A model study of wind turbine interference

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- Background
- Model and measurements
- Effect of turbine operating condition
- Yaw effects
- Conclusions

Background

- Turbine interaction reduces power output and increases dynamic loads

- Wake structure depends on turbine operating conditions. Is it always best to operate at turbine peak performance?

- Wake may be deflected by yawing the turbine. How much power is gained or lost by yawing?

Main purpose of investigation:

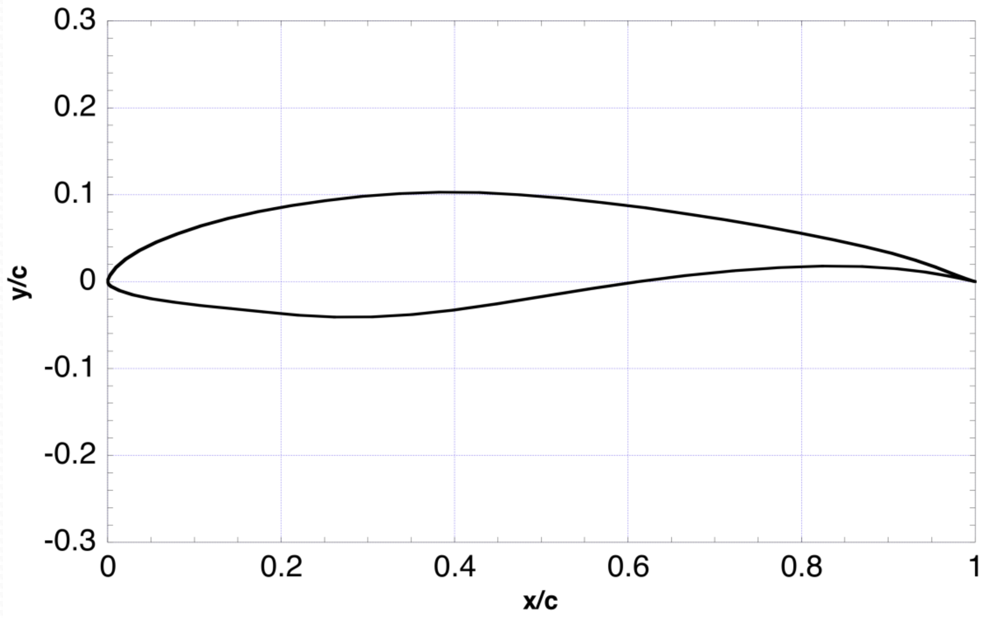
Measure turbine interaction under controlled laboratory conditions

- Model turbine designed using standard Blade Element Momentum theory
- Rotor diameter D=0.9m. Design tip speed ratio, λ=6
- Wind tunnel test section: Crossection=2x2.7m, total length=12m
- Power predictions performed with BEM and CFD (Fluent) software

Airfoil: NREL S826 14% thickness

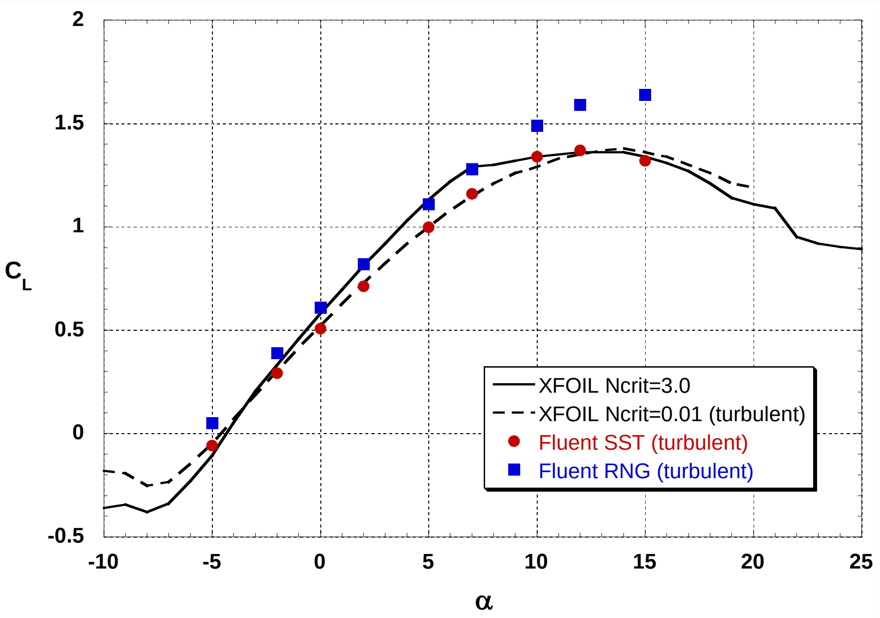
Characteristics:

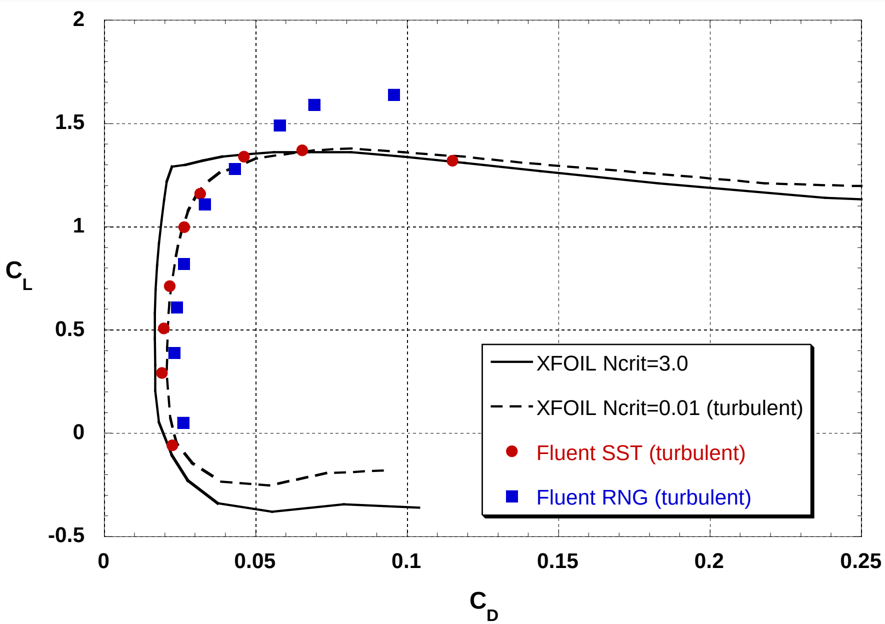
- Gentle separation due to trailing edge ramp
- Rapid transition on suction side due to small radius of curvature
- Low sensitivity to surface roughness
- Strong separation on lower side at negative angles of attack



