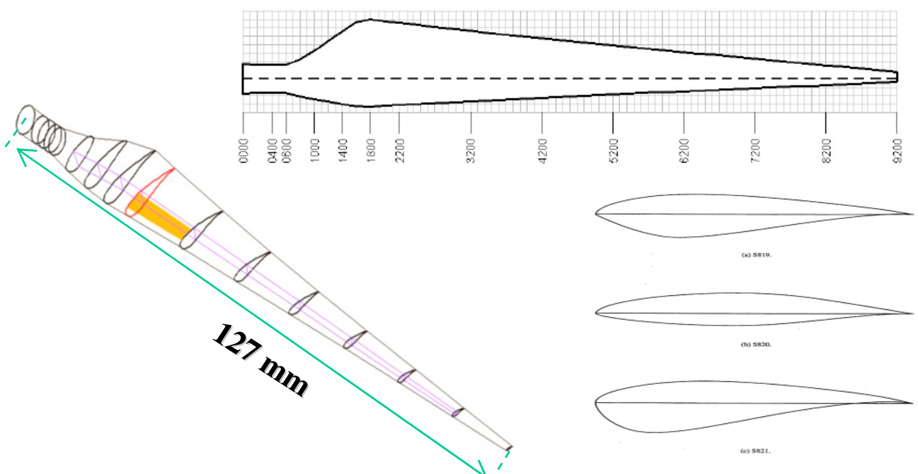




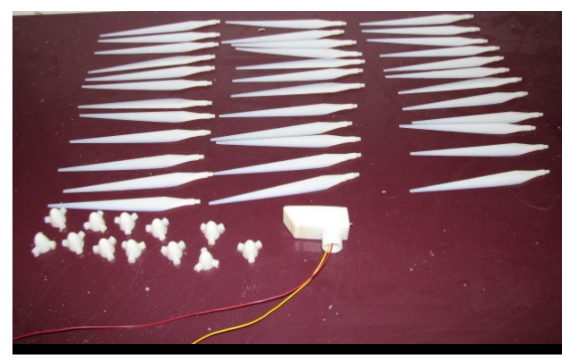


Parameter	*D (mm)*	*H (mm)*	*d_{pole} (mm)*	*$d_{nacelle}$ (mm)*	*α (deg.)*	*a (mm)*	*a1 (mm)*	*A2 (mm)*
Dimension	*280*	*225*	*18*	*18*	*5°*	*78*	*15*	*50*

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



ERS-100 turbine blade design by TPI



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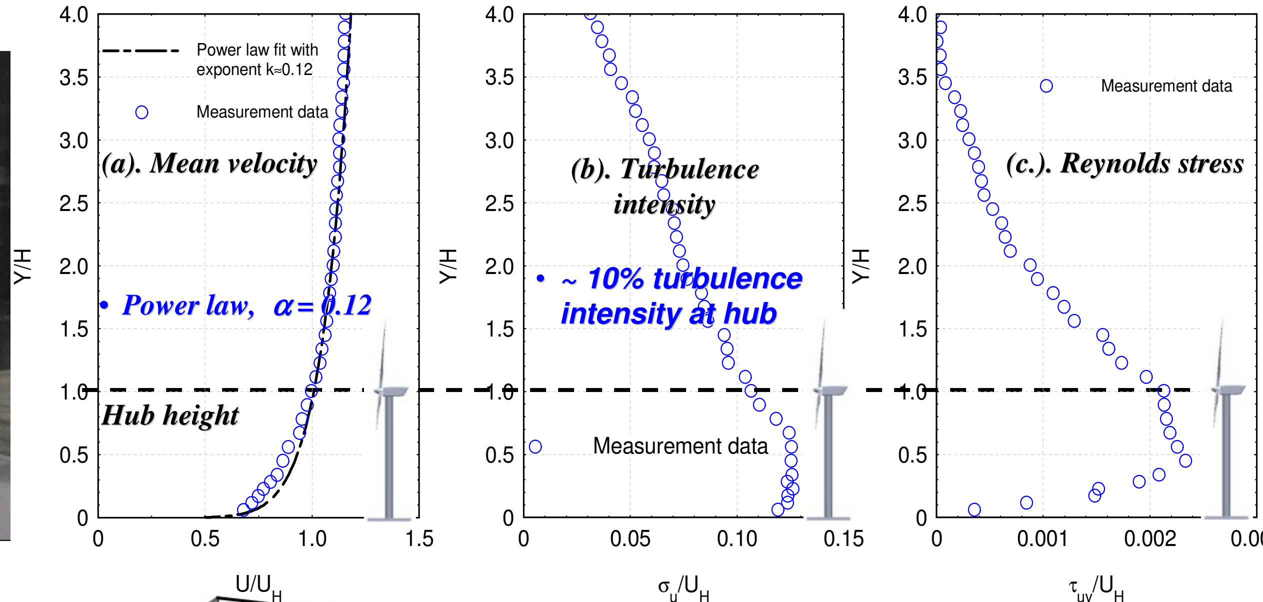
Experimental Setup to Study Wind Turbine Aeromechanics

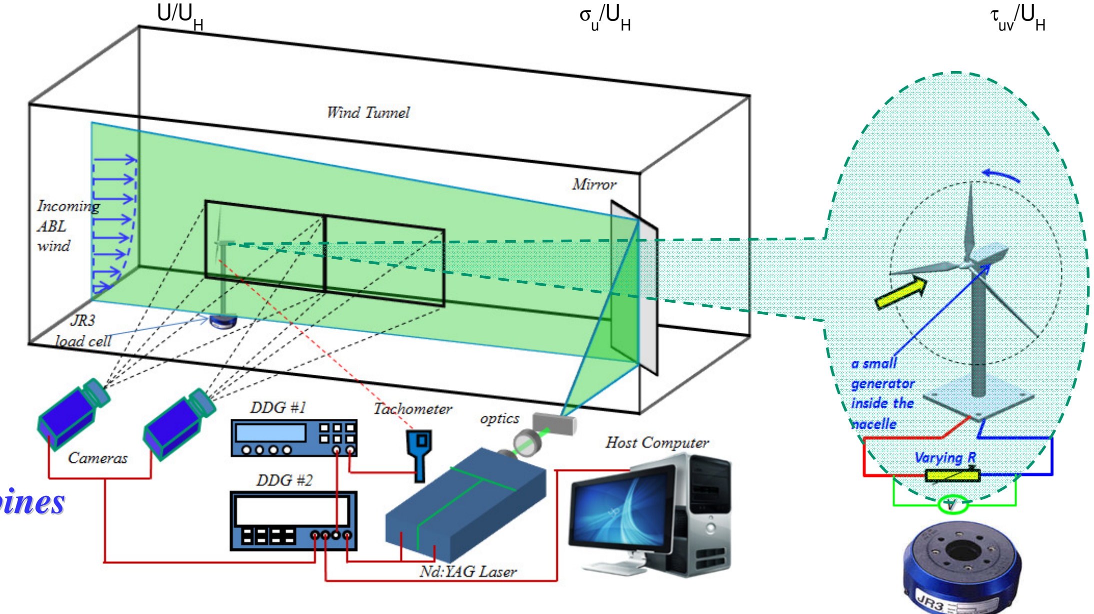


Test flow conditions:

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

Measured parameters:

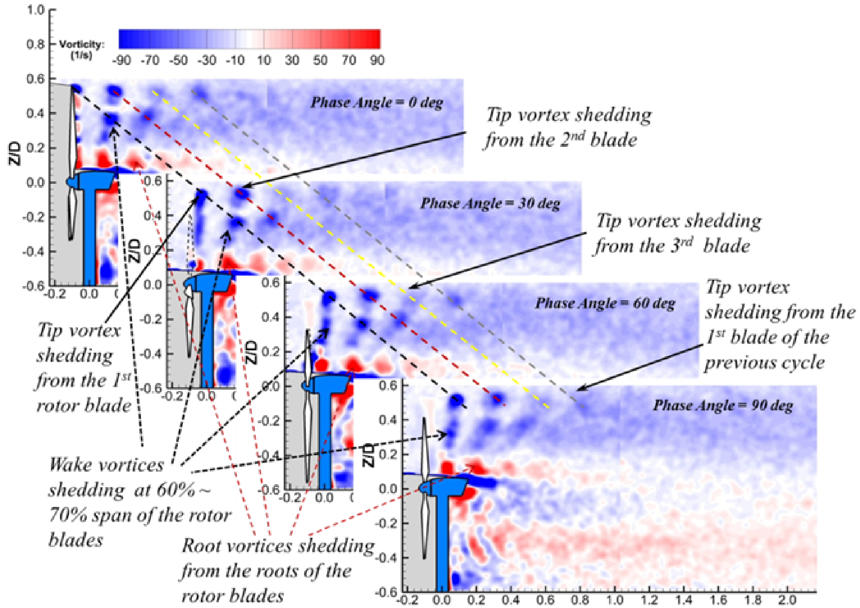
- Characteristics of turbine wake flows
- Power output of wind turbine models
- Dynamic wind loads acting on wind turbines

