# Differences in Modeling Blade- and Inflow-induced Rotor Aerodynamic non-Uniformities

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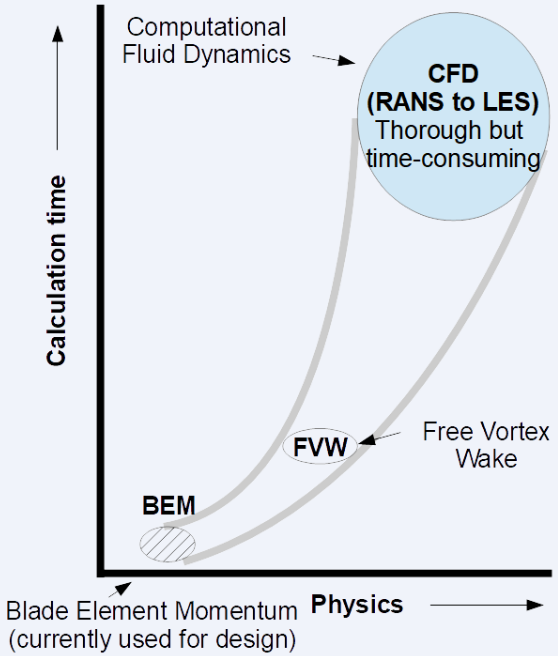
# Validation of aero-elastic codes

## Motivation

- Wind turbine design calculation require > 1M aerodynamic iterations

- Accuracy of these drive design in terms of power performance, loads, stability and noise

  Model accuracy becomes more critical for large hence flexible rotors




- Large nr of iterations necessitates usage of low fidelity models

  - How to improve and calibrate wind turbine aerodynamic models remains a research question until we can design wind turbines with Direct Navier Stokes
    - Aerodynamics is a Millenium Prize Problem (http://www.claymath.org/millennium/)

  - Need measurements for a large range of conditions and turbine types to improve and calibrate current aerodynamic models and to assess their general validity

*Nowadays there isn't a single designer to find who would dare to design a wind turbine with the aerodynamic modelling from the 1980's [1])*

[1]) J.G. Schepers *Engineering models in aerodynamics*, TUDelft *PhD thesis, November 2012*
[2]) Grol van, H.J., Snel, H., Schepers, J.G., *Wind Turbine Benchmark Exercise on Mechanical Loads, A State of the Art Report* ECN-C-91-030/31, 1991,
(a description of state of the art design models at the end of the 1980's)

# IEA Wind and aero-elastic model validation

- Since 80s there have been joint efforts to validate and improve rotor aerodynamic models
  - Field experiments, wind tunnel test, benchmarking against high fidelity models (CFD)

*Are we not be finished by now???*

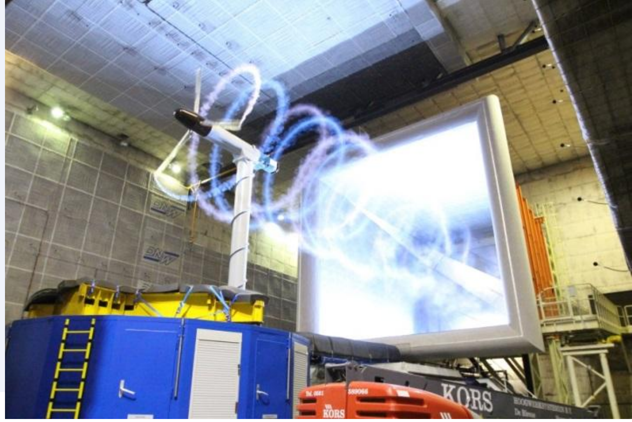
# Outline

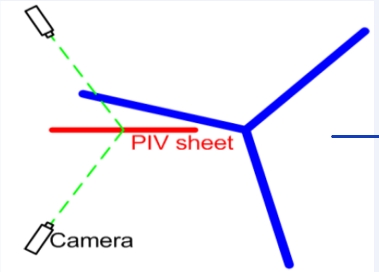
- Introduction
- Summary previous rounds
  - Wind tunnel to field
- DanAero
  - Sheared inflow
  - Cyclic pitching
- Conclusions and recommendations