2D predictions of S826 performance

Fully turbulent XFOIL predictions agree well with *k*-ω SST





C_L vs α

C_L vs C_D

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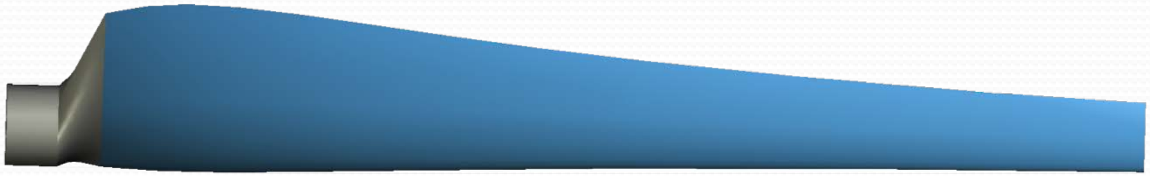
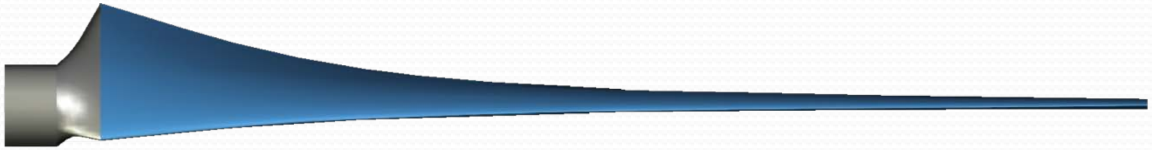
Standard Blade Element Momentum theory gives blade geometry

