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Experimental Investigations of Hydrokinetic and Wind Turbines at Full Dynamic Similarity

Marcus Hultmark, Mark Miller, Janik Kiefer,
Arthur Phidd, Christie Elford, and Dan Hoffman

E-ffiliates Annual Meeting 2015
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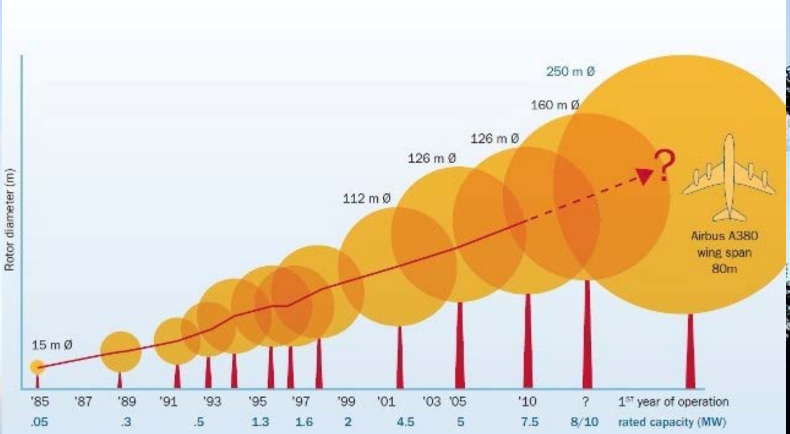


Source: Vestas Wind Systems A/S, General Electrics

Prediction of Performance

- Would like to know how a new design will perform before it is built
  - Power output
  - Forces/Moments
  - Life expectancy
  - Turbine-Turbine Interactions
- Traditionally two avenues
  - Numerical studies
  - Experimental studies
- The enormous size makes this very challenging!

Simulations (Experimental or Numerical)

Full Dynamic Similarity requirements:

- **All** non-dimensional parameters held constant between full scale and tests/simulations
- Geometric similarity
- Boundary and initial condition similarity

Governing equations

Navier-Stokes equations:

$$\rho\left(\frac{\partial \vec{U}}{\partial t}+\vec{U}\cdot\nabla\vec{U}\right)=-\nabla p+\nabla\cdot\bar{\bar{\tau}}^{(v)}+\rho\big(\underbrace{\Omega^2\vec{r}}_{\text{Centrifugal forces}}-\underbrace{\vec{\Omega}\times\vec{U}}_{\text{Coriolis forces}}\big)$$

Navier-Stokes equations (non-dimensional form):

Matching Flow Conditions

Full Dynamic Similarity requirements:

- **All** non-dimensional parameters held constant between full scale and tests/simulations

$$[TSR] = \frac{R\omega}{U_{wind}} = \frac{Tip\ Speed}{Wind\ Speed}$$

Typically between 5 and 8

Matching Flow Conditions

Full Dynamic Similarity requirements:

- **All** non-dimensional parameters held constant between full scale and tests/simulations

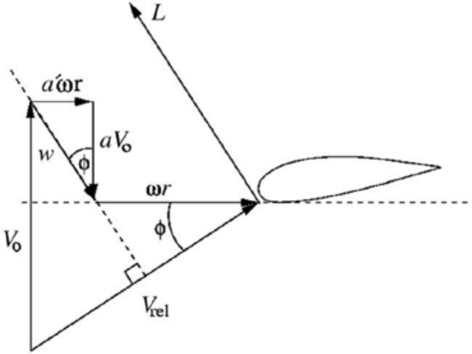
$$[Re] = \frac{\rho U L}{\mu}$$

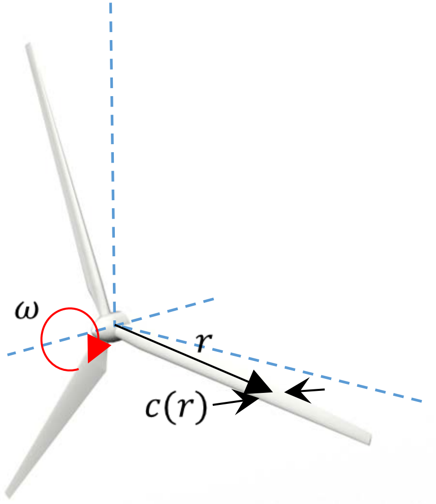
Several common Reynolds numbers:

$$Re_{tip} = \frac{\rho c(R) U_{rel}}{\mu}$$

$$Re_c = \frac{\rho c(0.75R) U_{rel}}{\mu}$$

$$Re_D = \frac{\rho 2 R U_{wind}}{\mu}$$



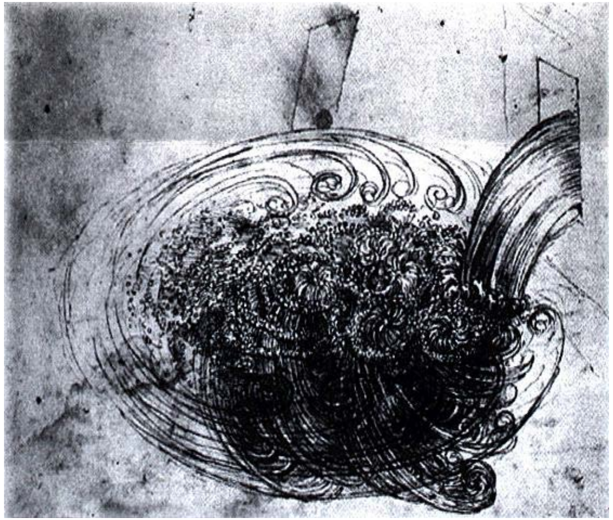


Reynolds number

- High Reynolds number → Turbulence!