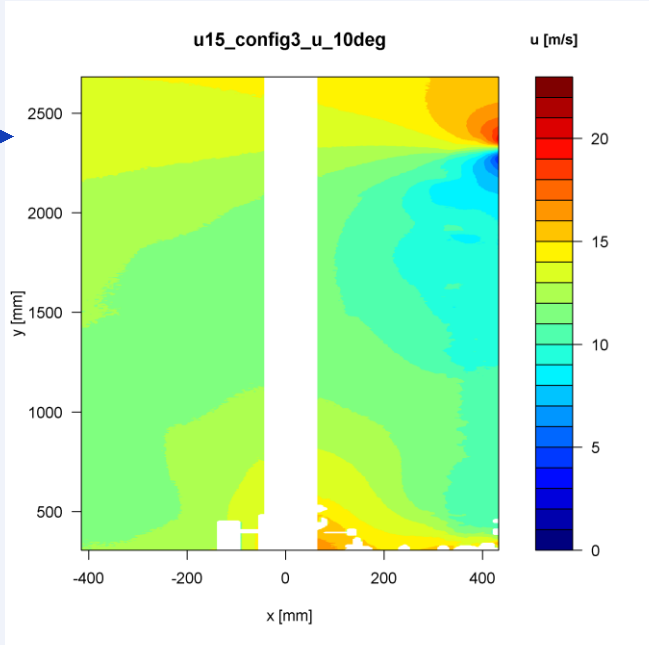
# EU MEXICO and New MEXICO

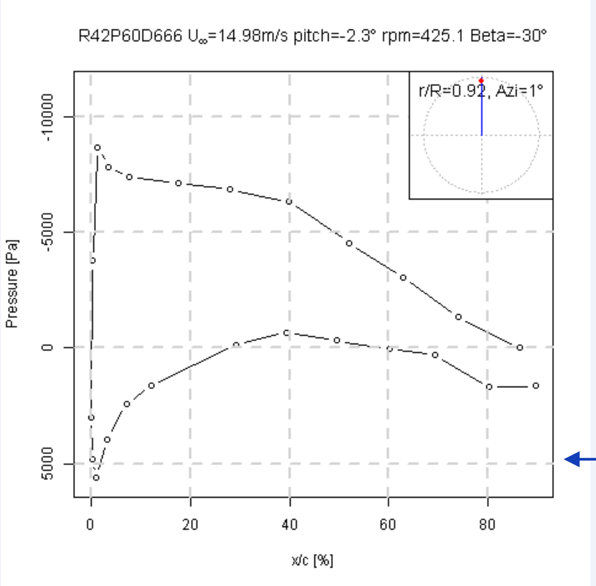
## Connecting loads and velocities: Momentum theory

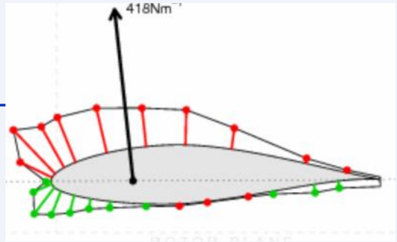
- Induced velocity around rotor plane (PIV)
- Sectional and rotor axial force (integrated pressures)