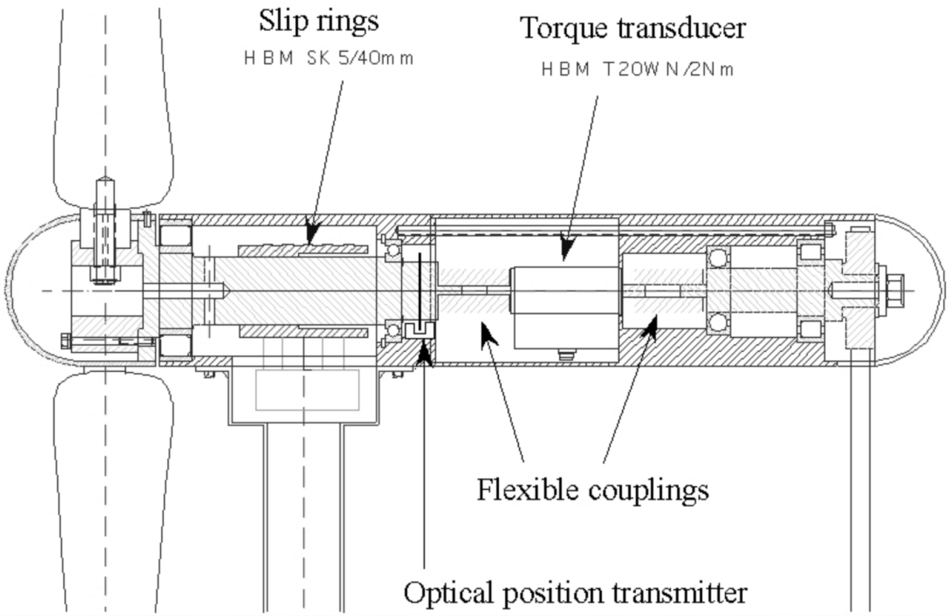


View in streamwise direction



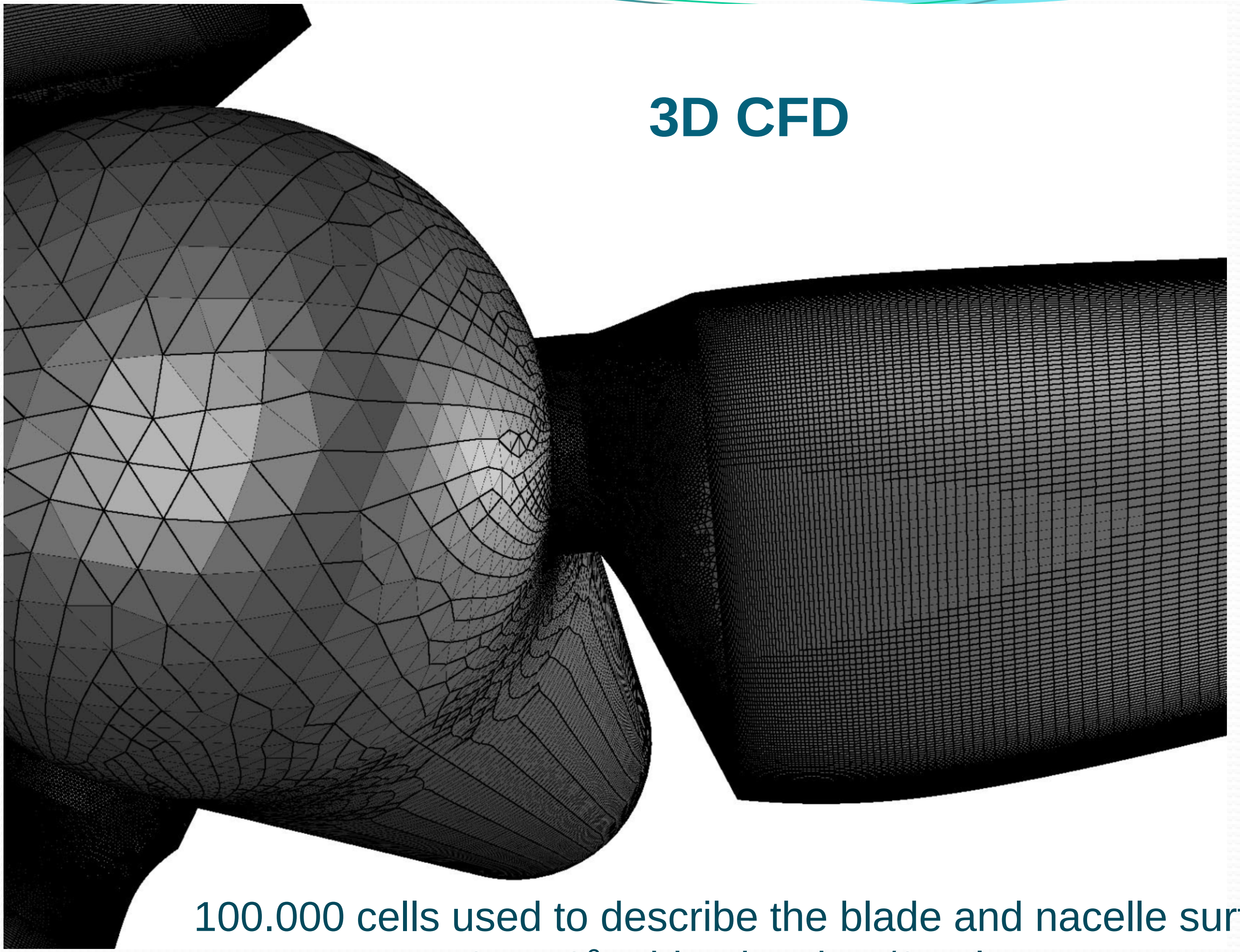
View in plane of rotation

Model and measurement systems



Model instrumentation

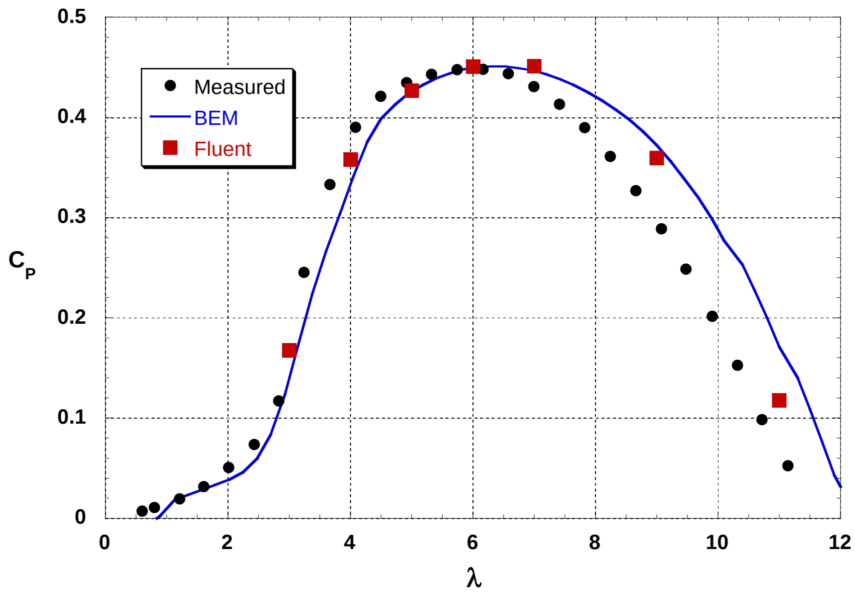
Model in wind tunnel



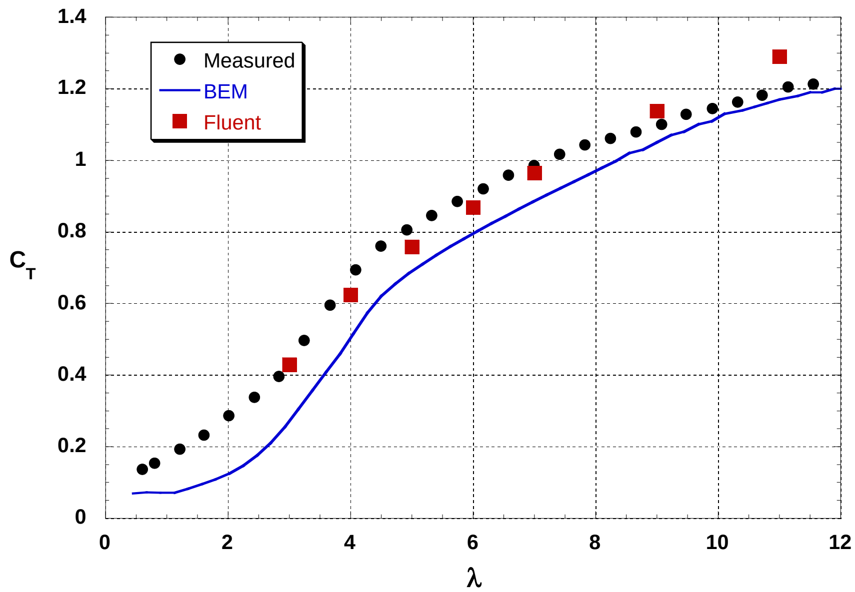
3D CFD

100.000 cells used to describe the blade and nacelle surfaces
3.5×10^6 grid points in 1/3 volume

Comparisons between predictions and measurements

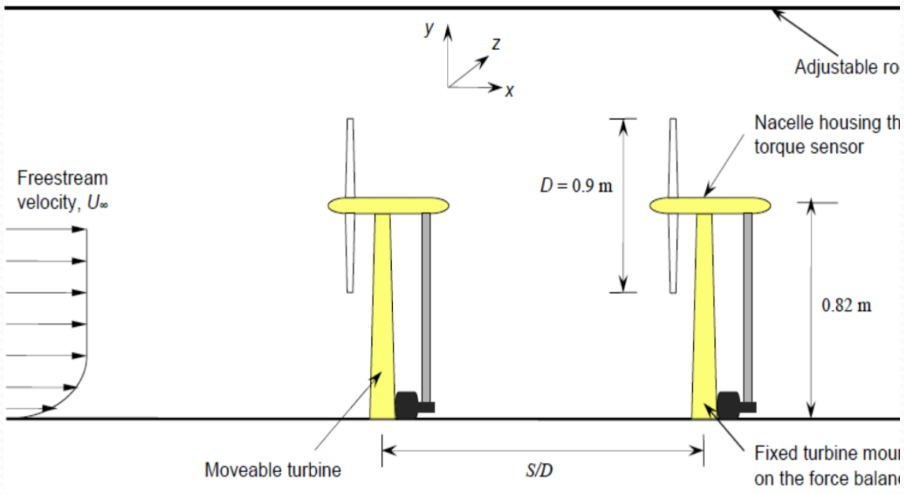


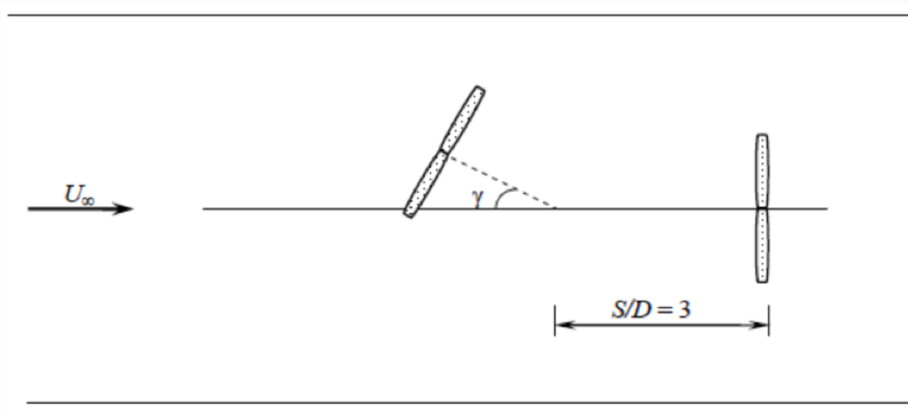
Power coefficient vs tip speed ratio



Thrust coefficient vs tip speed ratio

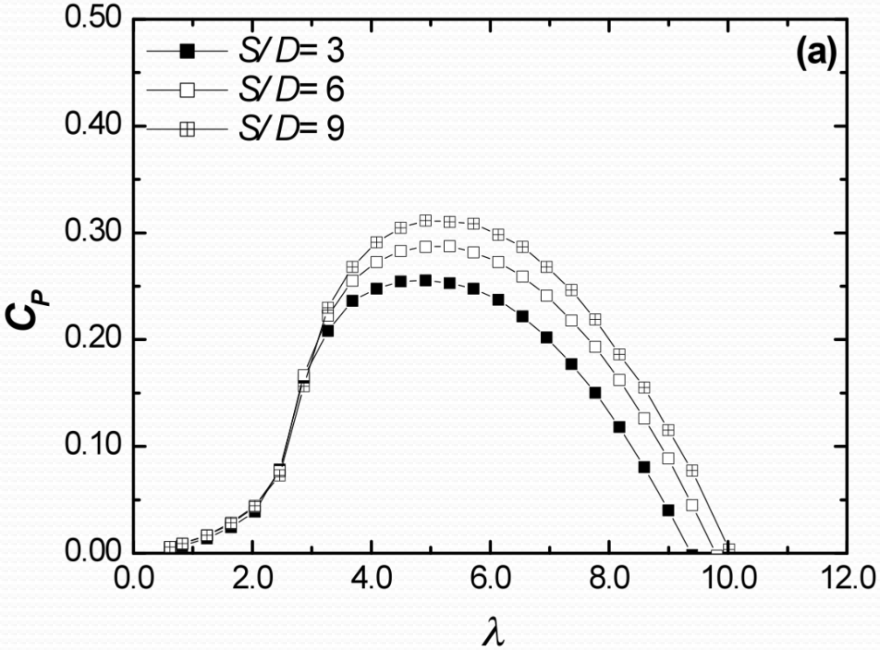
Measurements for 2 similar turbines (Simplified wind farm experiment)