$$Re = \frac{Inertial\ Forces}{Viscous\ Forces} \sim \frac{Large\ Eddies}{Small\ Eddies}$$

$$Re_D = \frac{\rho 2 R U_{wind}}{\mu} = \frac{1.2 \times 2 \times 50 \times 10}{1.8 \times 10^{-5}} = 67 \times 10^6$$

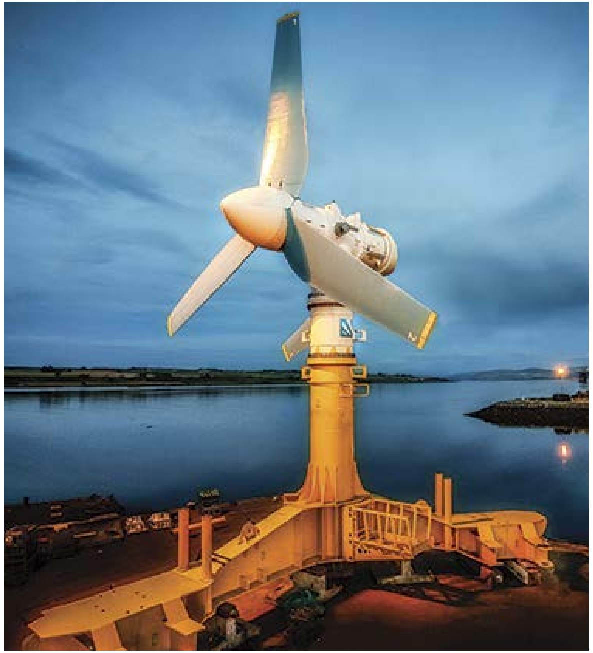


Drawing by Leonardo da Vinci dating from 1511–1515, held in the Royal Library, Windsor Castle.

Direct Numerical Simulations still many decades away!

Have to rely on modeling – needs empirical input

Fluid dynamics of wind/tidal turbines



- Similar Reynolds numbers and Tip Speed Ratios
- Similar fundamental questions
- Slightly different engineering questions

Experimental Investigations

- *"The tip speed ratio condition can easily be met, while Reynolds number criteria are **impossible** to achieve in model scale studies."* (Adaramola and Krogstad 2011)
- The enormous length scale is the reason
- Typically want to test with **smaller** turbine models

$$Re_{D,model} = \frac{\rho 2 R_{model} U}{\mu} = Re_{D,full}\left[\frac{R_{model}}{R_{full}}\frac{U_{model}}{U_{full}}\frac{\rho_{model}}{\rho_{full}}\frac{\mu_{full}}{\mu_{model}}\right]$$

$$TSR_{model} = \frac{R_{model}\omega_{model}}{U} = TSR_{full}\left[\frac{R_{model}}{R_{full}}\frac{U_{full}}{U_{model}}\frac{\omega_{model}}{\omega_{full}}\right]$$

Typical approach: Full/Large scale testing = $$$

Full-scale field testing

Source: Sandia.gov

Source: NREL.gov

Pros:
- High Reynolds numbers
- Atmospheric interactions

Cons:
- No control over inflow
- Very expensive
- No converged statistics
- Limited measurements

Large Scale Tunnel Testing

Source: NREL/NASA Ames

Source: IEA Wind

Pros:
- High Reynolds numbers
- Control over inflow

Cons:
- Very expensive
- Limited wake measurements
- Scalability?

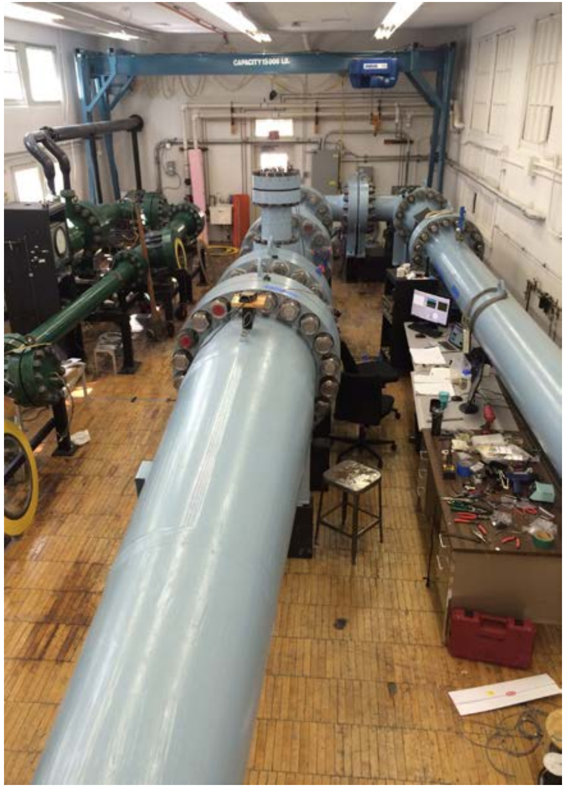
Our approach: Pressurized tests

$$Re_{D,model} = \frac{\rho 2 R_{model} U}{\mu} = Re_{D,full}\left[\frac{R_{model}}{R_{full}}\frac{U_{model}}{U_{full}}\frac{\rho_{model}}{\rho_{full}}\frac{\mu_{full}}{\mu_{model}}\right]$$

$$TSR_{model} = \frac{R_{model}\omega_{model}}{U} = TSR_{full}\left[\frac{R_{model}}{R_{full}}\frac{U_{full}}{U_{model}}\frac{\omega_{model}}{\omega_{full}}\right]$$