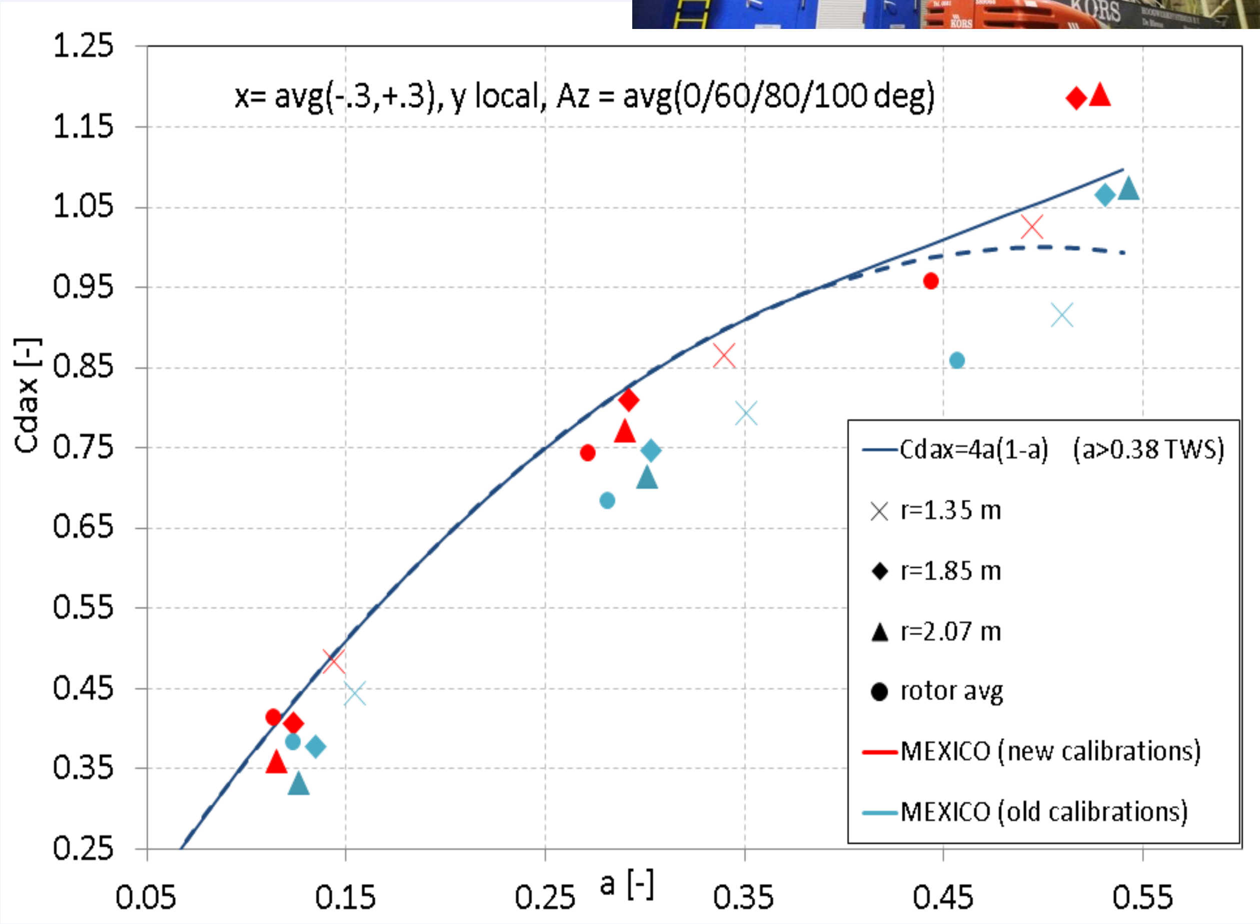


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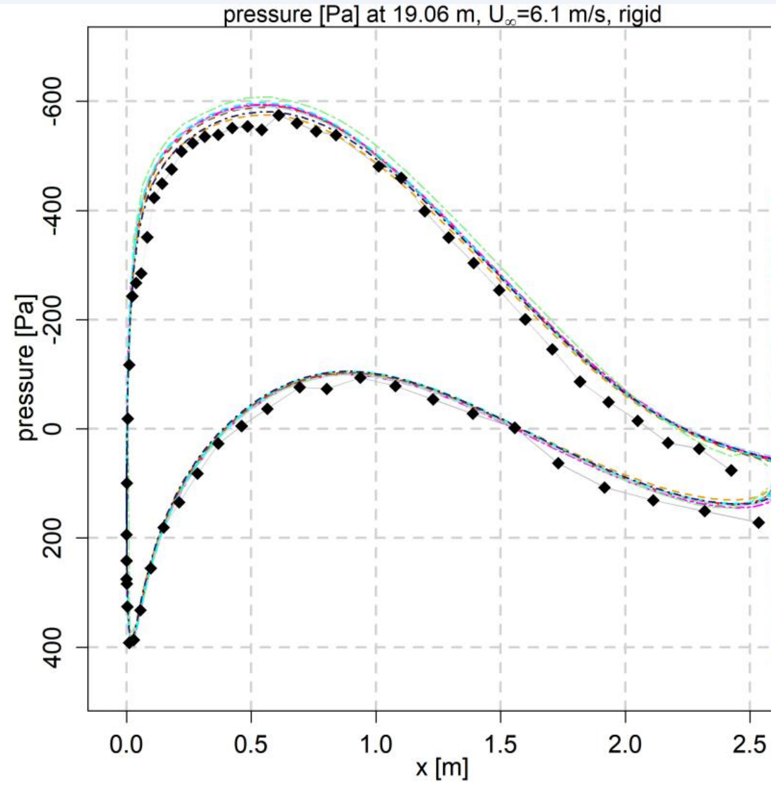
# IEA Wind Task 29: From wind tunnel to field

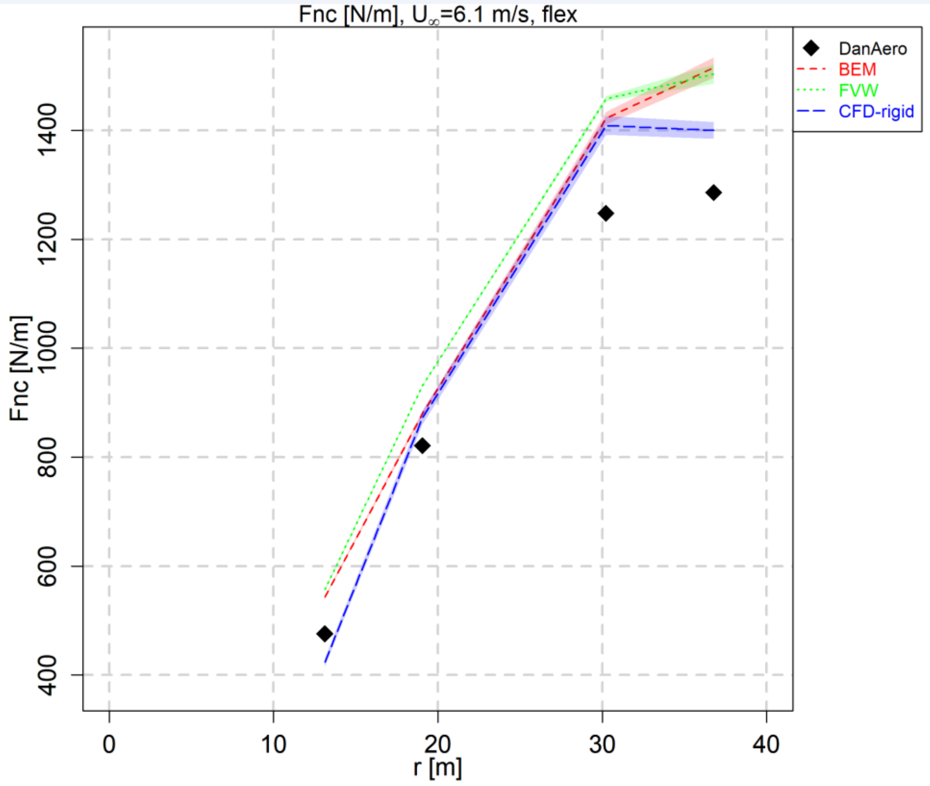
## Code comparsion against DanAero field rotor aerodynamics (NM80 turbine)

- Axial, constant, uniform inflow (low TI)

DanAero test set-up (≈80m)