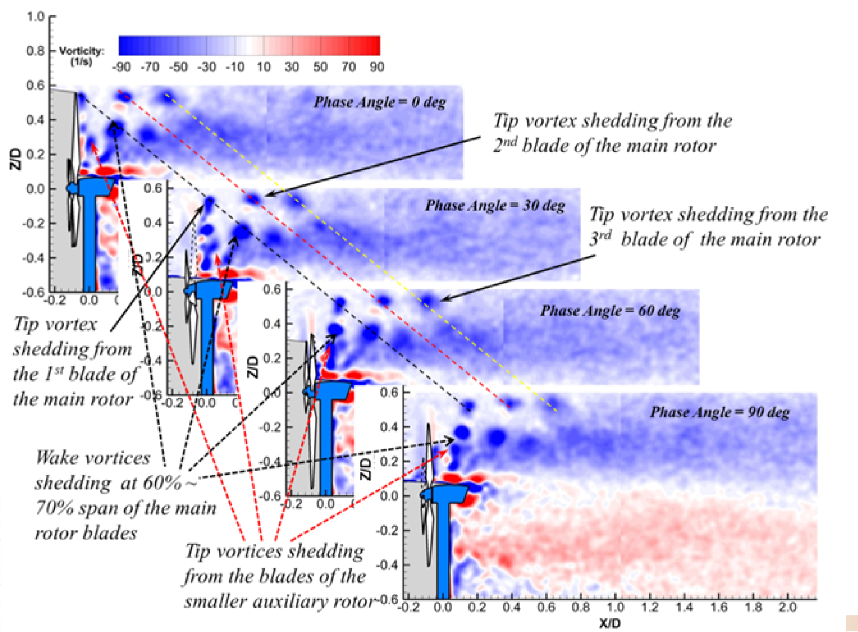


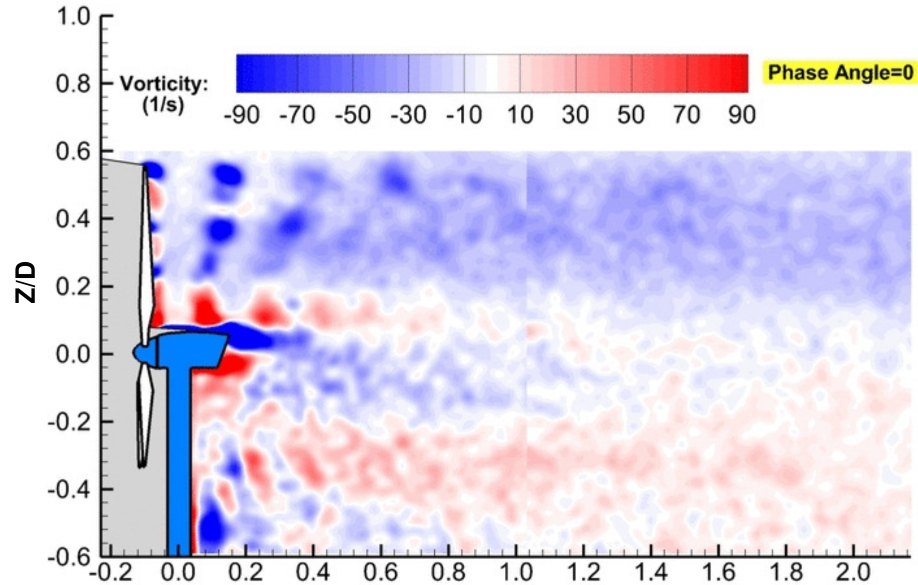
Experimental Setup

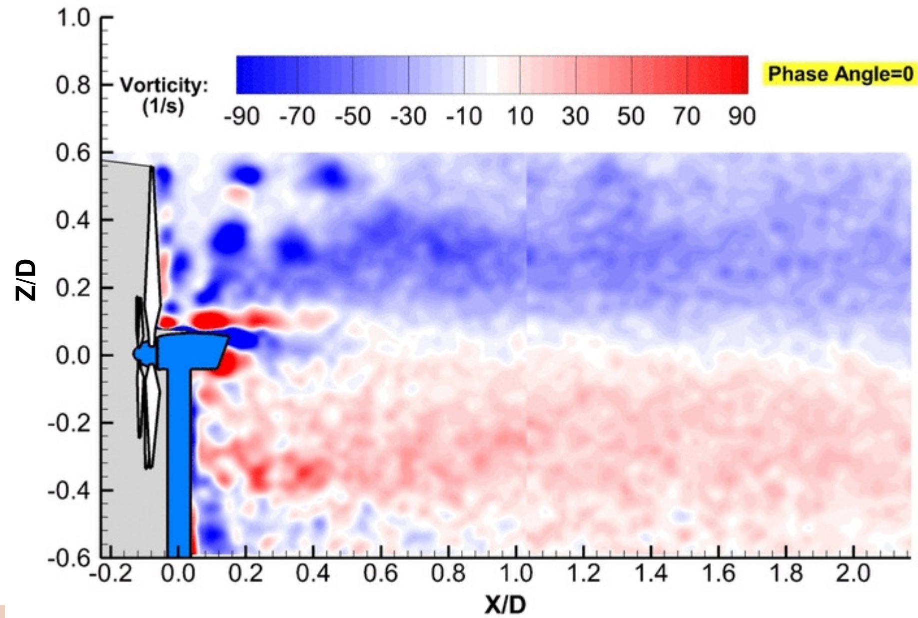
JR3 load cell

Phase-locked PIV measurements (TSR ≈ 5.0)