- Density of air is a strong function of pressure
- Viscosity is a very weak function

Our approach: Pressurized tests



The Princeton High Reynolds-number Test Facility (HRTF) is a pressurized wind tunnel:

- 0 to 24 MPa gauge pressure (0-238 atmospheres!)
- 0 to 10 m/s centerline velocity
- 50 cm test section diameter
- Fully instrumented test section with multi-component hot-wire anemometers
- Originally used for submarine measurements
- Highest Reynolds number in the world

Experiments at full dynamical similarity using a model with 10 cm blades:

$$Re_{D,model} = Re_{D,full}\left[\frac{R_{model}}{R_{full}}\frac{U_{model}}{U_{full}}\frac{\rho_{model}}{\rho_{full}}\frac{\mu_{full}}{\mu_{model}}\right] = Re_{D,full}\left[\frac{1}{135}\frac{1}{1}\frac{220}{1}\frac{1}{1.4}\right] = 1.16Re_{D,full}$$

$$TSR_{model} = TSR_{full}\left[\frac{R_{model}}{R_{full}}\frac{U_{full}}{U_{model}}\frac{\omega_{model}}{\omega_{full}}\right] = TSR_{full}\left[\frac{1}{135}\frac{1}{1}\frac{\omega_{model}}{\omega_{full}}\right]$$ up to about 6000 rpm

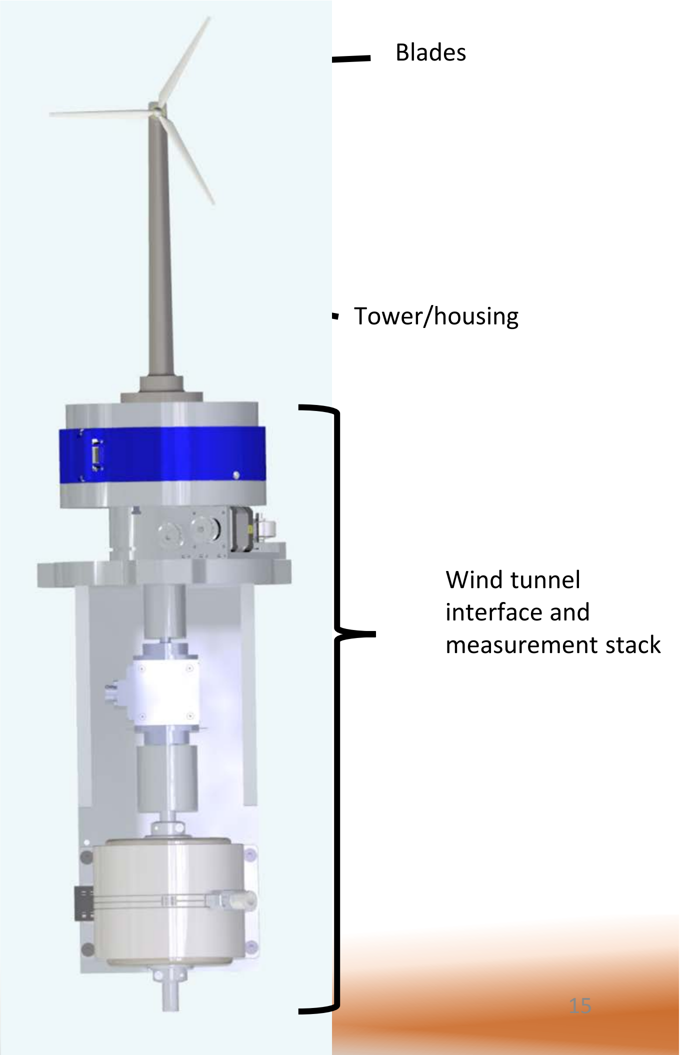
Building a Miniature Wind Turbine
-That can withstand the extreme conditions

Power and Forces proportional to density (pressure)

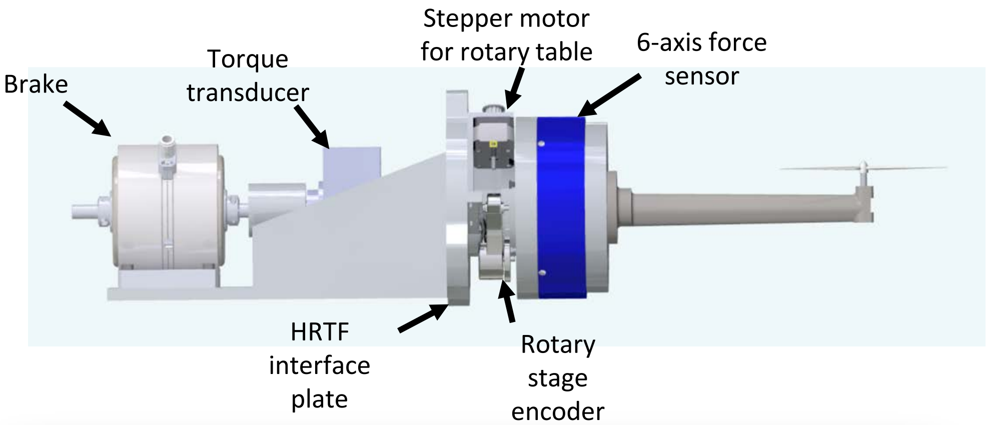
3 main components affected by model loading:
- Blades
- Housing/Tower
- Base or Tunnel connection

