CFD Modeling and Analysis of Rotor Wake in Hover Interacting with a Ground Plane

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Outline of Presentation

- **Problem Statement**
  - **Motivation: Brownout Phenomena**
  - **Simplification: Helicopter Landing**
  - **Problem: Rotor Wake in Hover Interacting with Ground Plane**
  - **Technical Challenges**
- **Objective**
- **CFD Methodology**
- **Results**
- **Conclusions**

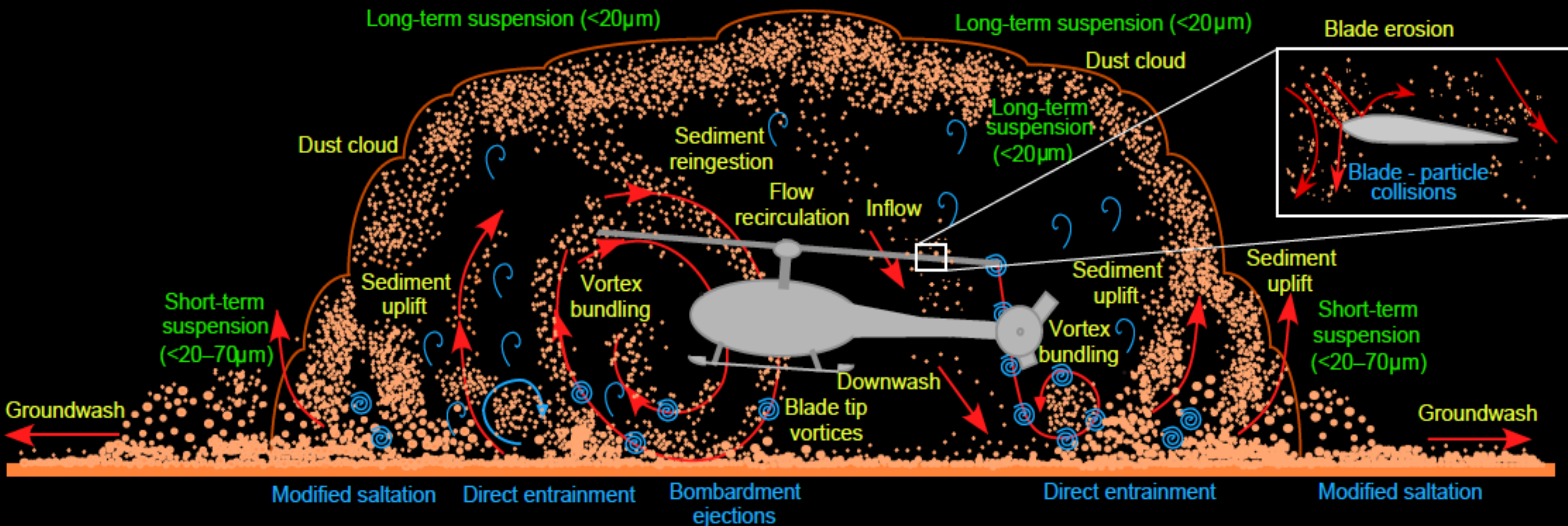
Motivation – Brownout Phenomena

- **Helicopters operating in ground effect uplift and entrain loose particles to form large dust clouds**
  - **Poor visibility leads to loss of situational awareness**
    - Increased rate of accidents
  - **Increased blade erosion**
    - More frequent blade replacement