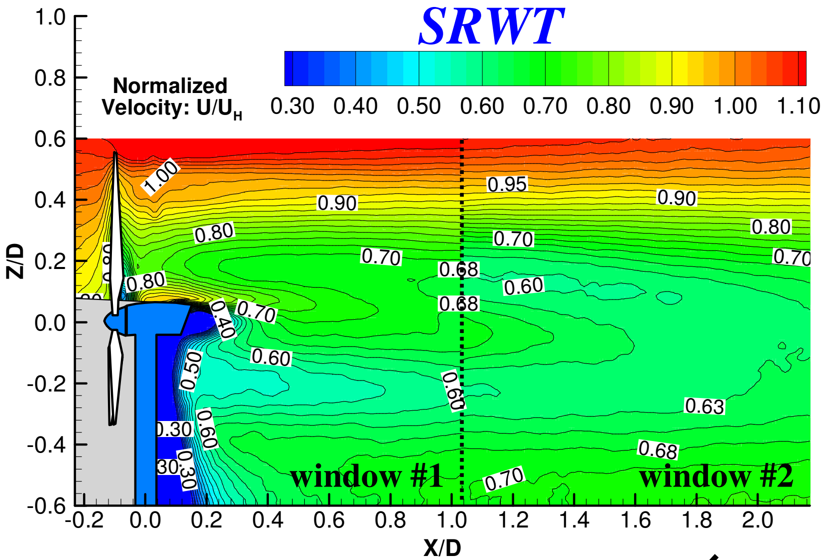


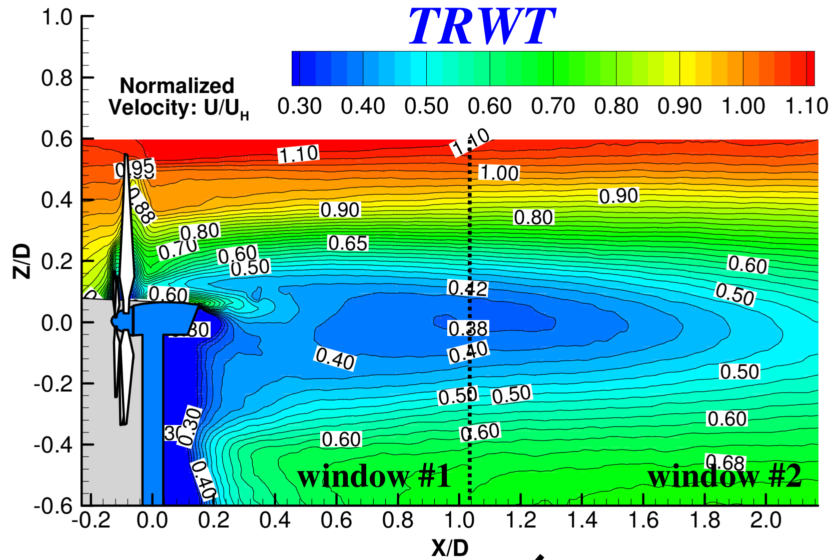


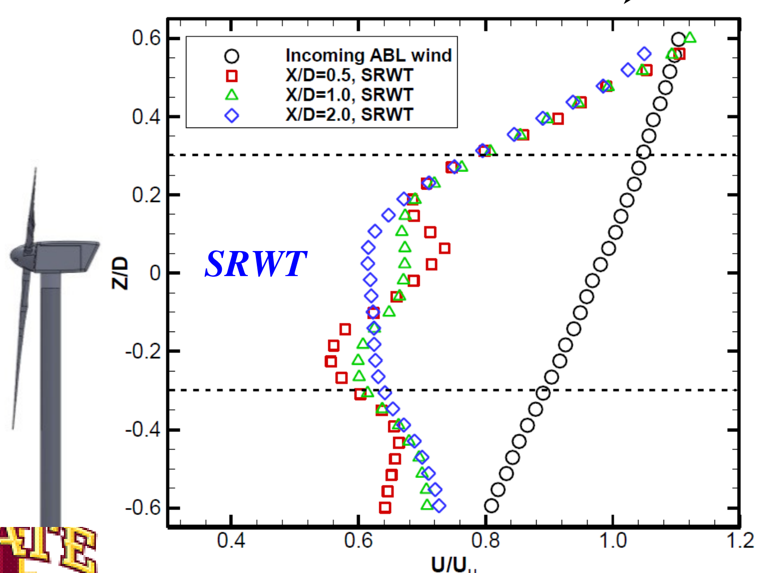


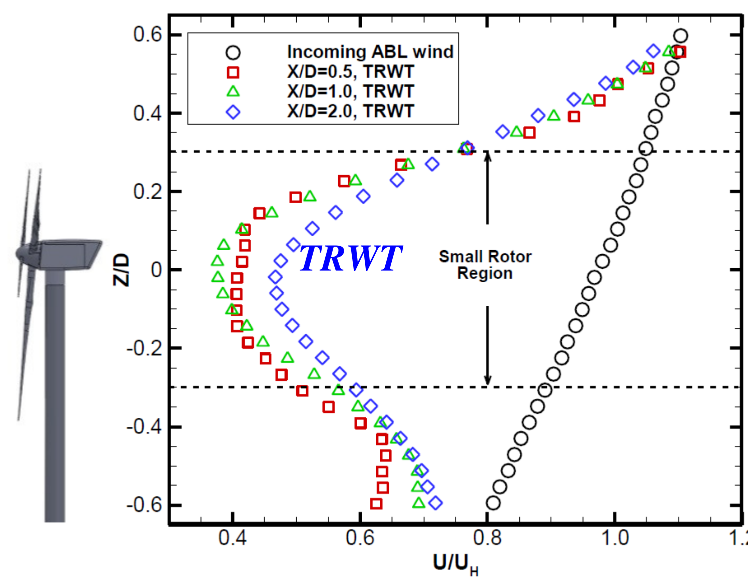


Ensemble-averaged PIV measurements



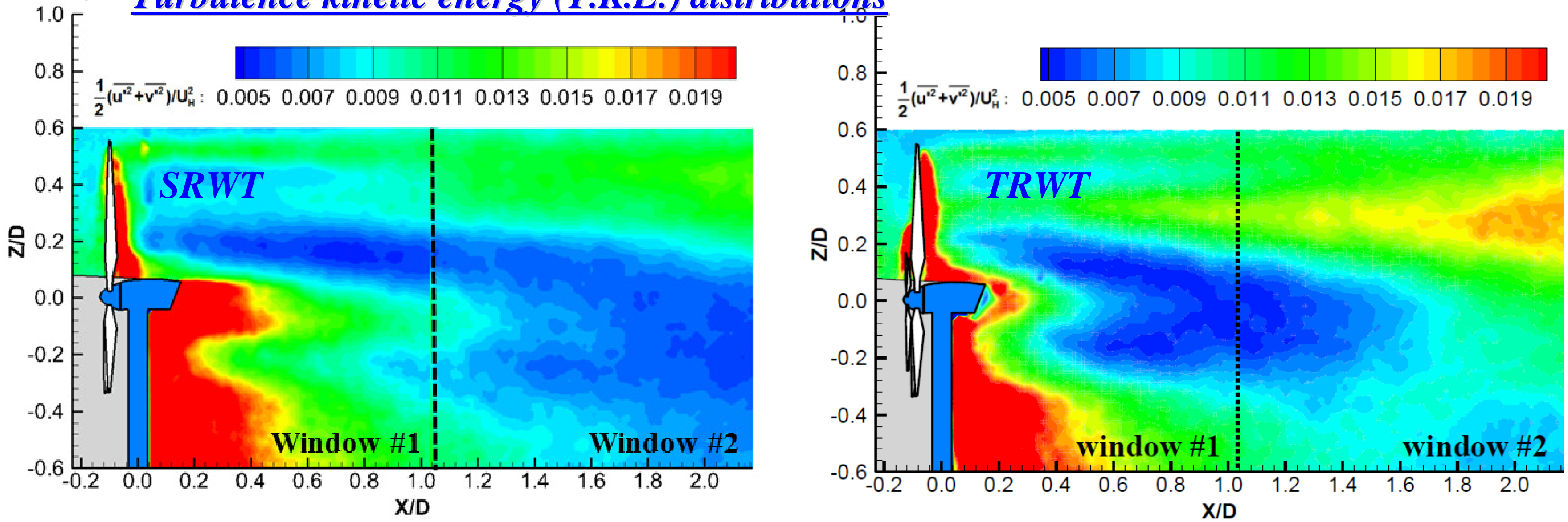




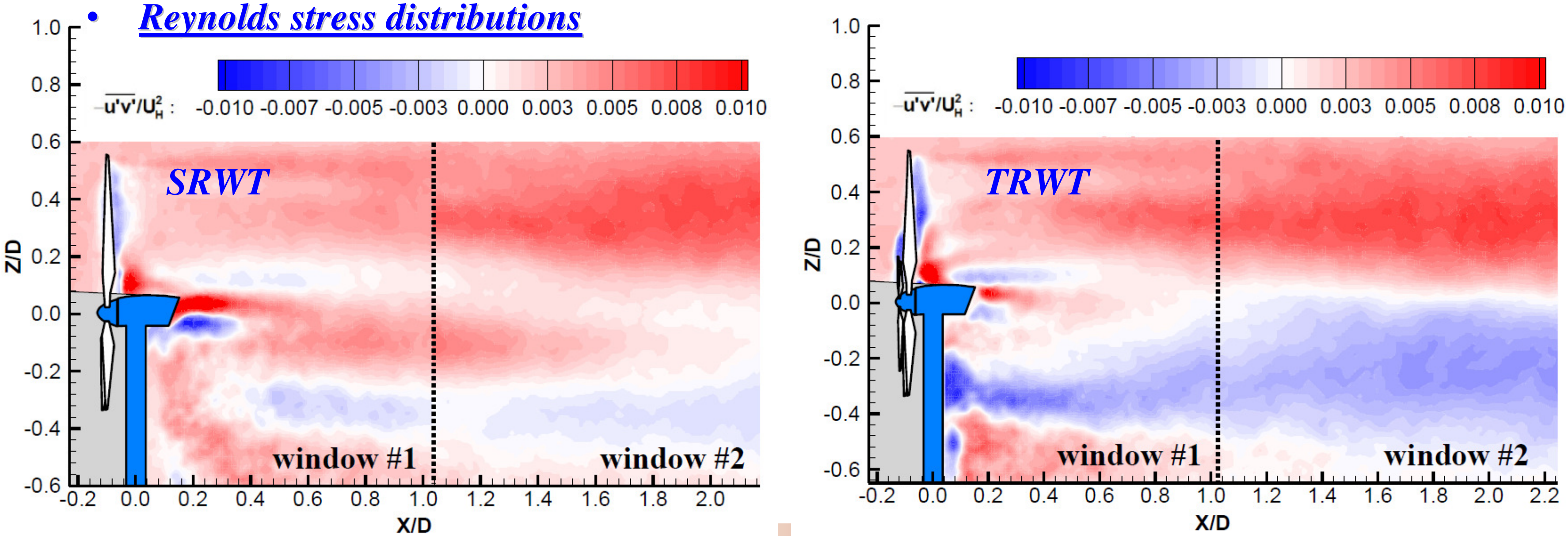


Ensemble-averaged PIV measurements

- ***Turbulence kinetic energy (T.K.E.) distributions***

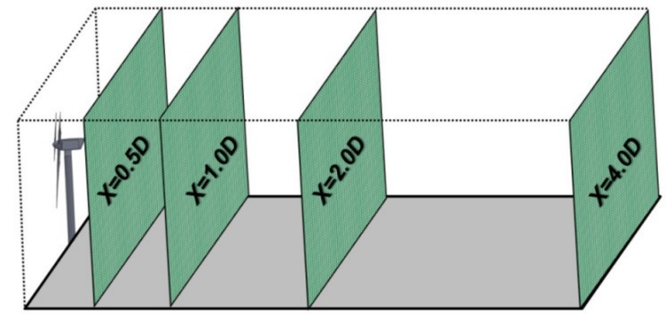


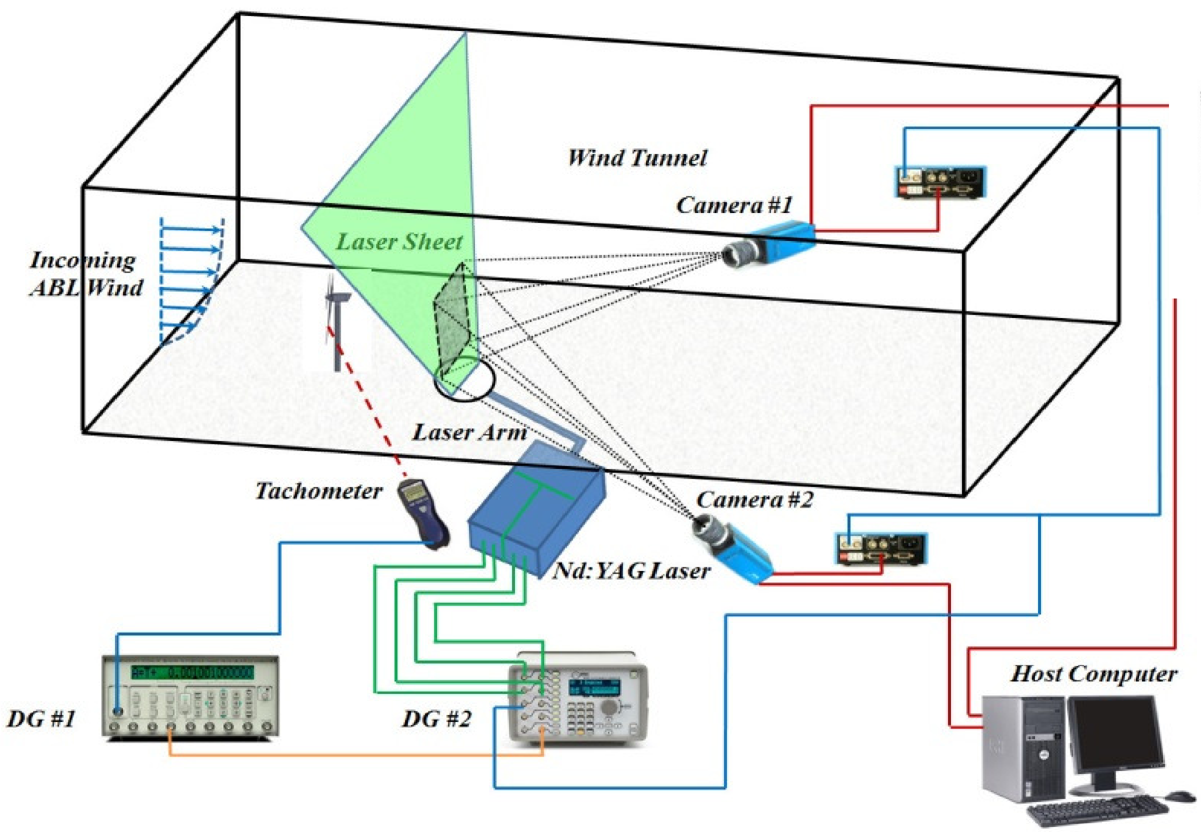