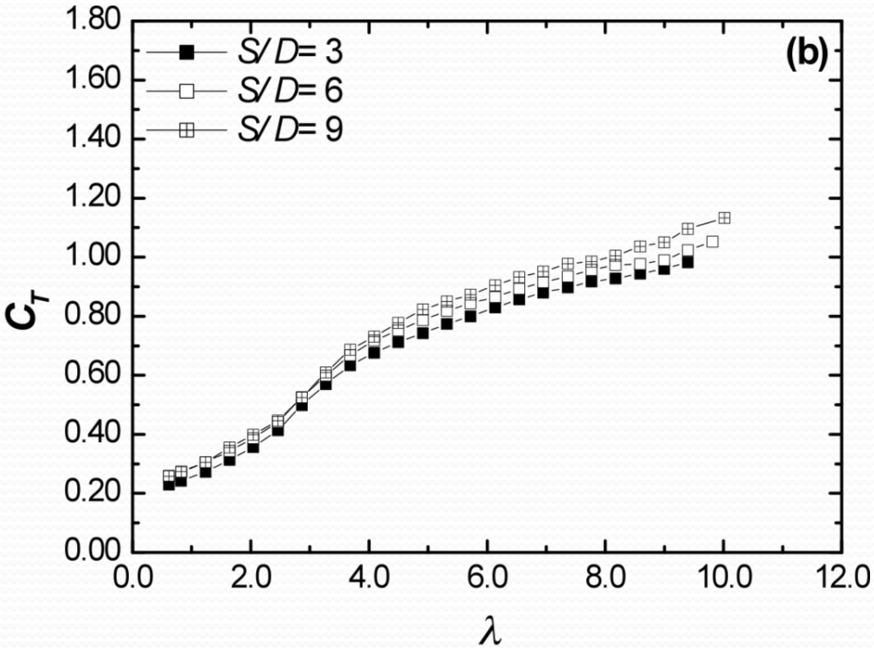


Two in-line turbines | **Yawed upstream turbine**

Effect of distance between turbines
Upstream turbine operating at peak efficiency



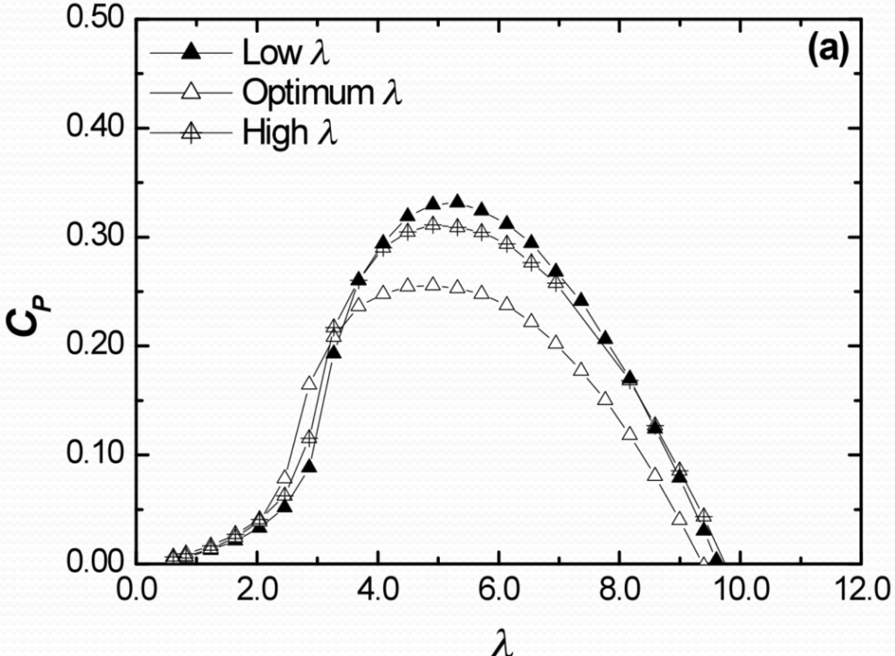
Power coefficient, downstream turbine



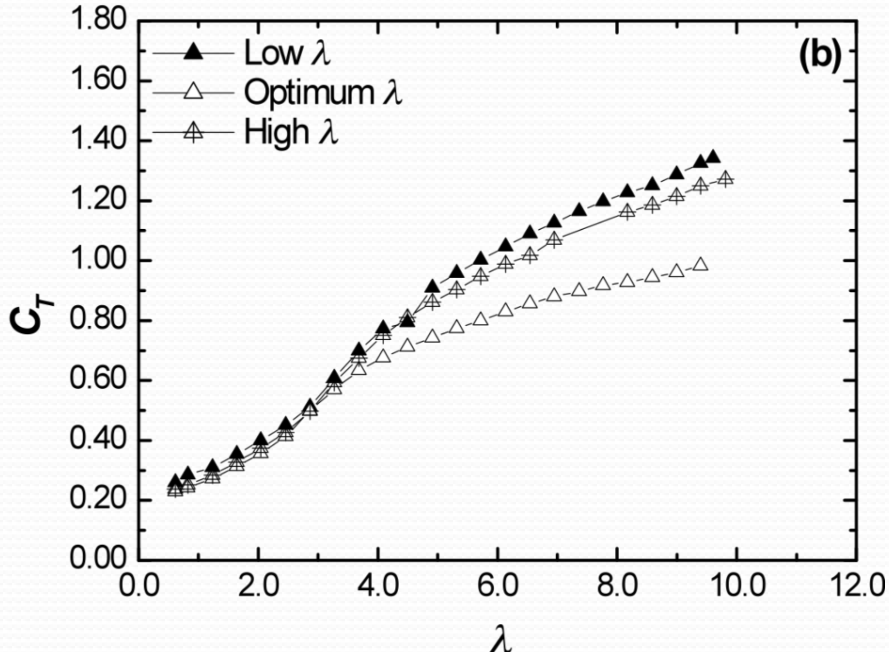
Thrust coefficient, downstream turbine

At a given distance, the output from the downstream turbine depends on the operating point of the first