Video courtesy OADS

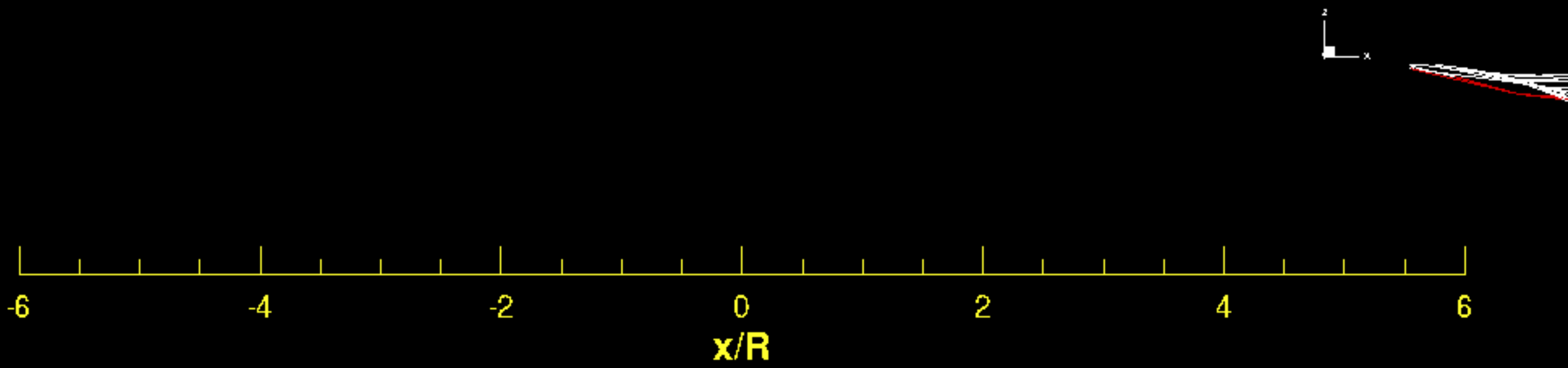
- **Possible solutions**
  - **Use of sensors**
    - Only deals with increasing situational awareness
  - **Change in flight path**
    - May lead to other undesired effects (e.g. higher than desired landing forces)
  - **Change in design**
    - Empirical evidence suggests brownout cloud is a function of rotorcraft design
    - ***Requires detailed understanding and modeling of physical phenomena responsible for brownout clouds that impact visibility and erosion***

Simplification: Brownout Phenomenon



- **Brownout phenomena very complicated, want to simplify**
  - **In general, a two phase flow problem**
    - Carrier phase: fluid flow induced by helicopter operating in ground effect
    - Sediment phase: dust particles transported by fluid flow
  - **If assume that the particles are dilute, decouples the phases**
    - ***Can investigate flow from helicopter landing, ignoring particles***

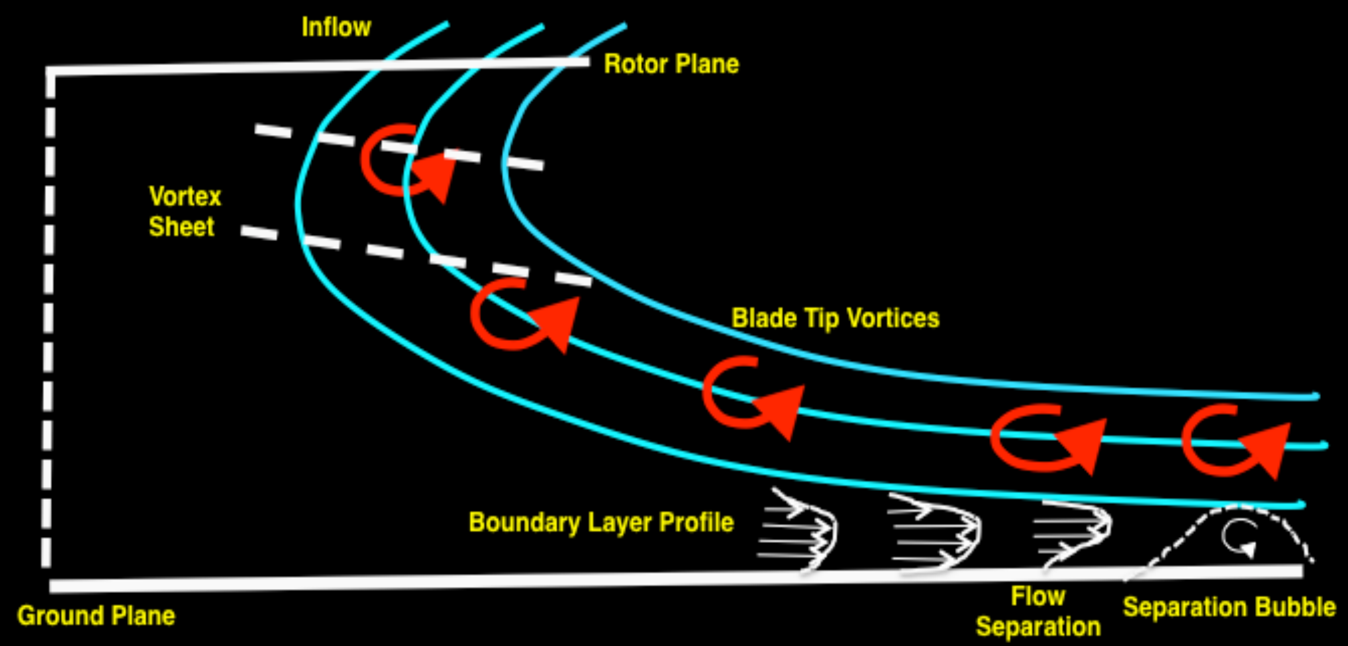
Rotor Wake in Hover Interacting with Ground Plane