- ***Reynolds stress distributions***



Stereo-PIV measurements

Measuring locations



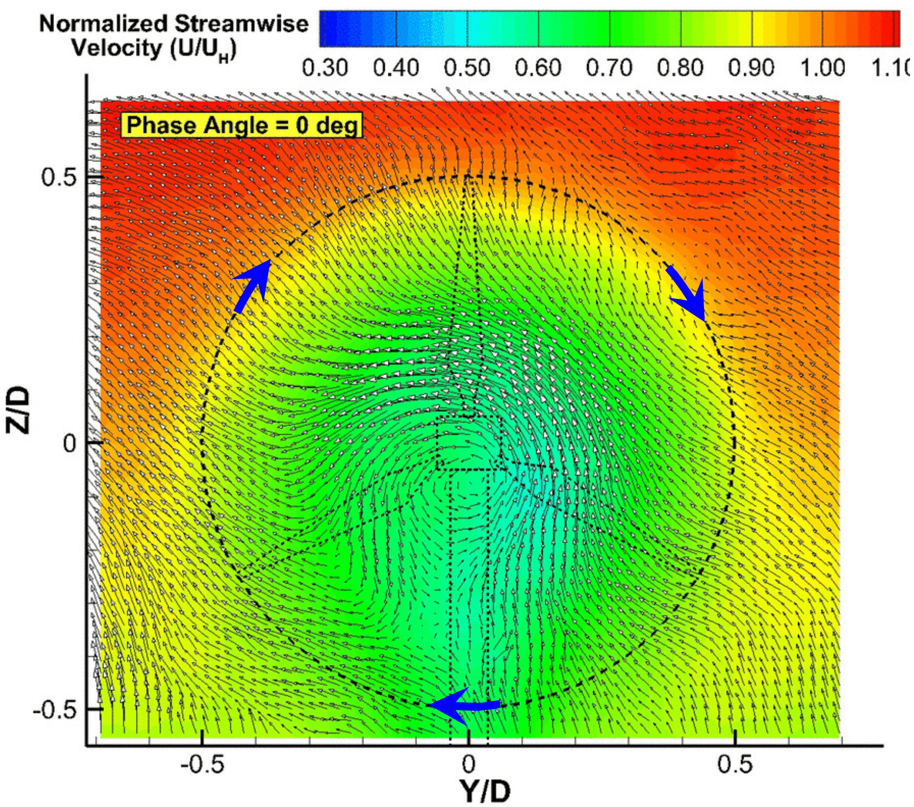


SRWT

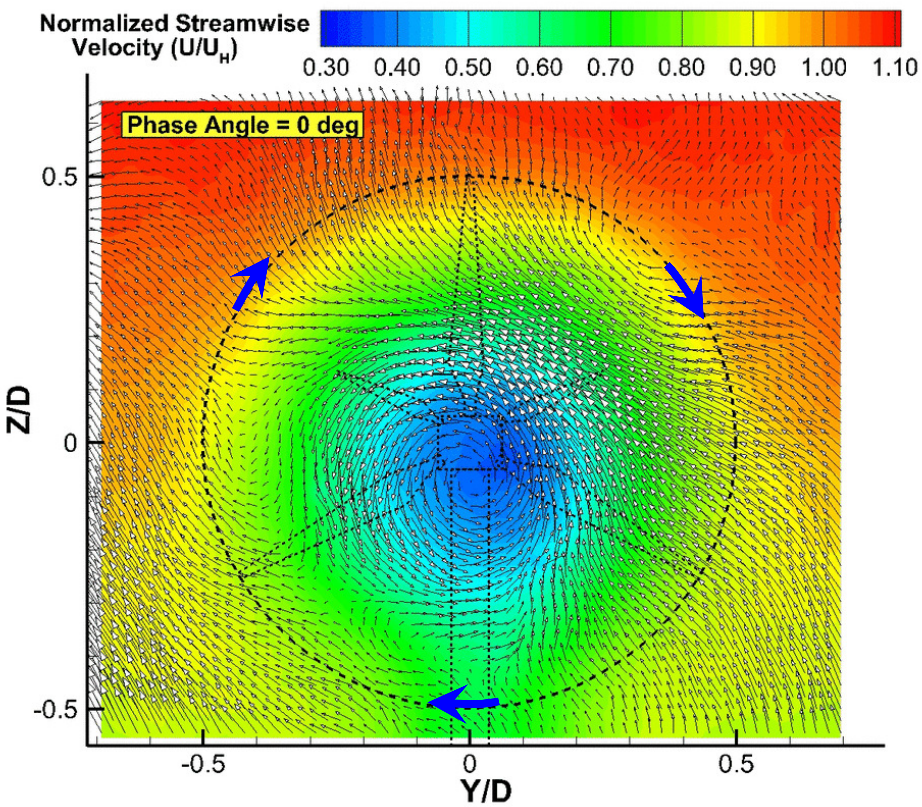
TRWT

Experimental setup for Stereo-PIV measurements

Stereo-PIV measurements

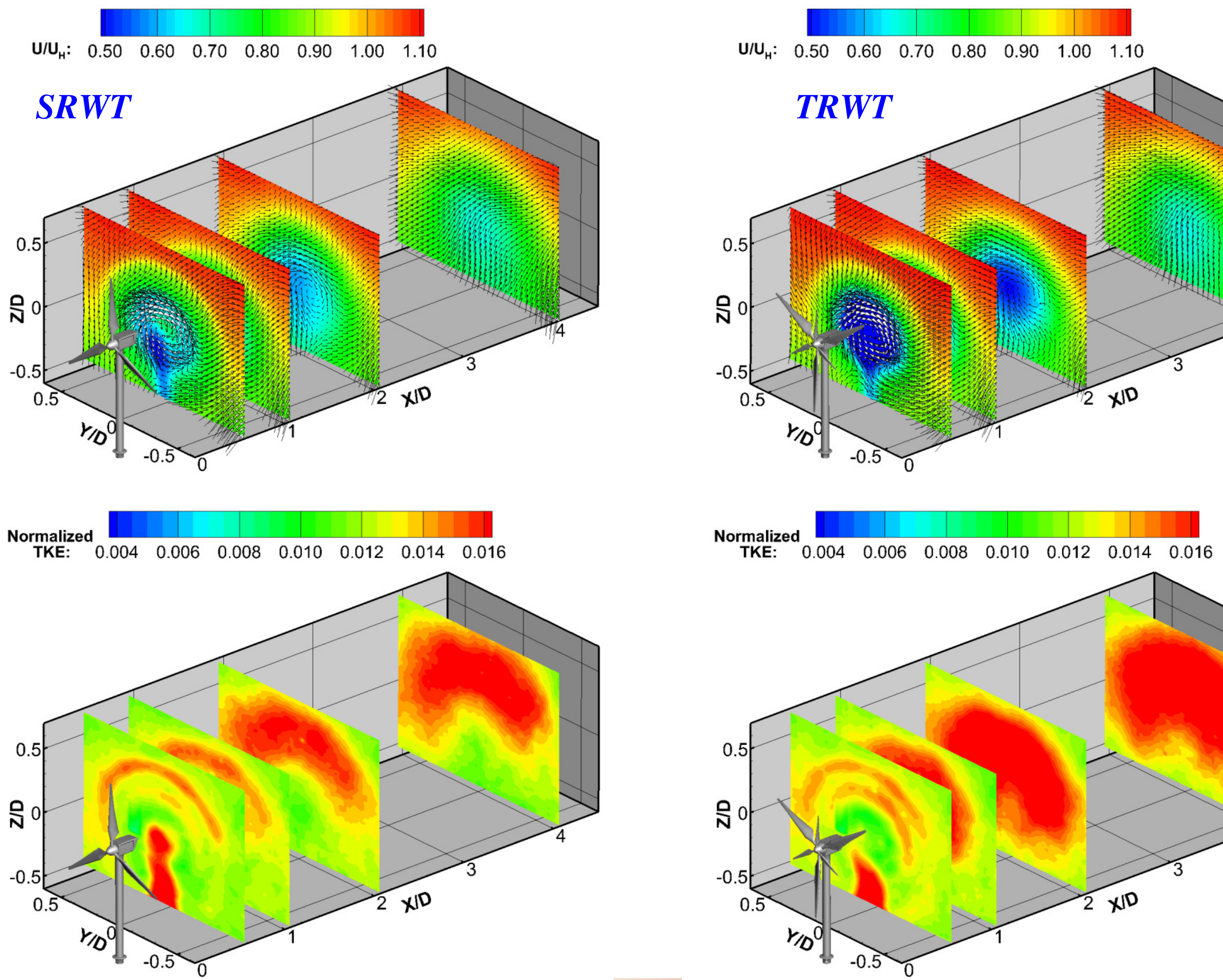


SRWT
X/D=1.0 cross plane

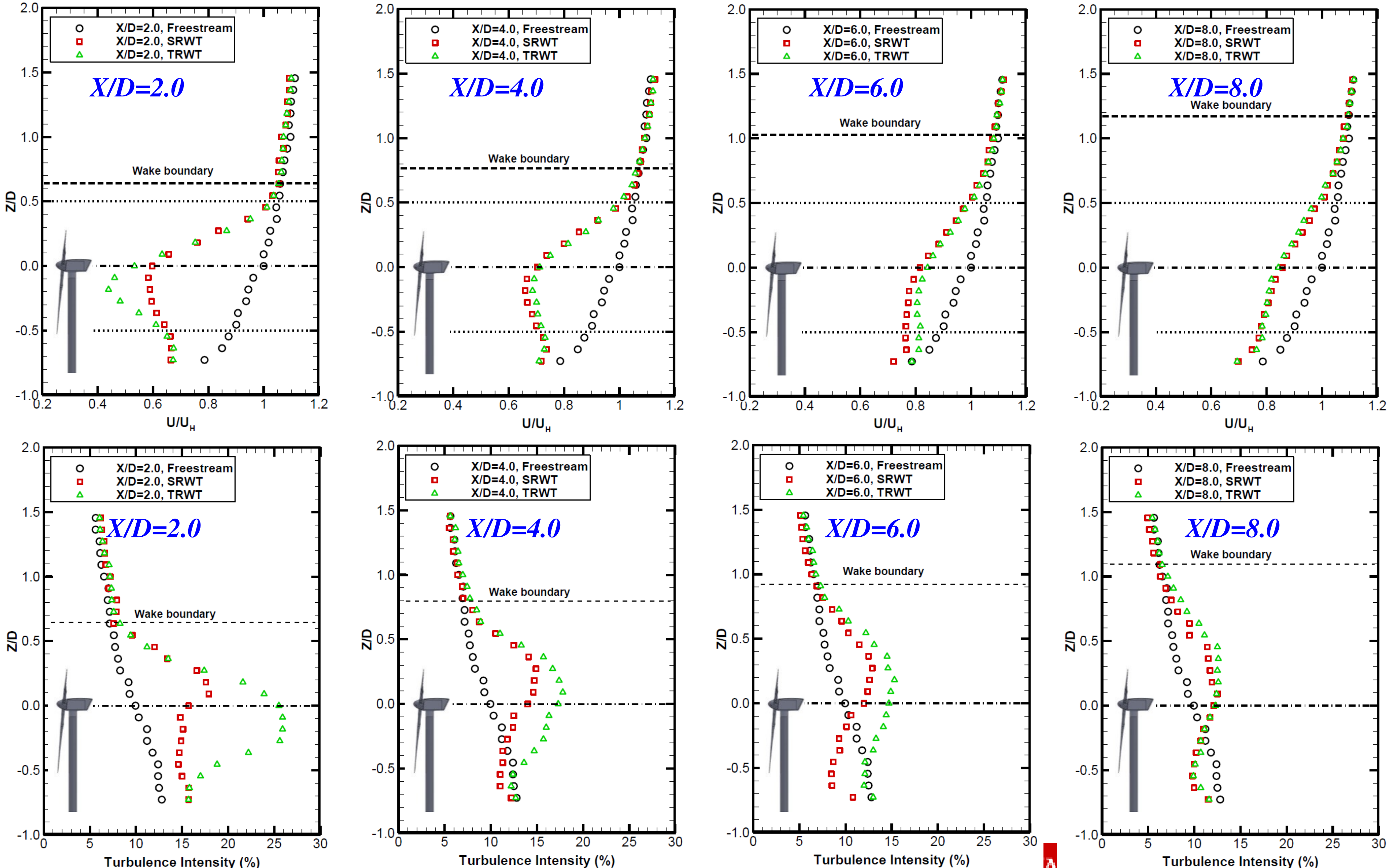


TRWT
X/D=1.0 cross plane

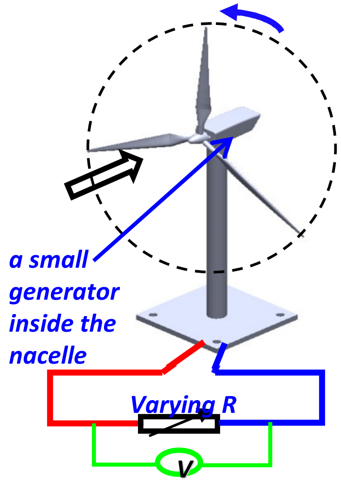
Stereo-PIV measurements



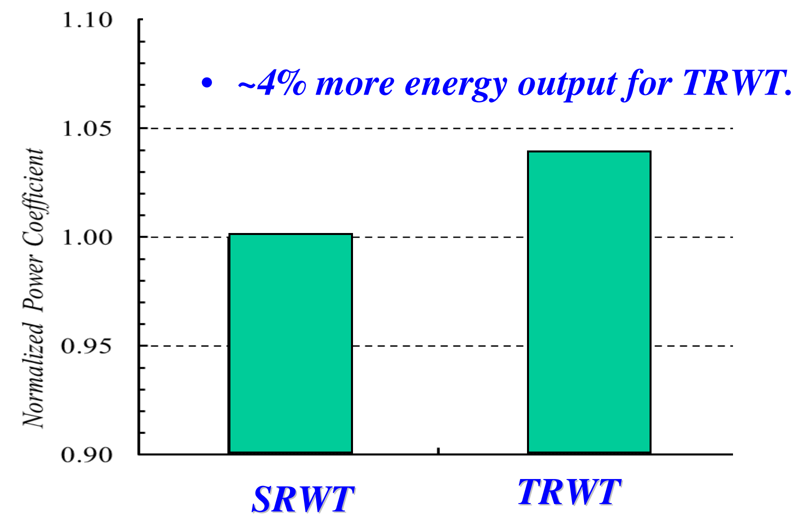