S/D=3



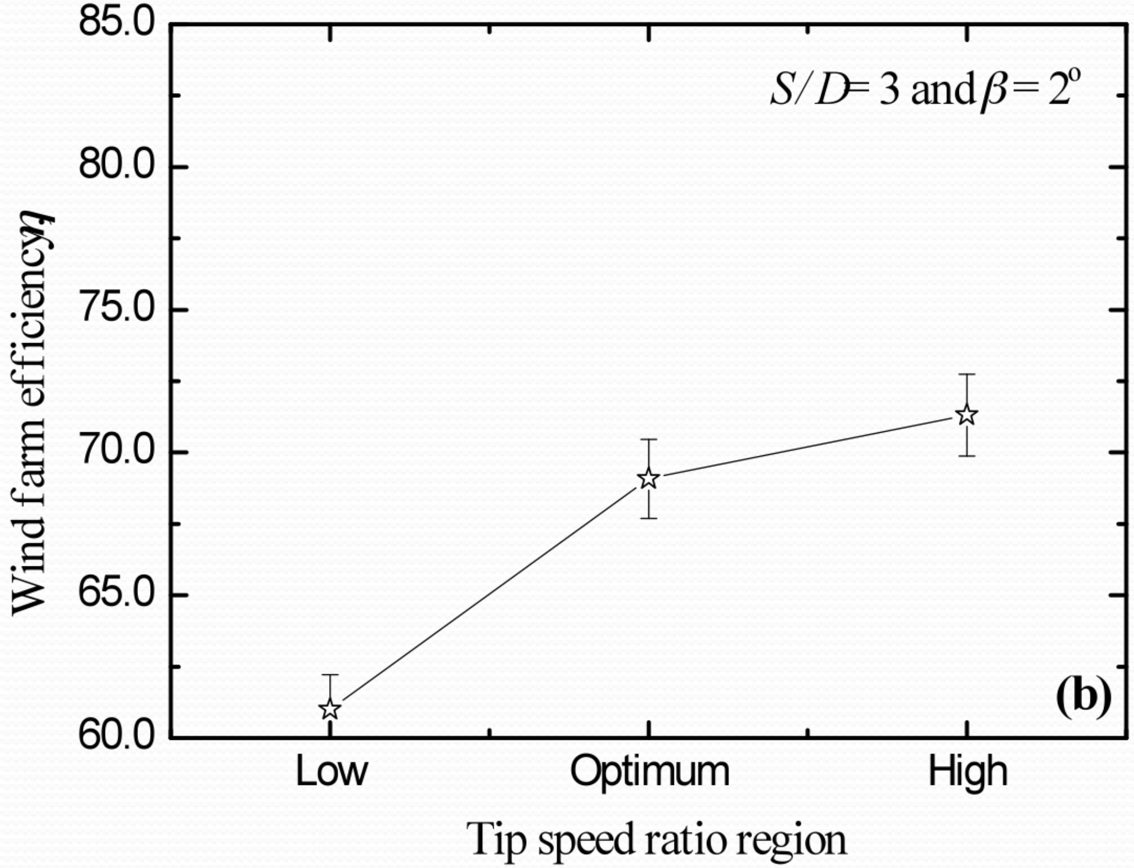
Power coefficient, downstream turbine



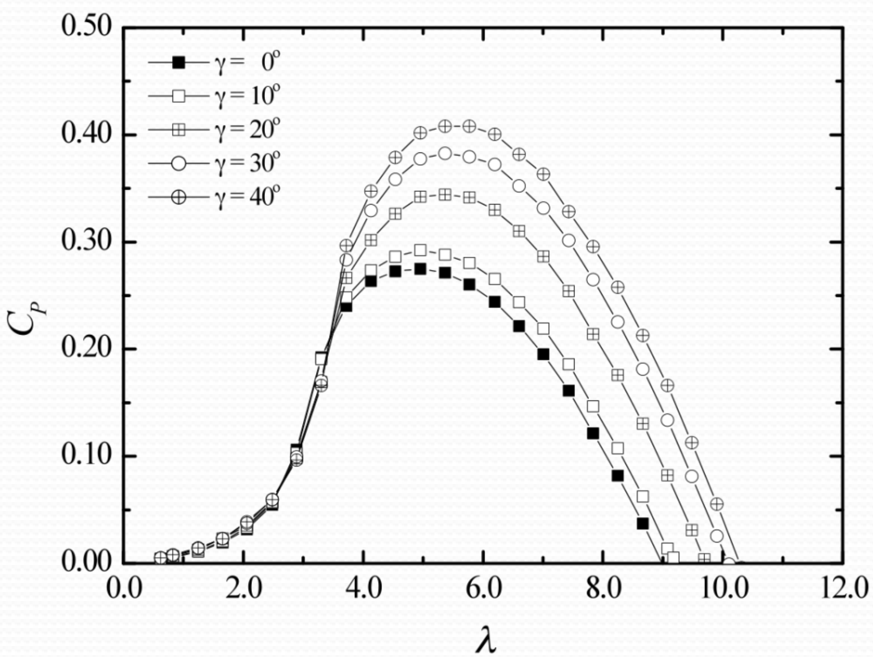
Thrust coefficient, downstream turbine

Total output compared to two unobstructed turbines

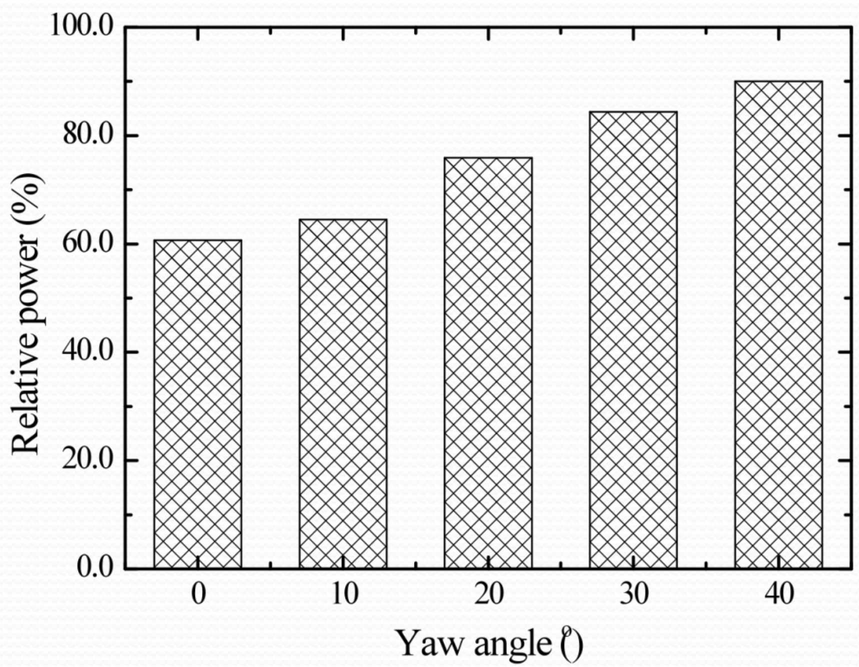
S/D=3



Effect of yawing upstream turbine
Upstream turbine operating at peak efficiency
S/D=3