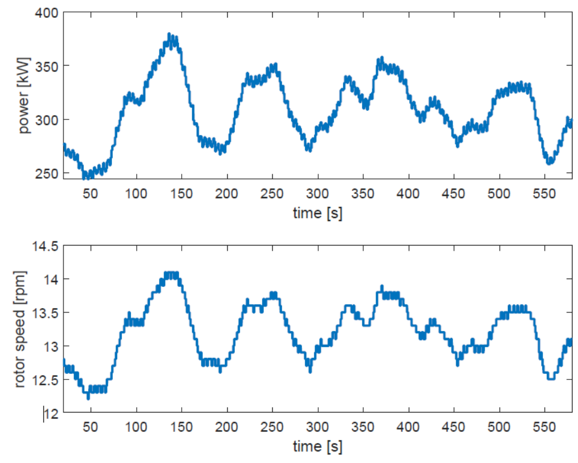

Pressure distribution at 19 m span



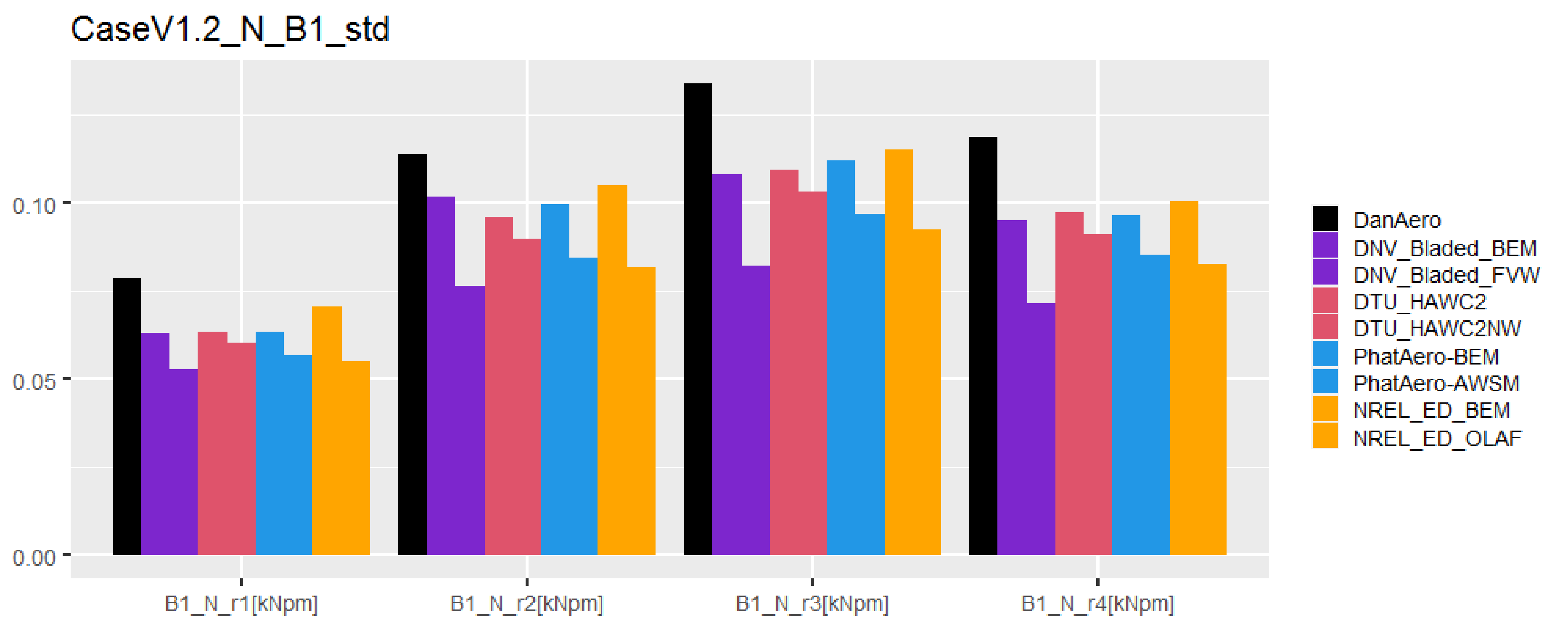

Comparison of integrated normal force as function of span

# IEA Wind Task 47

## DanAero turbulent inflow: statistics (standard deviation)

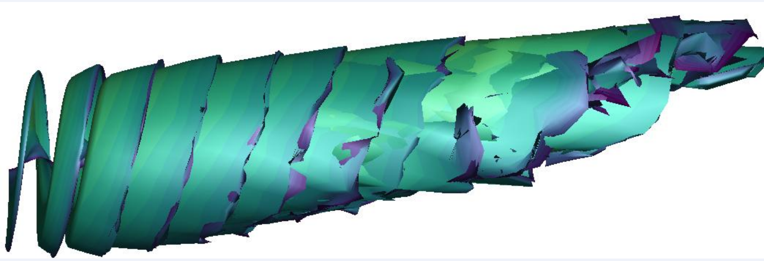



- Large differences in standard deviation, systematic difference between BEM and vortex type codes