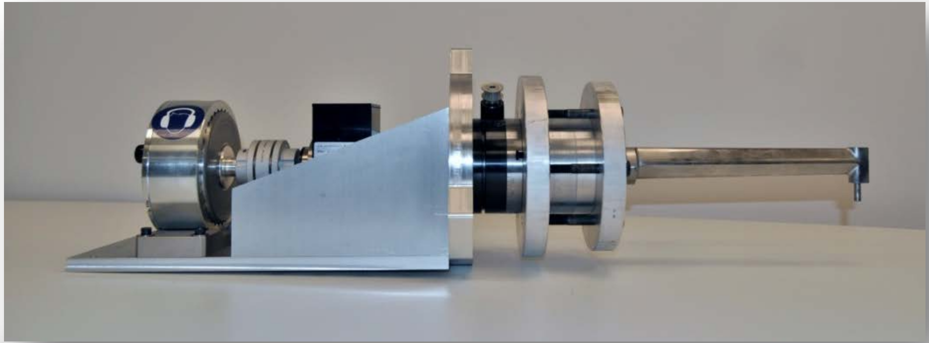
Measurement Points to consider:
- Power curve (power versus TSR and Re)
- Thrust force (Force versus TSR and Re)
- Forces produced by off-axis operation (yaw flow)
- Wake measurement via hot-wire anemometry

Sensor Goals:
- Power measurement accuracy at ±0.5 %
- Rotationally-resolved power measurements
- Force measurement accuracy at ±0.25 %



Measurement Stack Design





Images: C. Elford Senior Thesis (2015)

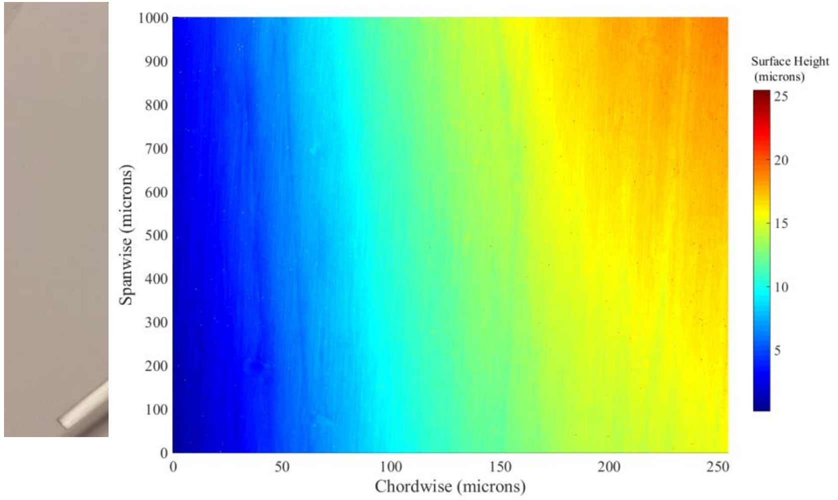
Need a rotor!

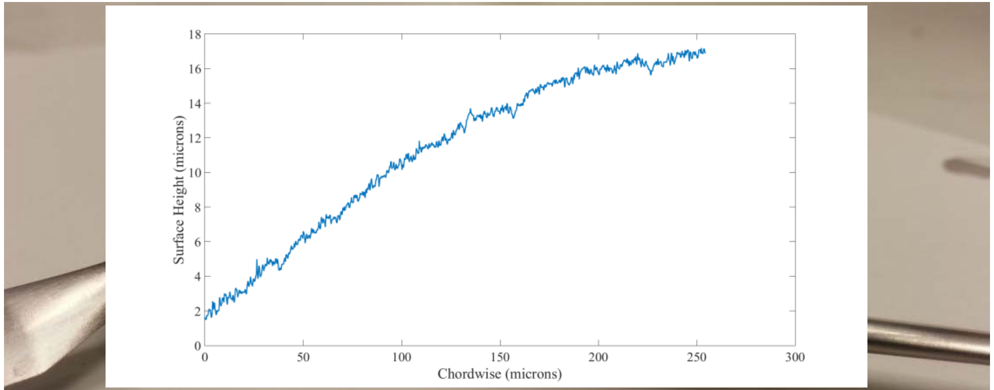
Turbine Rotor

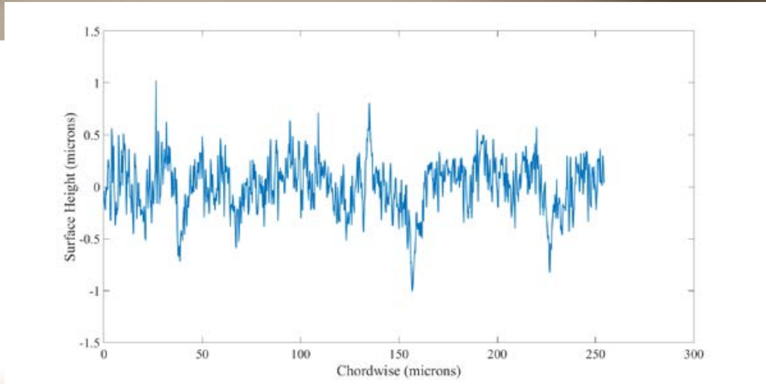
Need to design and manufacture a turbine rotor that is geometrically similar to the large scale version (airfoil shape, blade profile and roughness) .

- Miniature version of Sandia's Swift facility
- Vestas V27
- Publically available blade profiles
- Reference data

Still Impossible?