Flow Characteristics in the far wake



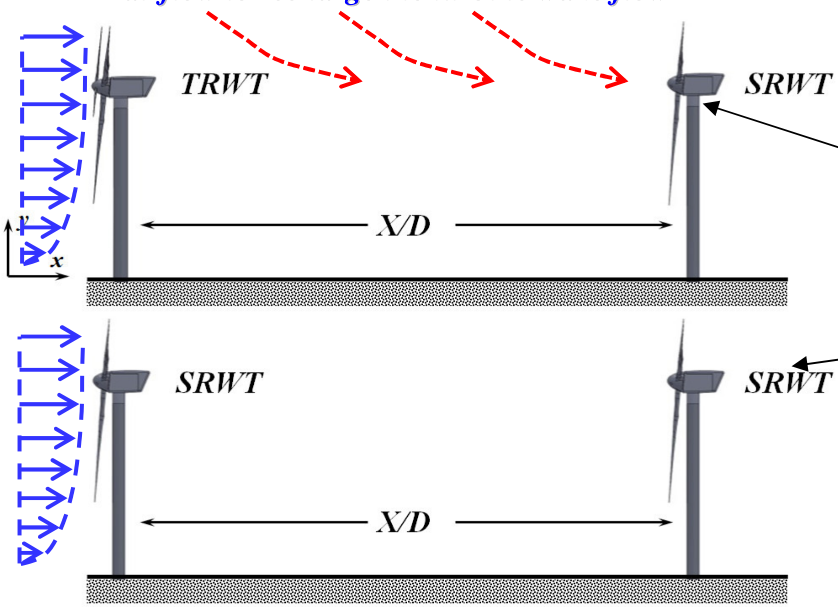
Power outputs of SRWT and TWR models

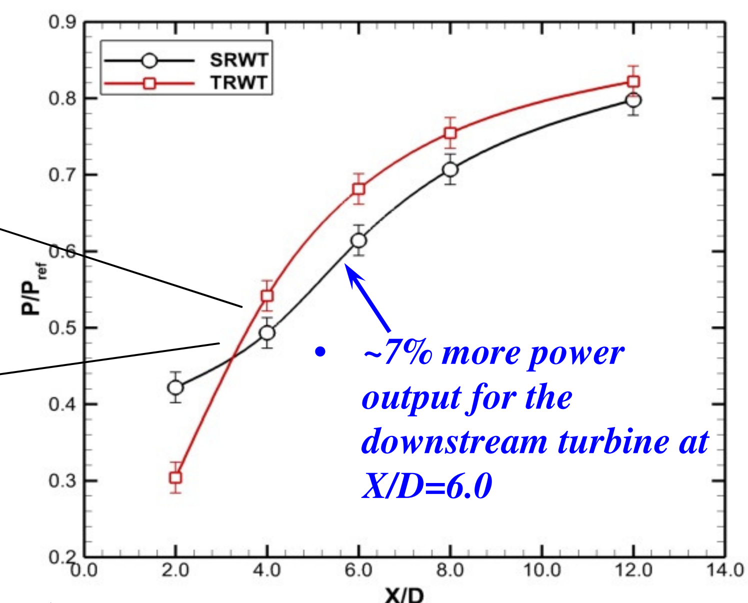


32



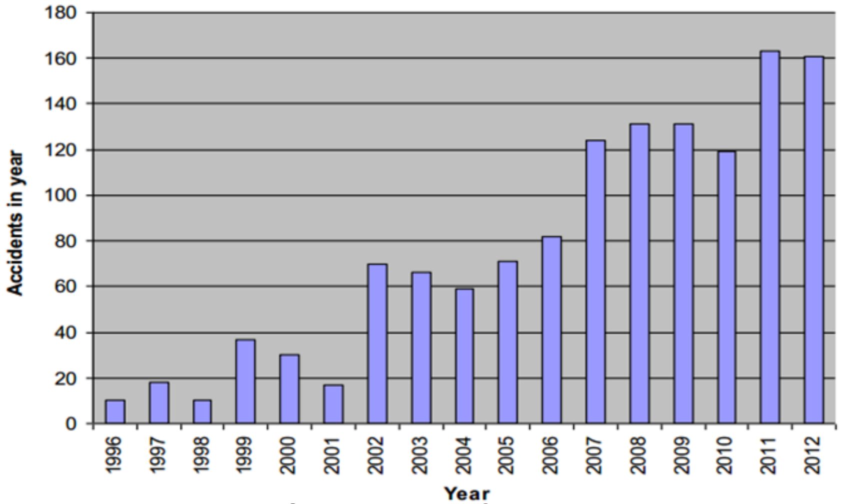
- *Entrainment of high-momentum surrounding airflow to recharge the turbine wake flow*





➢ *P_{ref} is the power output for an isolated SRWT*

Wind Turbine Failures



Caithness Wind Farm, UK

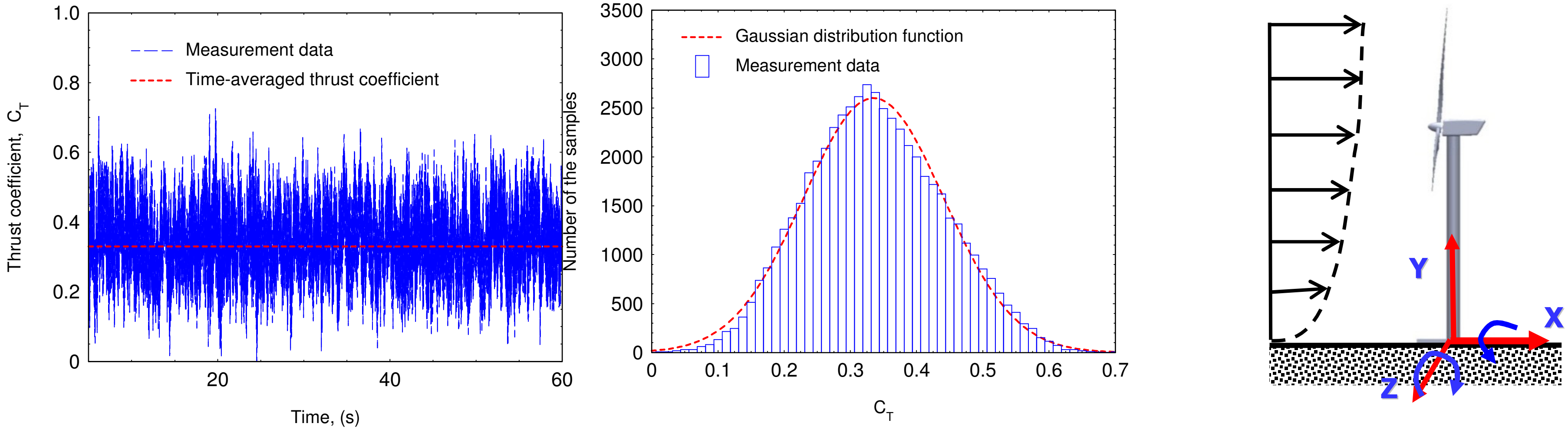
http://www.caithnesswindfarms.co.uk/