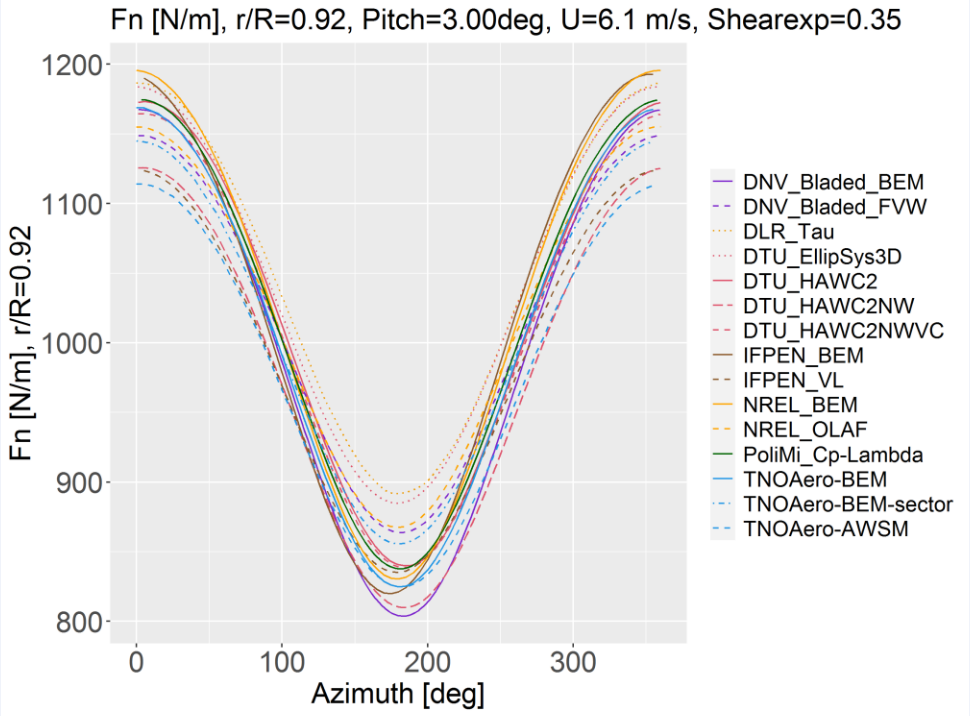

Measured chord normal force from pressure distributions at 4 radial stations and comparison to simulations

# Modeling non-uniform conditions

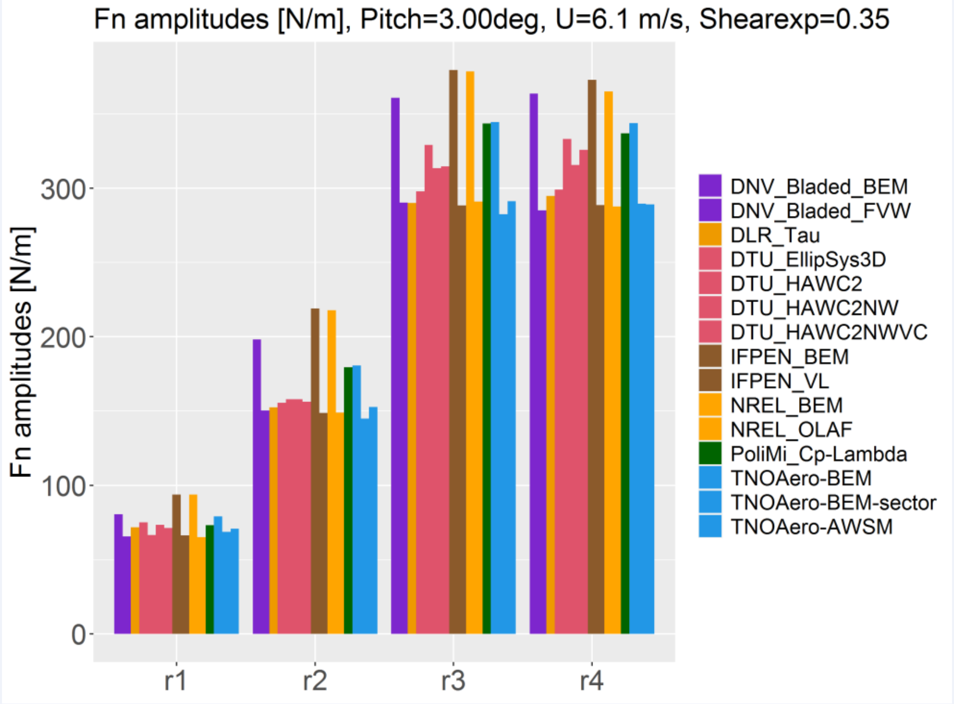



## DanAero vertical wind shear case

- More systematic case to study modeling of non-uniformity in controlled manner
- No measurement data, but with CFD as 'numerical wind tunnel'



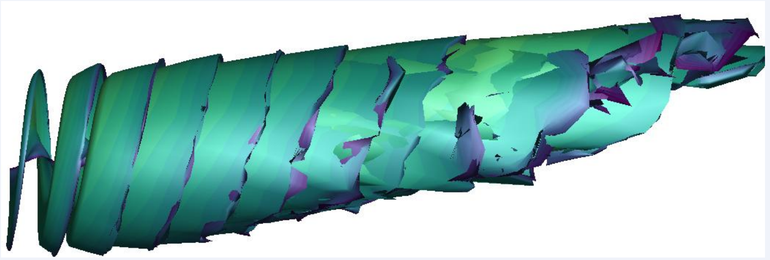

Chord normal force variation at 92% span radial station




Chord normal force amplitudes at 4 radial stations

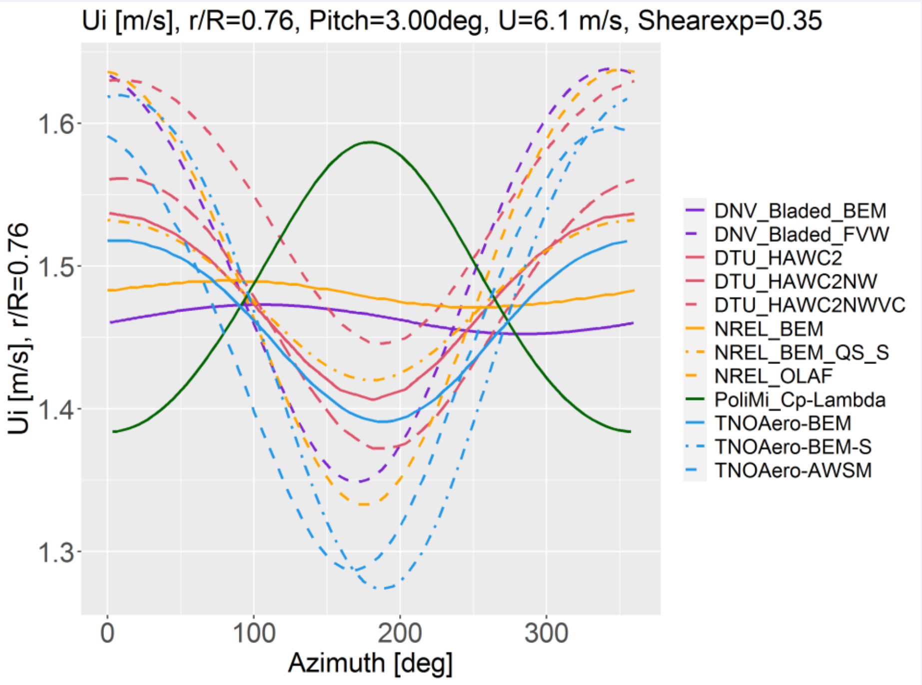
- Apparent difference between BEM and vortex code types, where CFD agrees with the latter