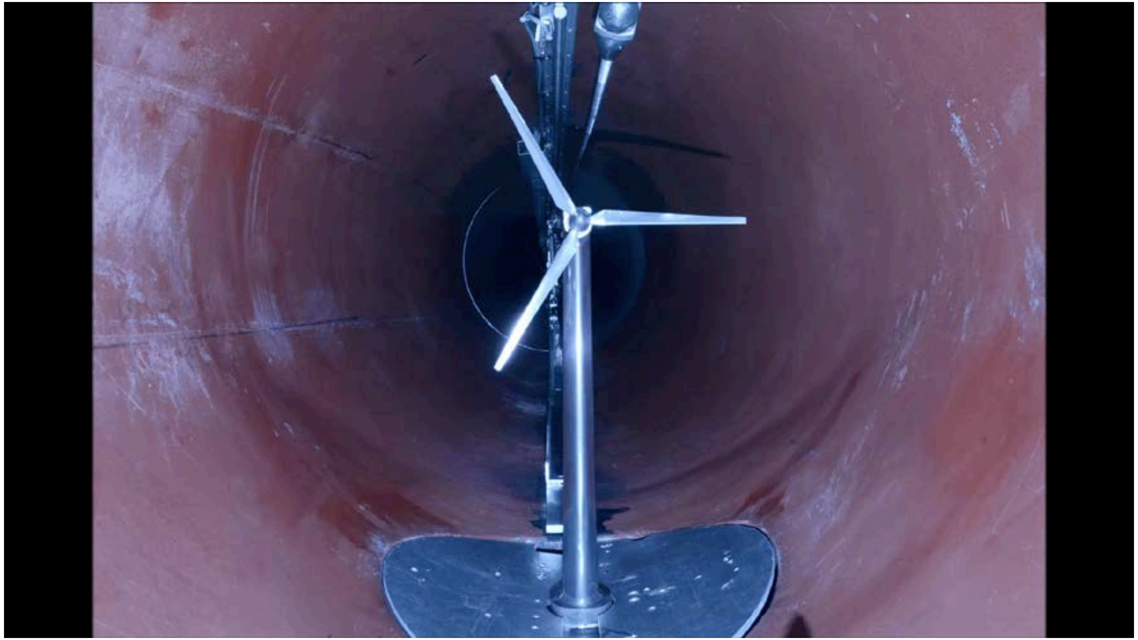




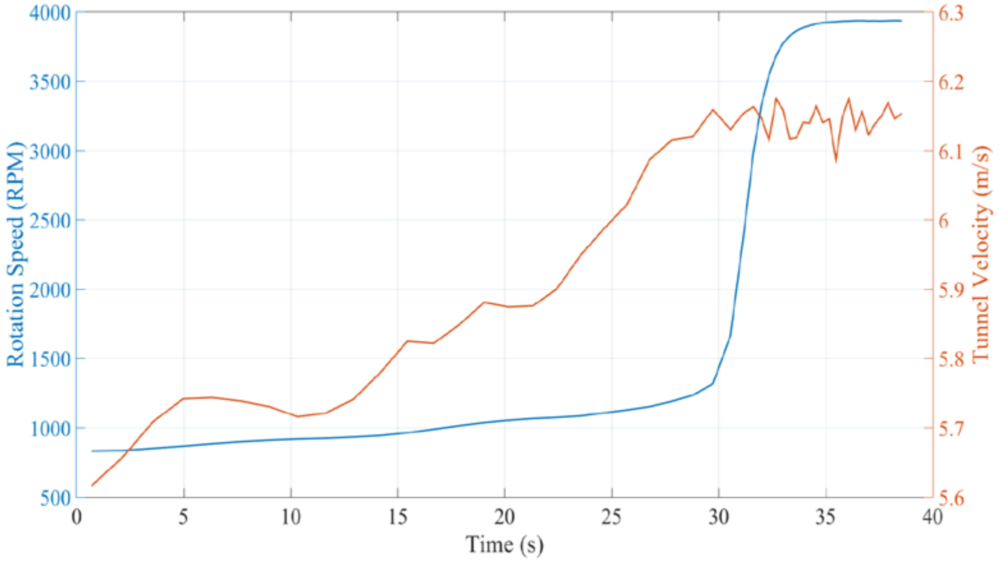
Very small surface roughness
$k_{rms} \leq 0.4\ microns$

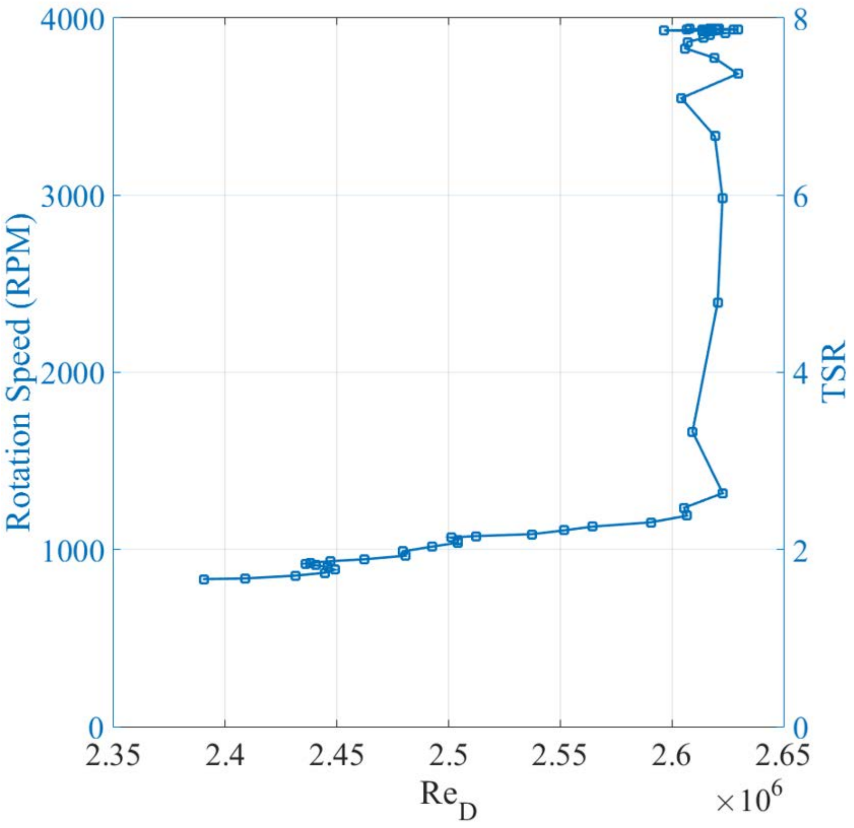
This equates to a full-scale roughness of:
$54\ microns \leq$ real full scale roughness