(202 WT in operation + 198 in construction)

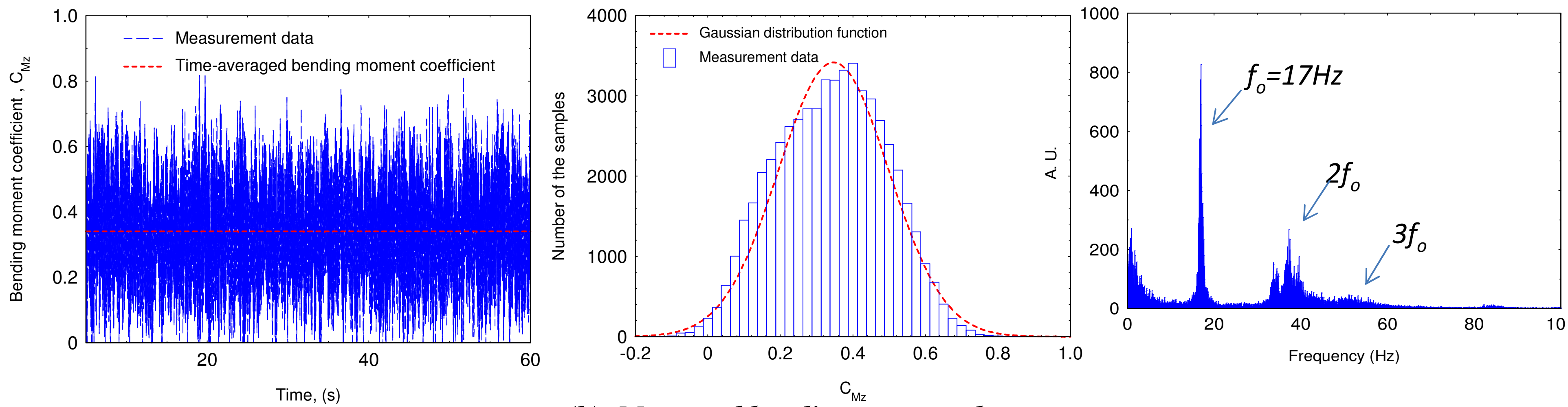
Total number of accidents: 1405

- *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 Measurement Results



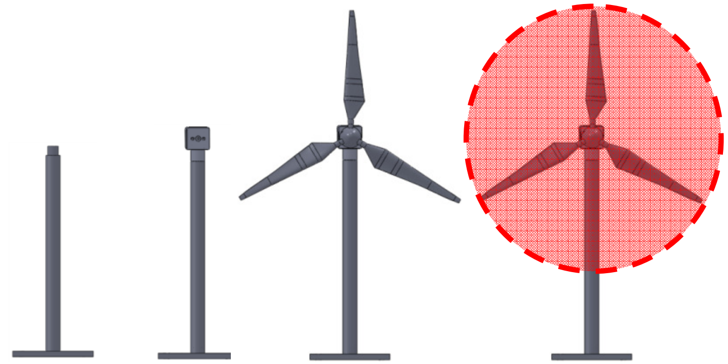
(a). Measured thrust coefficient data



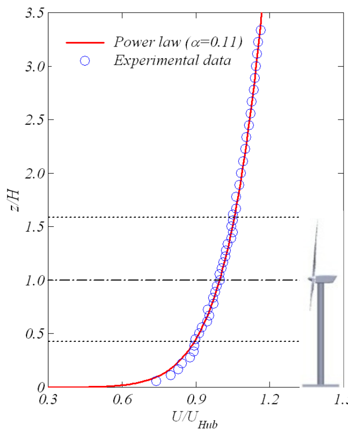
(b). Measured bending moment data

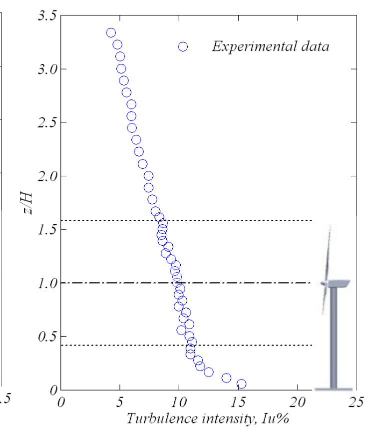
(Tian, Ozbay, Hu, Physics of Fluids, Vol. 26, No.12, 125108, 2014)