# Modeling non-uniform conditions



## DanAero vertical wind shear case: Induced velocities and momentum theory

- Large differences in underlying induced velocities
  - Are these models in agreement with momentum theory???




Axial induced velocity variation at 76% span radial station

Reprocess lifting line results and compare to $C_t = 4a\,(1-a)$

From forces to $C_t$:

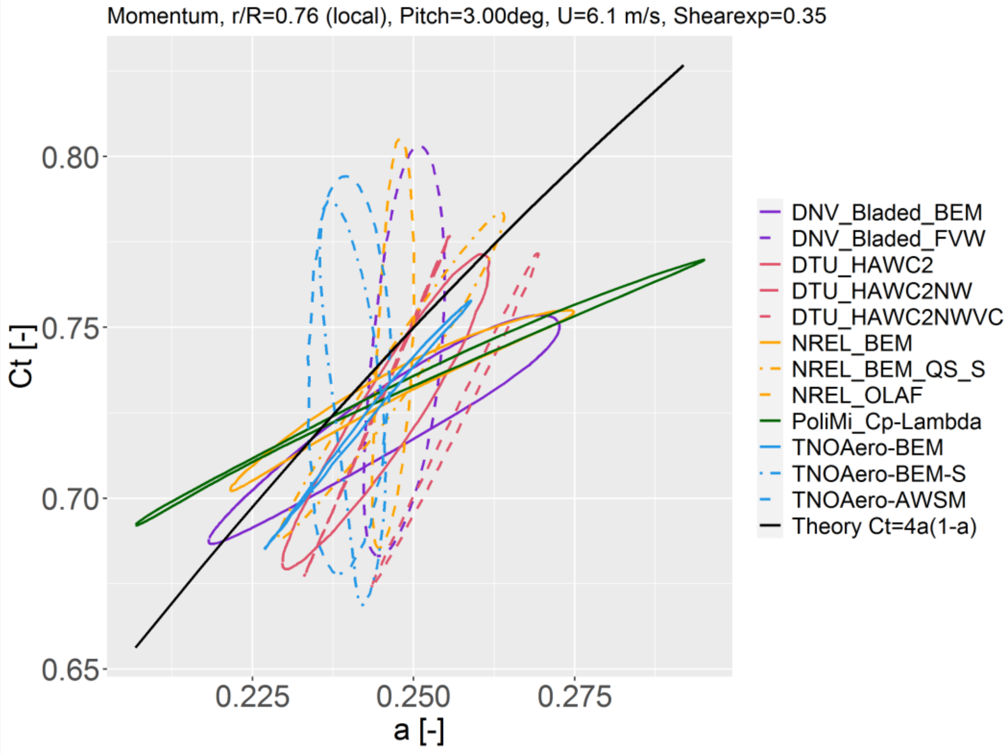
$C_t = F_{ax} / (0.5 \text{ rho } U_{ref}\text{\^{}}2 \text{ A})$,
$F_{ax} = F_n * \cos(\text{phi}) - F_t * \sin(\text{phi})$,
$\text{phi} = \text{pitch} + \text{twist}$

From axial induced velocity to a-factor:

$U_i * F_{Prandtl} = a * U_{ref}$

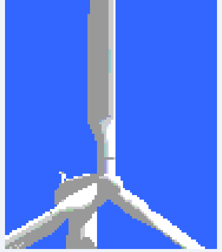
Local BEM option:

$U_{ref} = U_{wind}(\text{azi})$, $U_i = U_i(\text{azi})$,
$F_{ax} = F_{ax}(\text{azi})$




Post-processed momentum curve (Thrust coefficient Ct versus axial induction factor a) at 76% span radial station