Wind Turbine In the Tunnel

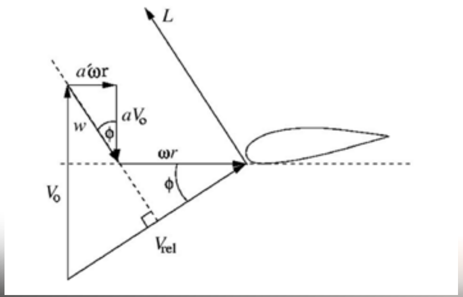


First Test:

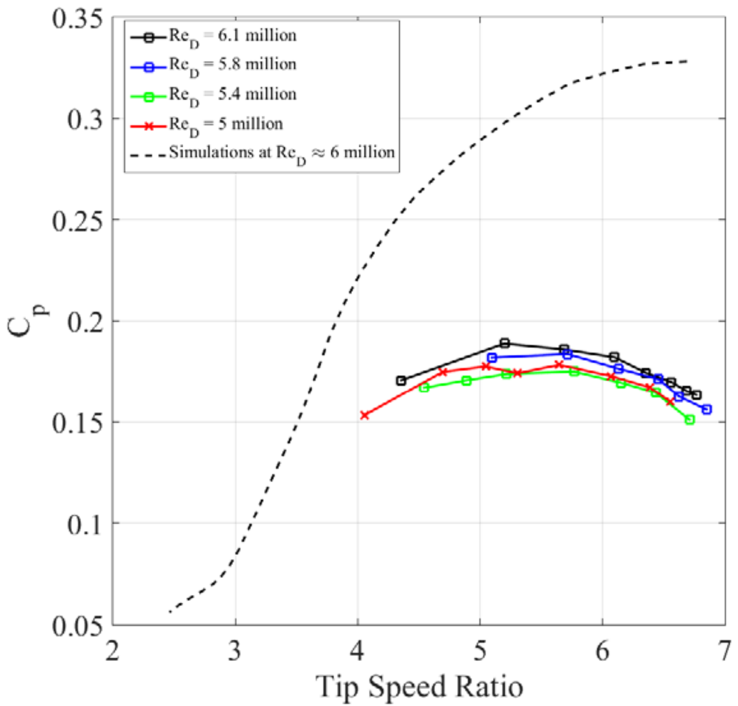


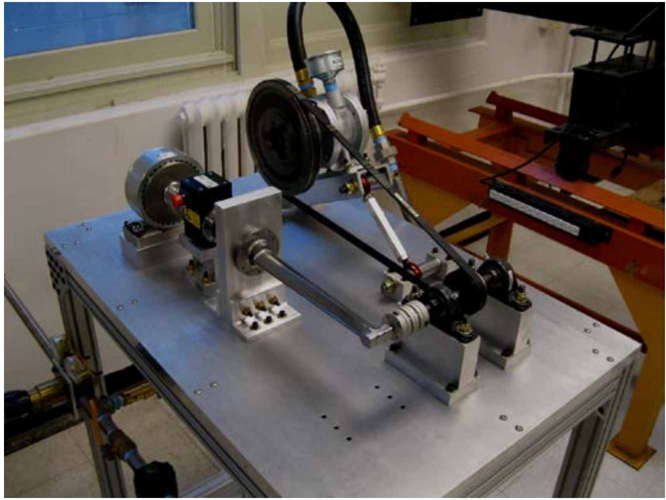


$$Re_c = \frac{\rho c(0.75R)U_{rel}}{\mu}$$



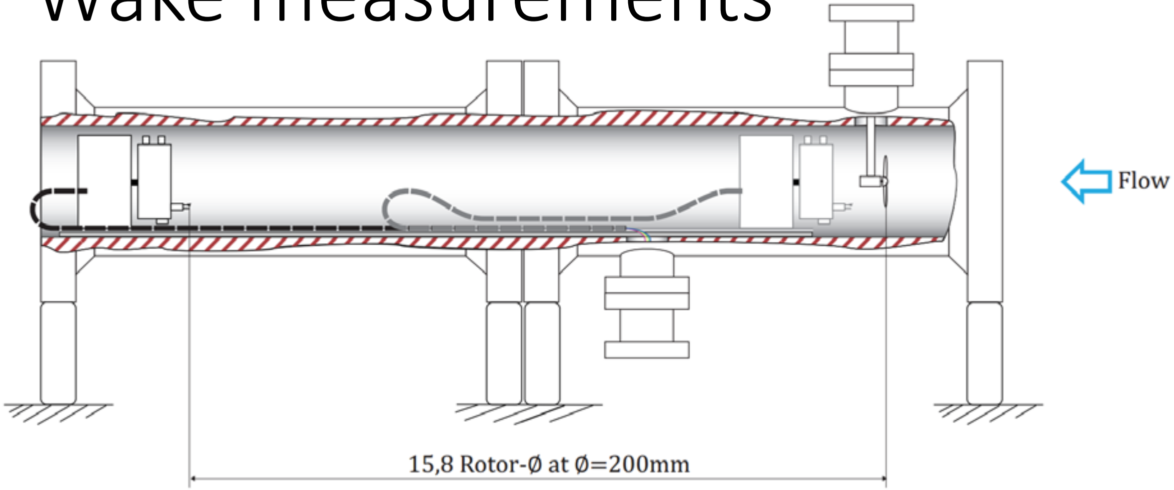
Preliminary Results

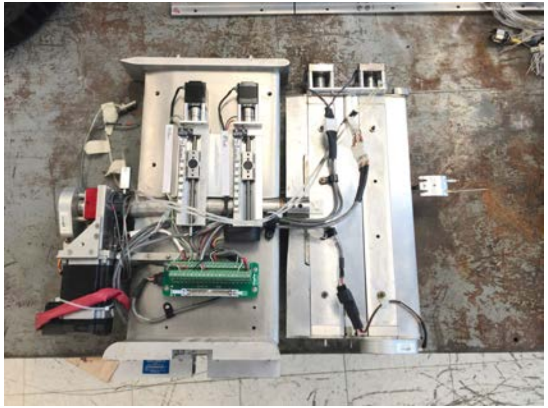