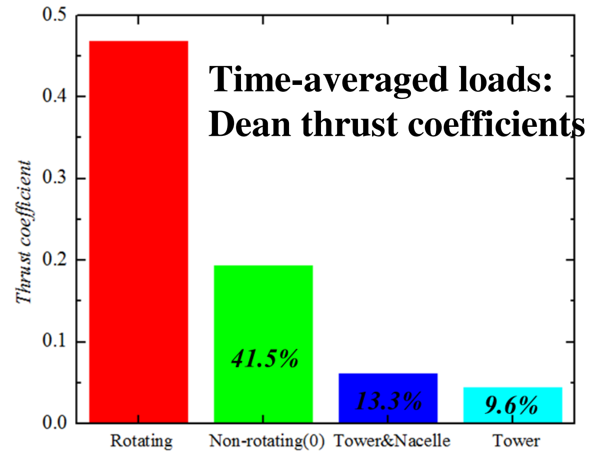
Wind Loads Acting on Various Components of Wind Turbine

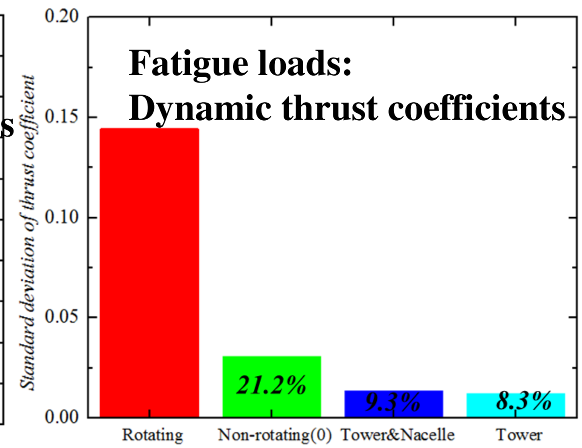


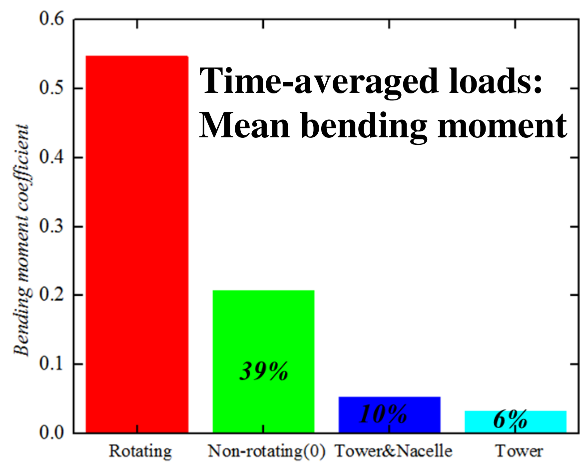
Tower **Tower + nacelle** **Non-rotating turbine** **Rotating turbine**

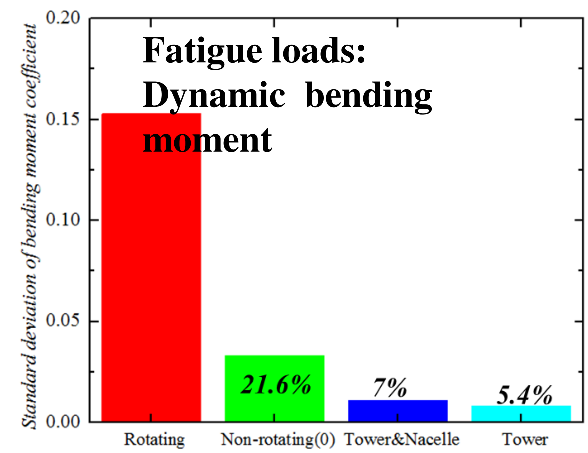










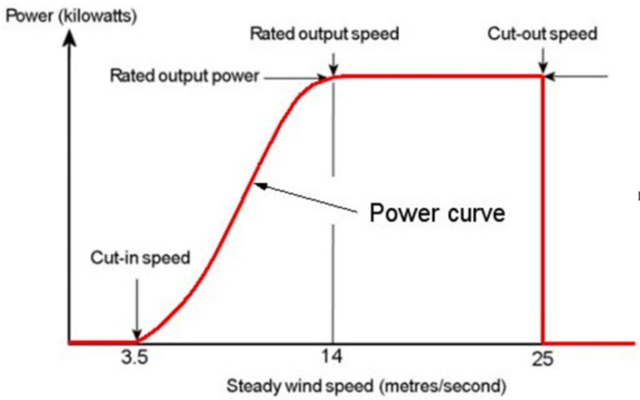


Test conditions:

- *Oncoming ABL wind*
- *Velocity at hub height U_{Hub}= 6.0 m/s*
- *Chord Reynolds number, Re≈10,000*
- *Tip-speed-ratio, λ = 5.0*

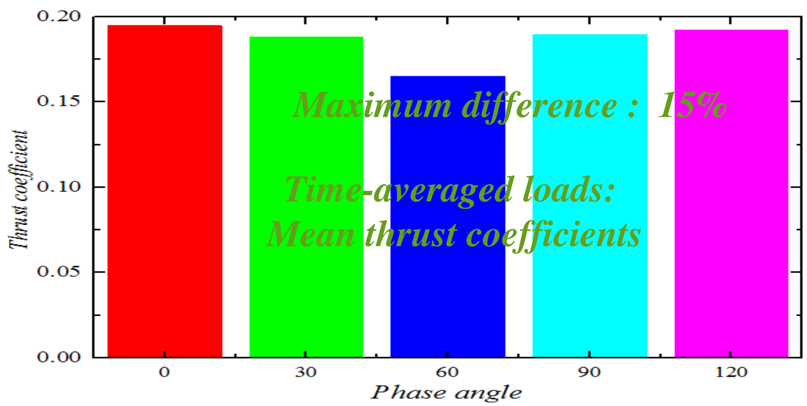
(Tian, Ozbay, Hu; Physics of Fluids, Vol. 26, No.12, 125108, 2014)

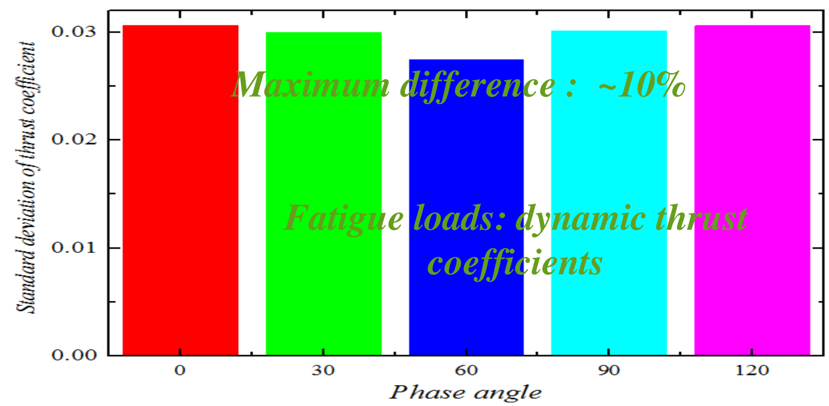
Wind Loads Acting on Wind Turbine at Different Phase Angles

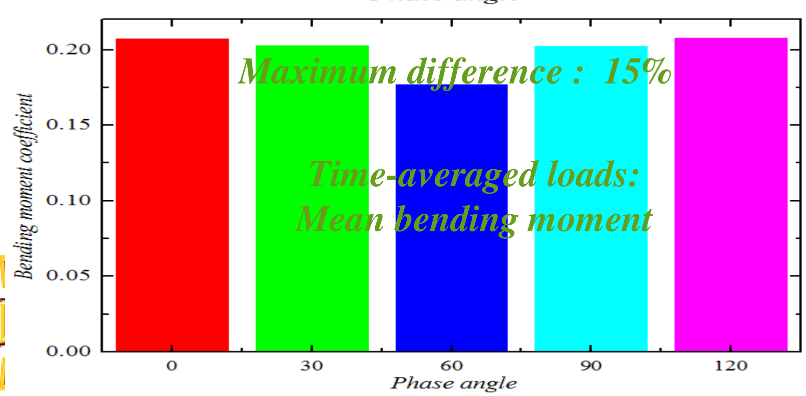


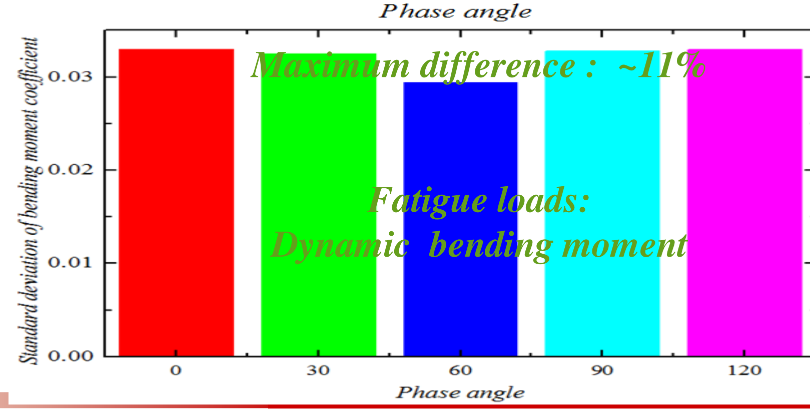
Typical wind turbine power output with steady wind speed.