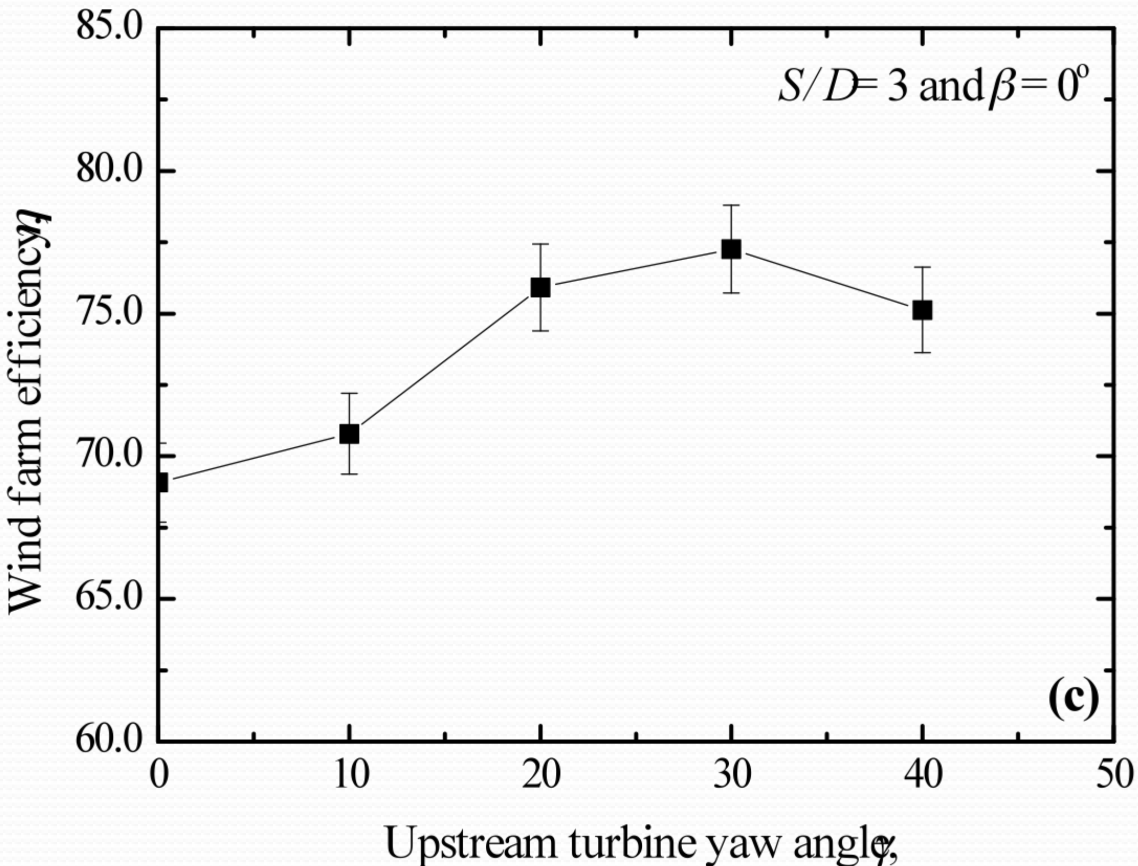
Power coefficient, downstream turbine



Power coefficient, downstream turbine, compared to single, non-yawed turbine

Results

Total output compared to two unobstructed turbines
Upstream turbine operating at peak efficiency
S/D=3



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Conclusions

- When two wind turbines are placed in-line and both operated at best efficiency, the output of a turbine at S=3D is less than 60% of that upstream

- The power reduction is influenced by the wake characteristics from the turbine upstream and therfore by its operating point

- By reducing the power extracted from the first, the TOTAL output may be increased

- Yawing a turbine reduces its power by $\cos^3\gamma$. But it also deflects the wake which increases the output further downstream

- Two turbines operating in-line at best efficiency may increase the total output from about 69% of two unobstructed turbines at zero yaw, to 78% when the first is yawed 30 degrees. (Figures taken for S/D=3.)

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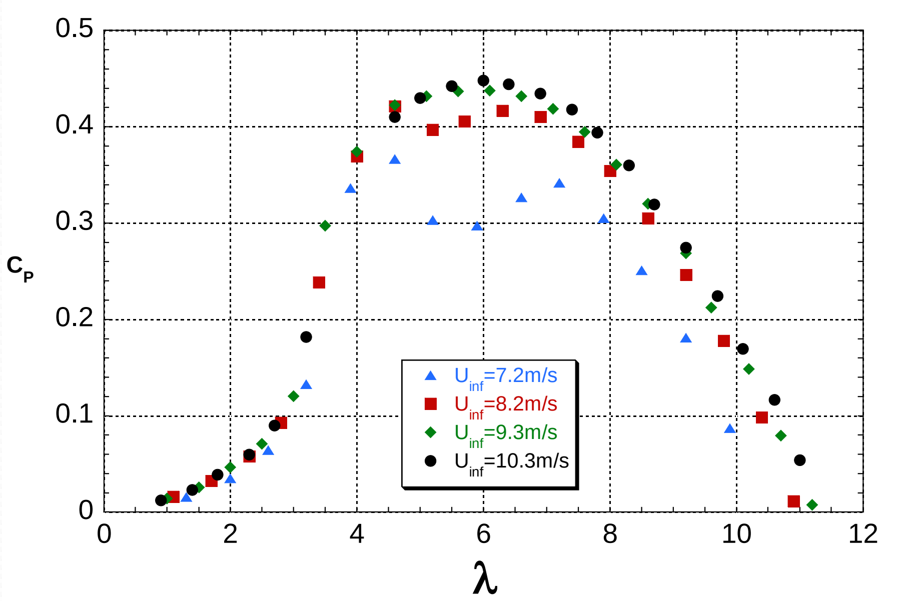
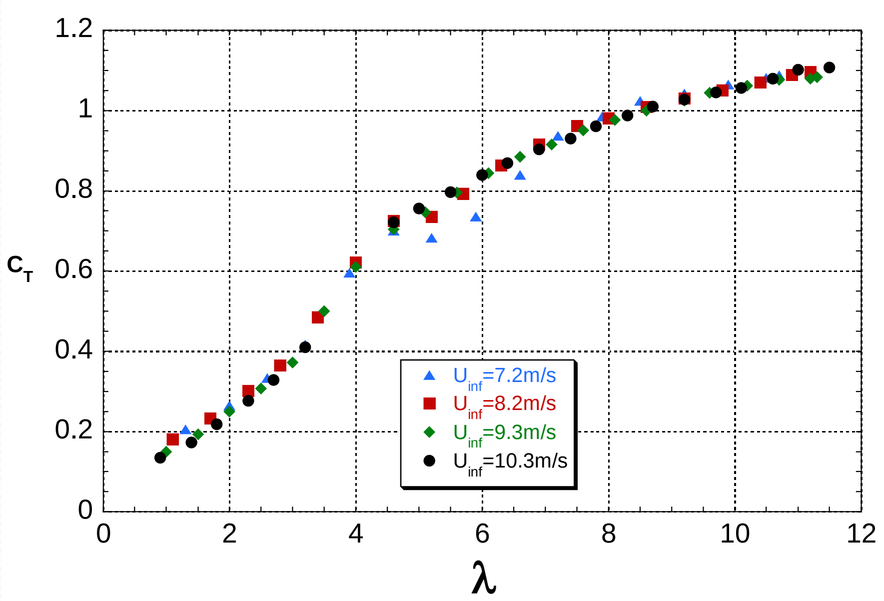
Reynolds number dependence