Turbine-Turbine Interactions

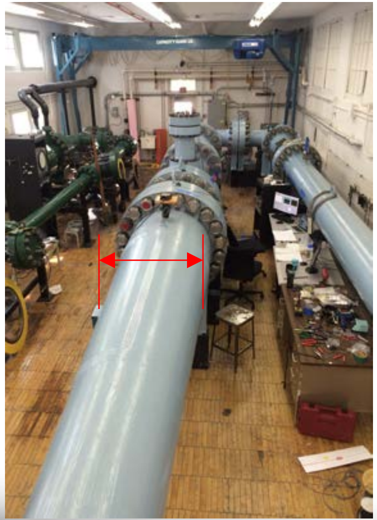
Wake measurements

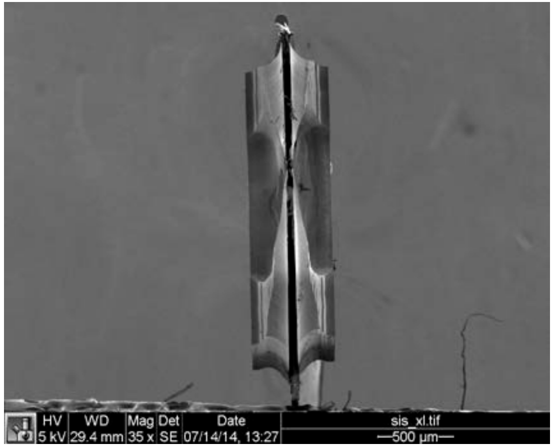


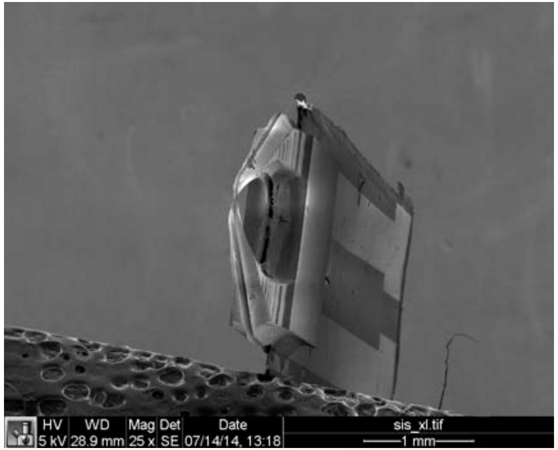


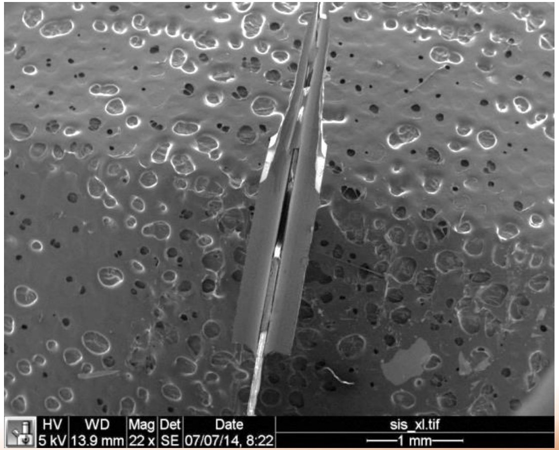
Side Effect of Pressurizing

$$Re = \frac{Inertial\ Forces}{Viscous\ Forces} \sim \frac{Large\ Eddies}{Small\ Eddies}$$