$\theta = 0$ deg. $\theta = 30$ deg. $\theta = 60$ deg. $\theta = 90$ deg. $\theta = 120$ deg.

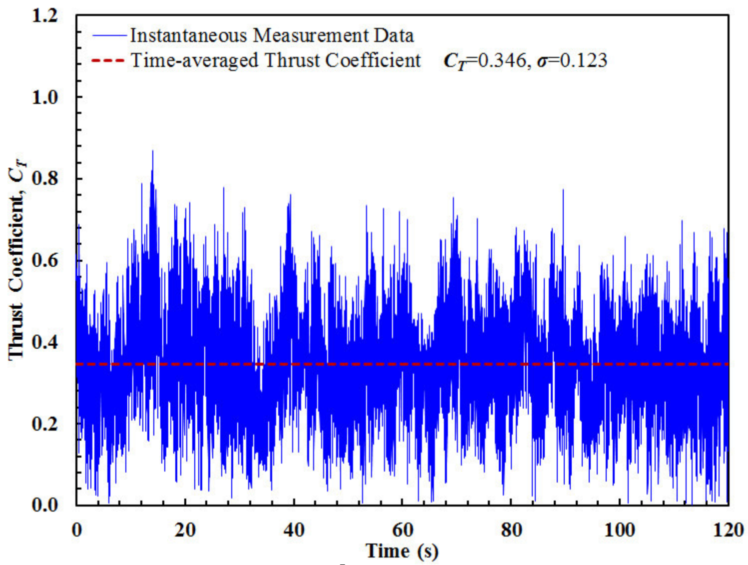


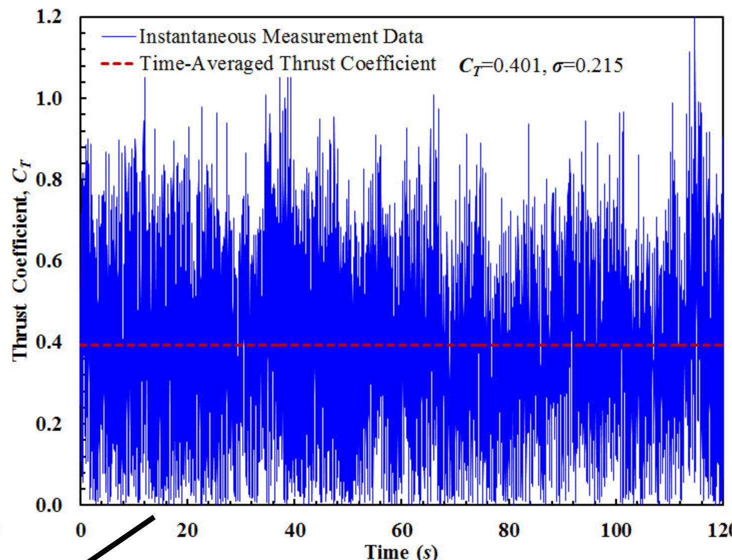






Dynamic wind loads of SRWT and TRWT models





$$C_T = \frac{F_x}{0.5\rho U_H^2 \pi R^2}$$

$$C_M = \frac{M}{0.5\rho U_H^2 \pi R^2 H}$$

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(C_j - \overline{C_j})^2}$$

Where:
F_x ----- Force acting on streamwise direction
R ----- Radius of main rotor
$\overline{C_j}$ ----- Time-averaged coefficient

SRWT

TRWT

	SRWT	*TRWT*
Mean thrust coefficient, C_T	*0.346*	*0.401*
The standard deviation of the thrust coefficient, σ_{CT}	*0.123*	*0.215*
Mean bending moment coefficient, C_M	*0.411*	*0.475*
The standard deviation of the bending moment coefficient, σ_{CM}	*0.133*	*0.324*

- ***~ 15% increase in time-averaged wind loads.***
- ***up to 140% increase in the fluctuating amplitudes of the instantaneous wind loads.***

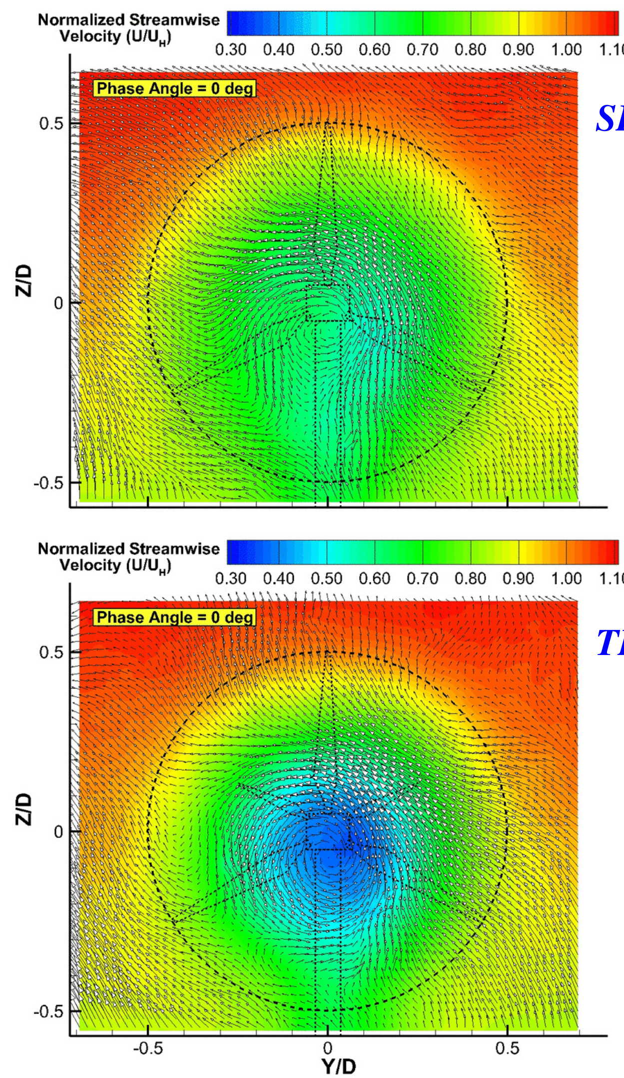
Summary

- The aeromechanic performance and wake characteristics of a novel twin-rotor wind turbine (TRWT) design, which has an extra set of smaller, auxiliary rotor blades appended in front of the main rotor blades, was evaluated experimentally, in comparison with those of a conventional single-rotor wind turbine (SRWT).
- TRWT design was found to be capable of not only harvesting more energy from the same incoming wind by reducing the root losses of the main turbine rotor, but also improving wind farm efficiency by mitigating the wake losses for the downstream turbines through enhanced turbulent mixing of the turbine wake flows.
- The dynamic wind loadings acting on the TRWT model were found to be much greater (i.e., ~ 20% increase in time-averaged wind loads, up to 140% increase in the fluctuating amplitudes of the instantaneous wind loads) than those acting on the SRWT model.
- While the findings derived from the present study are helpful to gain further insight into underlying physic related to aeromechanic characteristics of TRWT, more comprehensive studies are still needed (e.g., Reynolds number effects, fatigue loading reduction, cost analysis,…) to explore/optimize design paradigms for higher power yield and better durability of wind turbines.

SRWT TRWT

Thank You Very Much for Your Time! Questions?

SRWT TRWT



SRWT

TRWT

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  - **Postdocs & scholars:** Drs. R. Waldman; W. Tian; F. Chen; J. Guo
  - **Current Graduate Students:** A. Ozbay (PhD); K. Zhang (PhD); J. Ryon (PhD); Z. Wang (PhD); Y. Liu (PhD); W. Zhou(PhD); K. Morteza (PhD); A. Bolding(PhD); P. Premaratne (PhD).
  - **Former Postdocs&Scholar:** B. Johnson, W. Chen, W. Yuan, W.H. Ma; Drs. Z. Jin; H. Ma, Z. Yang
  - **Former PhD Students:** M. Zhang (PhD); M. Yu (PhD), Z. Yang (PhD); Z. Jin (PhD); N. Cooper (PhD)
  - **Former MS Students:** Dvorak; T. Grager; A.Kumar; H. Igarashi; L. Clemens; J. Murphy; K. Varma; M. Tamai.

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