Turbine was designed for $\lambda = 6$ and $U_{ref} = 10m/s$



Power coefficient vs tip speed ratio



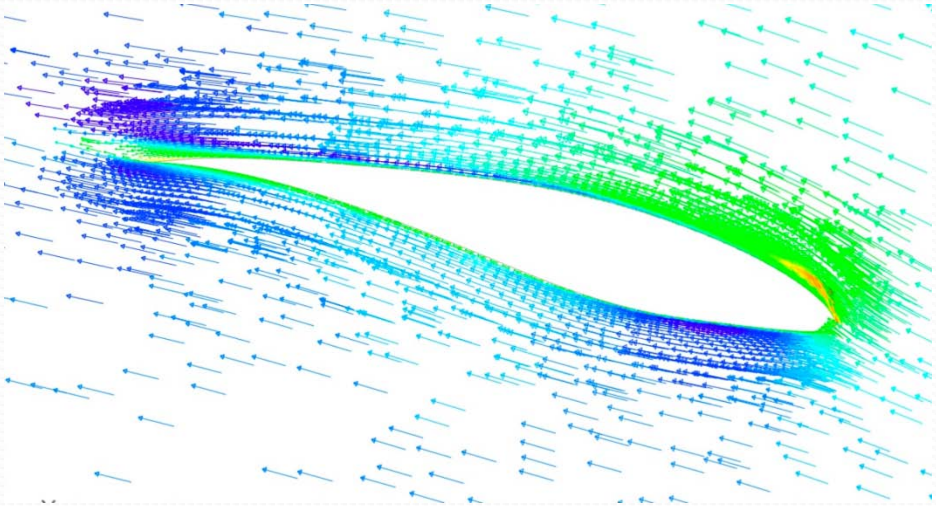
Thrust coefficient vs tip speed ratio

3D CFD details

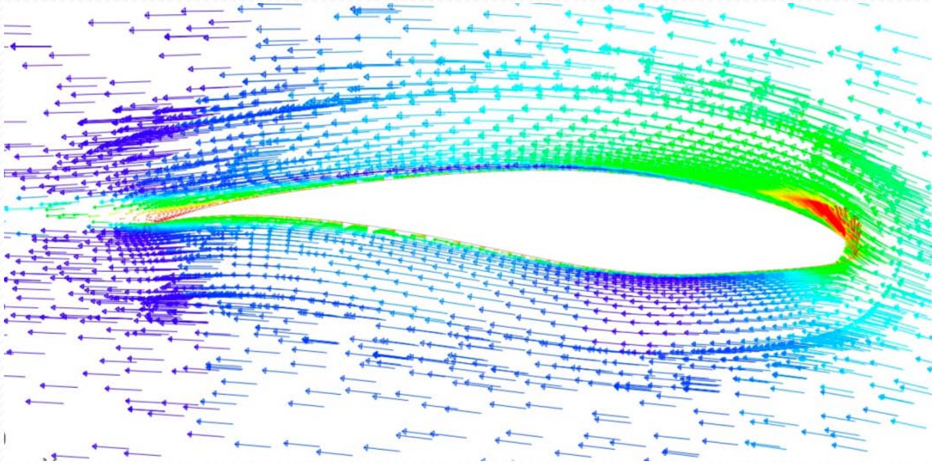
- 1/3 of the rotor including the nacelle was simulated.
- CFD domain same as wind tunnel test section (-4.5D to 7.8D in streamwise direction, 2.9D in spanwise direction).
- k-ω SST turbulence model with $y^+<5$ for first grid point.
- Structured boundary layer grid around blade up to 0.1c, tetrahedral grids used further out.
- QUICK and SIMPLEC schemes used for convective and pressere terms.
- 100.000 cells used to describe the blade and nacelle surfaces, $3.5*10^6$ grid points used.
- 4CPU PC parallel processing, ≈ 24 hours computing time per case

At design tip speed ratio (λ = 6)
Flow almost two-dimensional

- Flow mostly attached except at the trailing edge separation ramp
- Angle of attack close to 7^o over most of the blade
- C_L ~ 1.2



r/R=0.44



r/R=0.89

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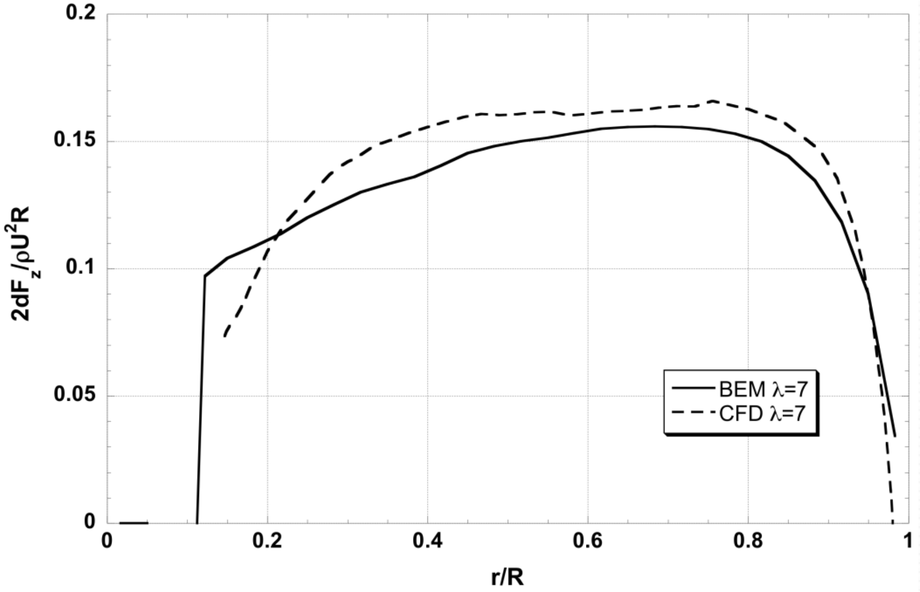
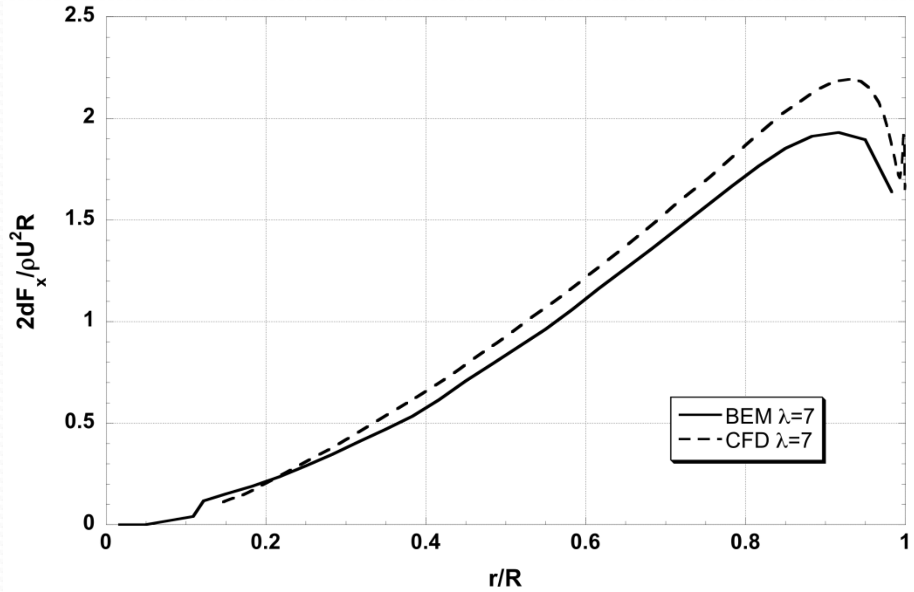
Force distributions near design tip speed ratio