# Modeling non-uniform conditions



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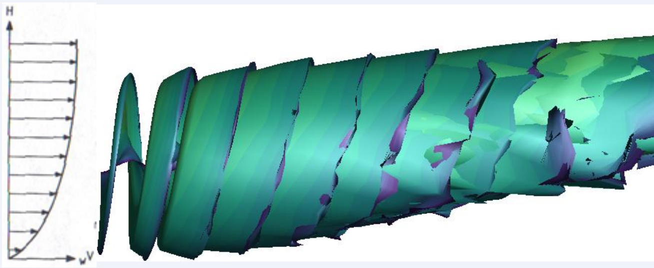
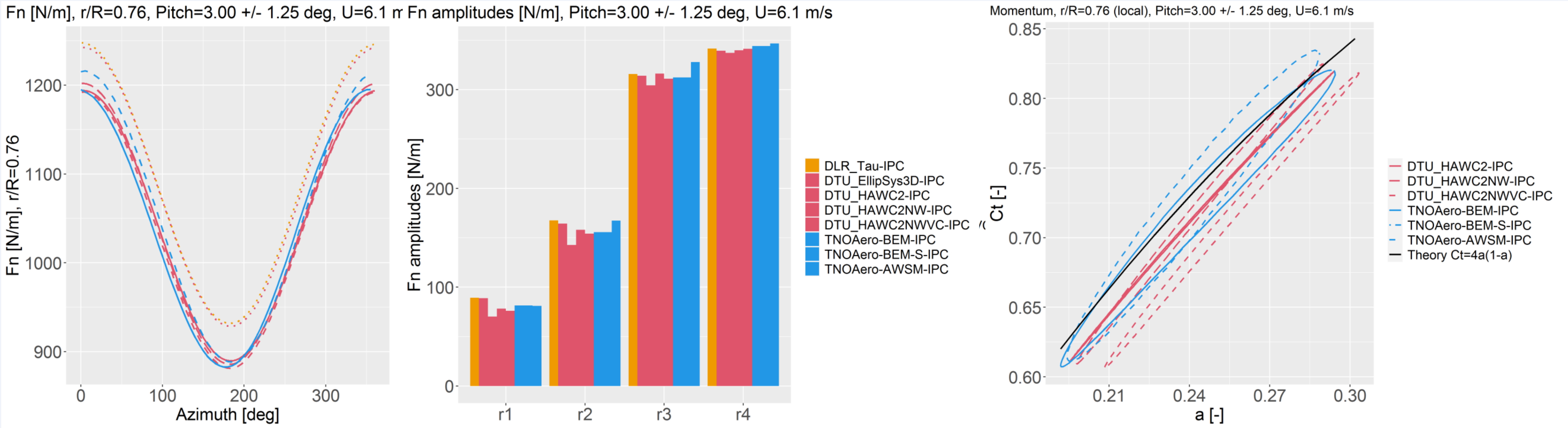
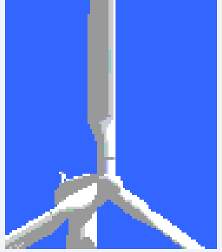


## DanAero vertical wind shear case vs load variation due to cyclic pitch

- What happens if we create a similar force variation by means of harmonic pitch variation instead of vertical shear?



# Modeling non-uniform conditions



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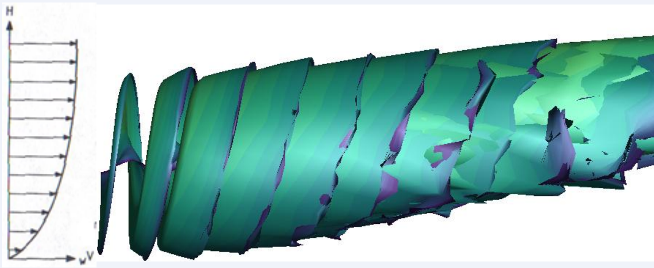
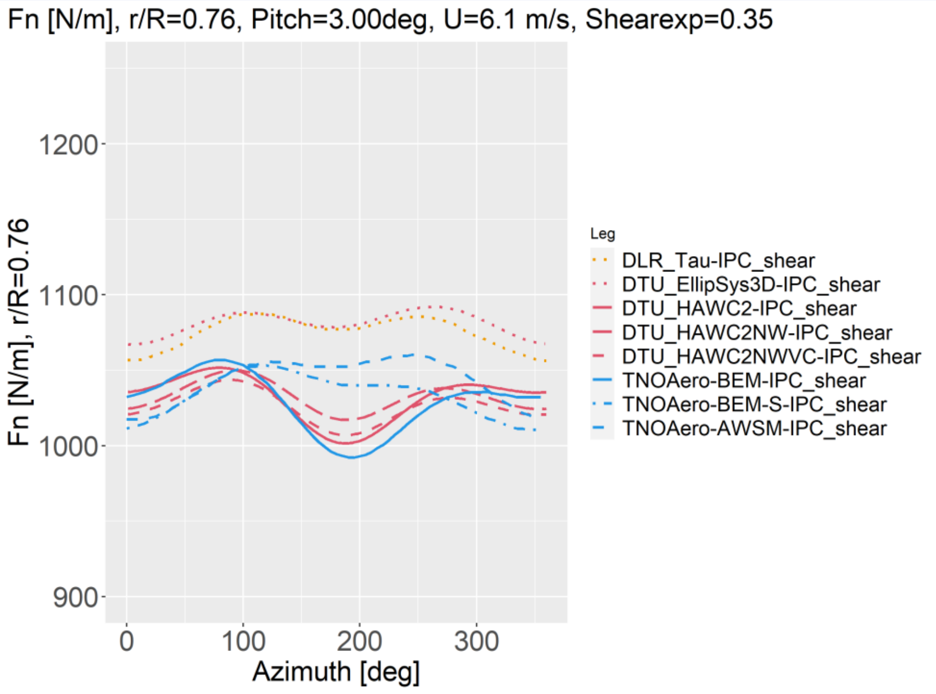
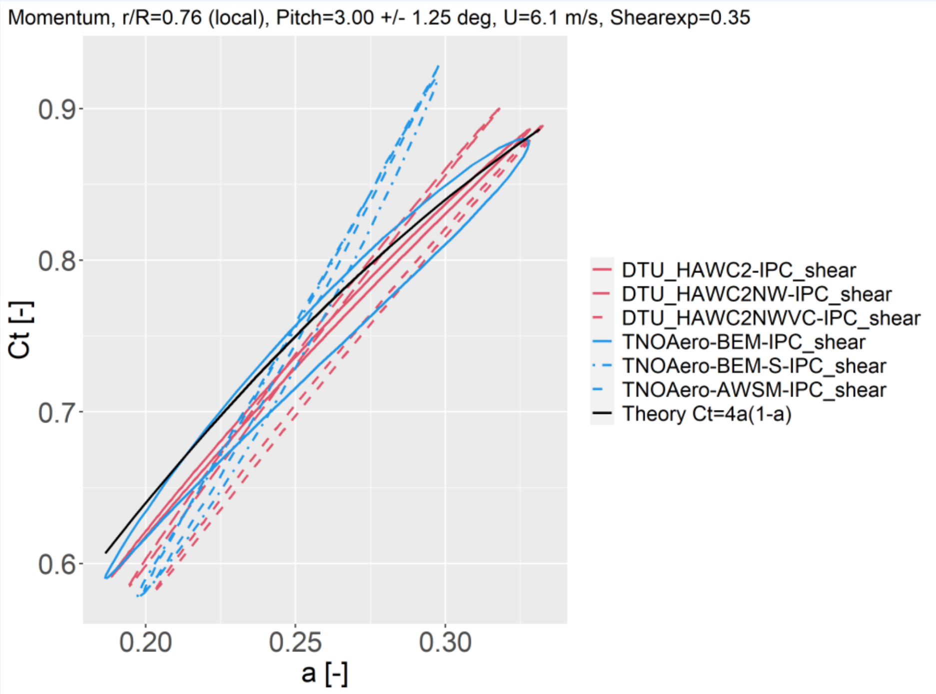