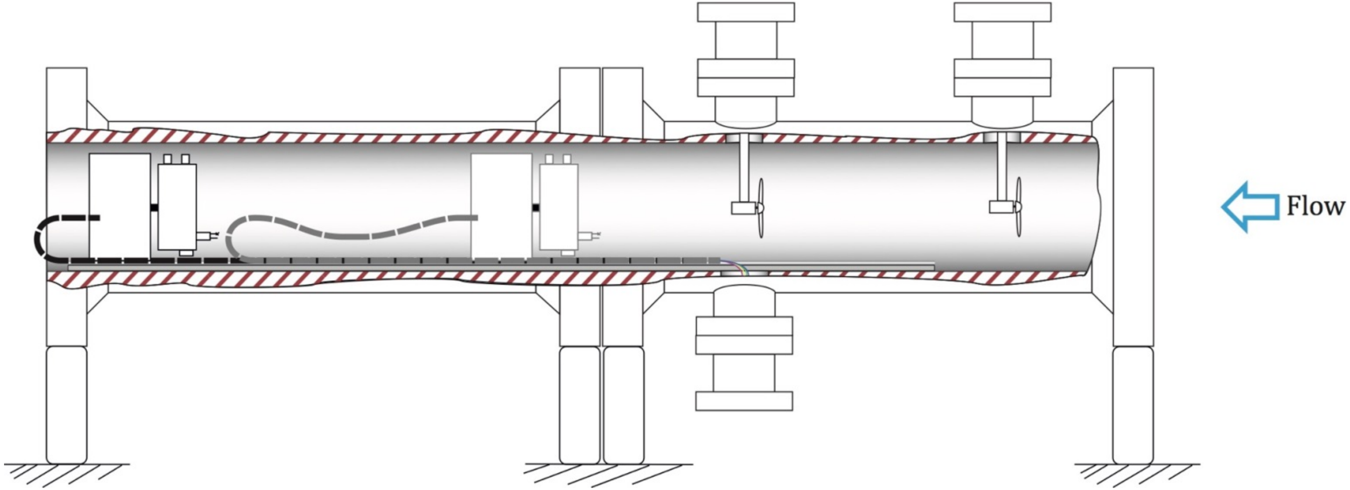








Turbine-Turbine Interactions

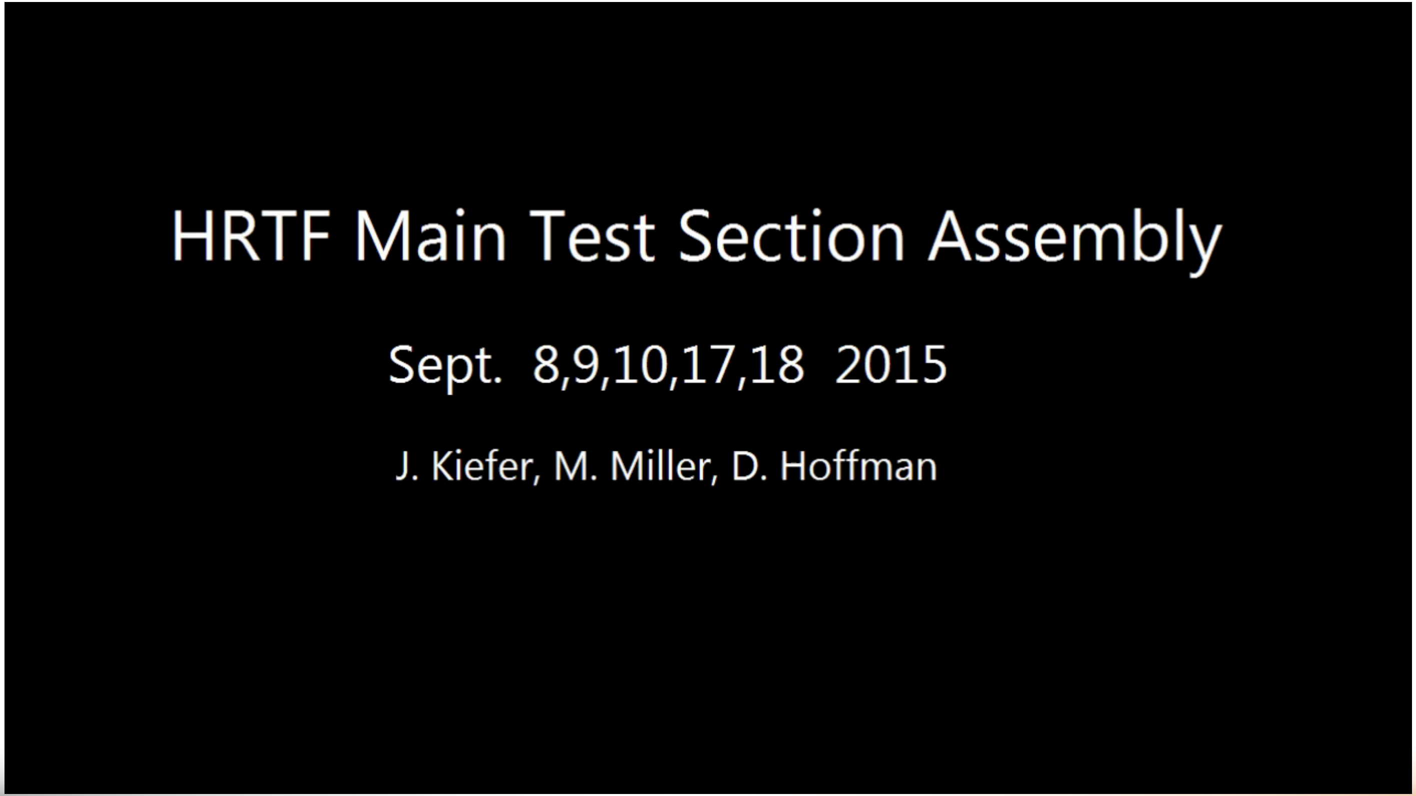


Future Investigations:

- Fundamental Fluid Mechanics
  - Rotational effects on the aerodynamics at high Reynolds numbers
  - Wake meandering
  - Reynolds number effects on wake dynamics
  - Rotational effects on wake dynamics
  - Wake-Wake interactions
- Engineering Questions
  - Torque characteristics
  - Off-axis (yaw) operating conditions
  - Modeling accuracy
  - Data collection

Thank you!

Questions?


HRTF Main Test Section Assembly
Sept. 8,9,10,17,18 2015
J. Kiefer, M. Miller, D. Hoffman