Good agreement between BEM and CFD

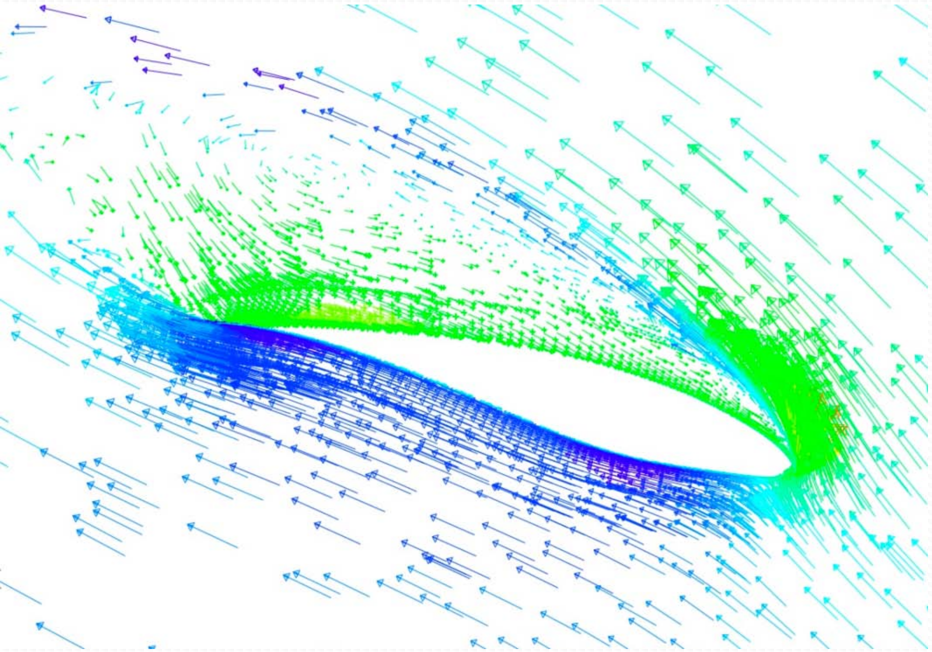


Tangential force



Streamwise force

At low tip speed ratio (λ = 3) the blade operates in deep stall mode and the flow is highly three-dimensional.
BEM expected to fail severely



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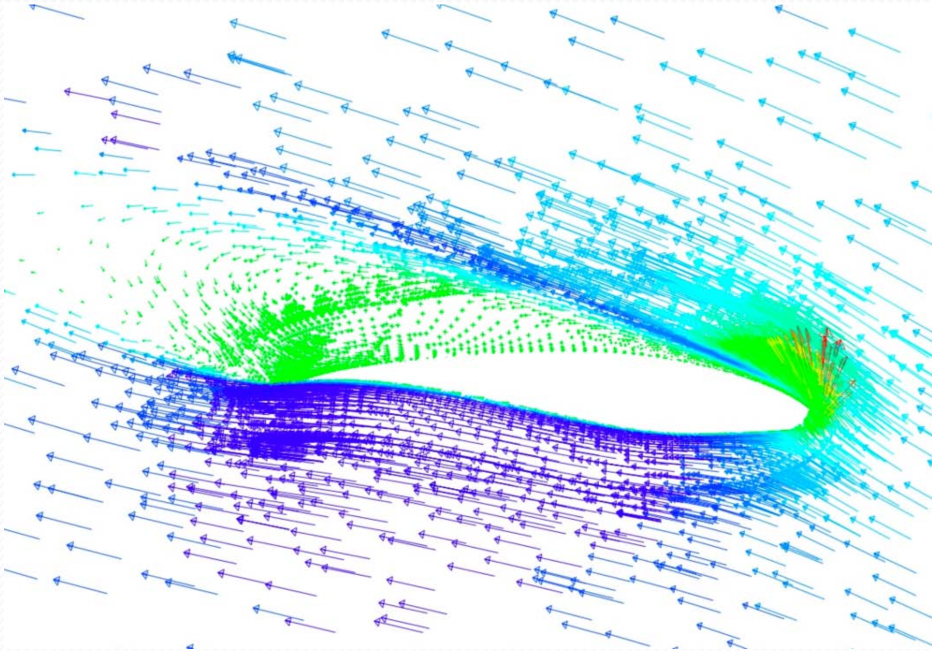
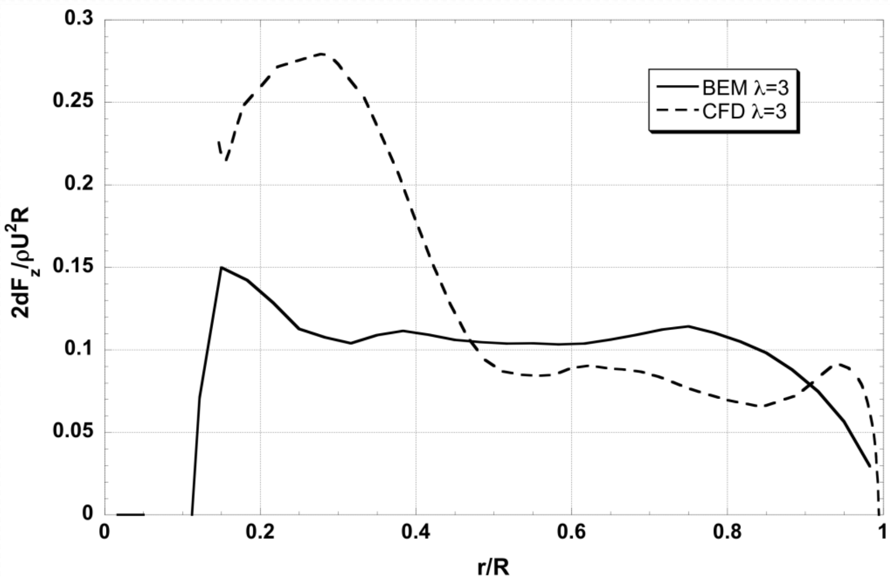


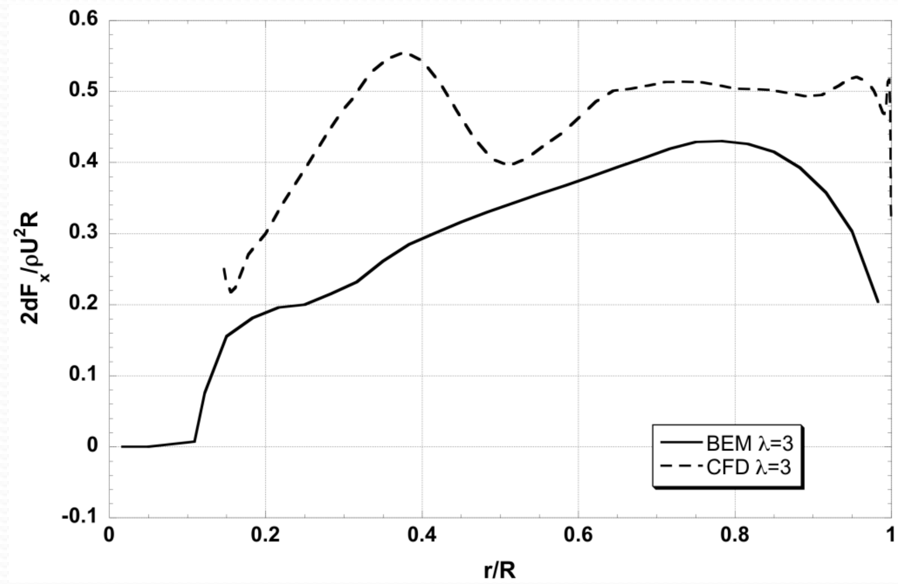
r/R=0.89

Force distributions for λ = 3

Significant differences between BEM and CFD distributions.

(Still C_P predictions virtually identical, but BEM C_T severely under-estimated)





Tangential force

Streamwise force

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