## DanAero vertical wind shear case + load variation due to cyclic pitch

- What happens if we create a force variation by means of harmonic pitch variation to cancel out vertical shear?



# Modeling non-uniform conditions

## Discussion: Applicability of local momentum theory

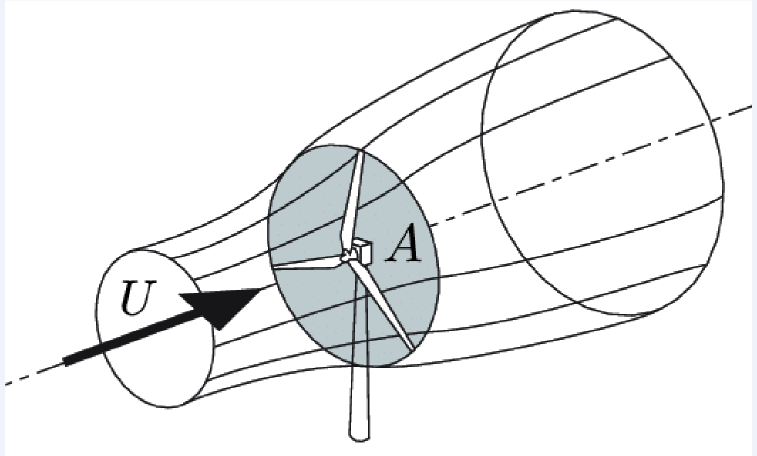
- In local BEM, we balance blade force against local momentum
  - A variation of blade element force with azimuth (e.g. by cyclic pitching) does not pose violations to BEM theory besides possible unsteady effects
  - Azimuthal non-uniformity in inflow (e.g. by vertical wind shear or an incoherent gust) also leads to a violation
- How valid is the local BEM implementation taking the local ‘element’ wind as reference wind speed?
  - In CFD all streamtube velocities are considered instead of a single reference wind speed
- Playing with this idea has led to various implementation changes with potential for improvement [1]

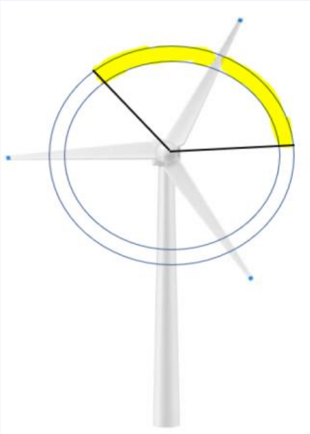
$$2a(1-a)\rho U_{\mathrm{m}}^2 2\pi r \mathrm{d}r = \sum_B c0.5\rho W^2 c_l(\alpha)\cos(\phi)\mathrm{d}r,$$

where

$$\phi = \mathrm{atan2}(U_{\mathrm{e}}(1-a), \Omega r), \ \alpha = \phi - \epsilon \text{ and}$$

$$W = \sqrt{U_{\mathrm{e}}^2(1-a)^2 + (\Omega r)^2}$$



[1] K. Boorsma et al, *Challenges in Rotor Aerodynamic Modeling for Non-Uniform Inflow Conditions*, J. Phys.: Conf. Ser. 2767 022006

# Summary

## What have we learned from this exercise?

- Load prediction in non-uniform inflow (which is increasingly important for large rotors) problematic for most BEM codes
  - Large implementation differences between BEM codes
  - FVW and CFD codes are mostly in agreement
- However, if we create a similar non-uniform force variation by means of cyclic pitch variation, good agreement exists between all code types
- Explanation for differences between blade- and inflow induced non-uniformity lies in violation of BEM assumptions
- By doing so, did we remove physics without being able to repair it??
  - Further analysis of results is pending[1] plus suggestions for improvement are under development

[1] G. Pirrung et al, *A polar grid BEM implementation suited for individual pitch and dynamic pitching*, WESC2025, Friday 26th June 0840h-1020h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