- **Helicopter landing still complicated**
  - **Approach to landing**
    - Dominated by end of the landing approach → ***consider only hover***
  - **Helicopter**
    - Fuselage and tail rotor affects secondary → ***consider only isolated rotor***
  - **Complicated ground terrain**
    - Details of terrain secondary → ***consider flat ground plane***

Want to understand and simulate: a rotor wake in hover interacting with a ground plane, with ramifications for brownout

CFD Modeling Challenges



- **Rotor Wake in Hover Interacting with Ground Plane**
  - **Global physics due to ground effect**
    - Modifications to thrust, power, inflow, ground-jet outwash→ ***conservation***
  - **Tip vortex formation and initial convection**
    - Effect of tip geometry / tip blowing → ***mesh resolution, turbulence***
  - **Vortex convection and interaction with ground**
    - Diffusion, stretching, aperiodicity → ***numerical diffusion, turbulence***
    - Perturbations to steady outwash, separation → ***turbulence, pressure***

Previous work to capture rotor wake in hover IGE

First principle based approach (RANS/DNS)

- **Hariharan et al.(2011) –** RANS
- **Morales and Squires (2011) –** Euler(DNS)-Lagrangian
- **Kutz at al. (2012) –** RANS
- **Thomas et al. (2011 and 2012) –** Hybrid FVM-RANS

Inviscid wall

Rotor not modeled

Vortices not resolved well

FVM for wake convection

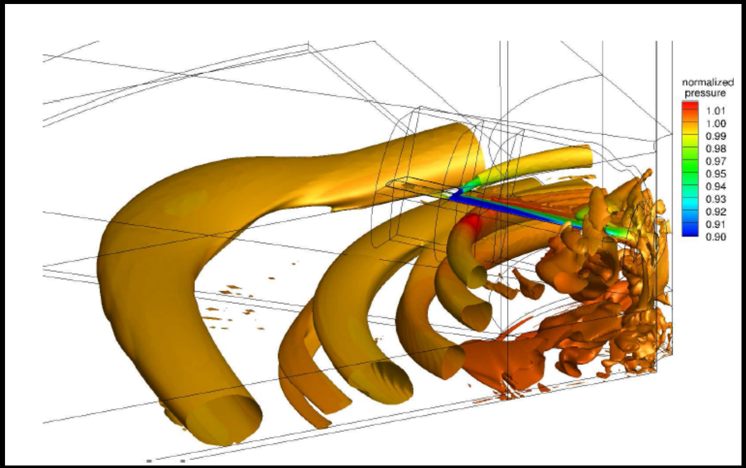


Figure courtesy: Kutz et. al

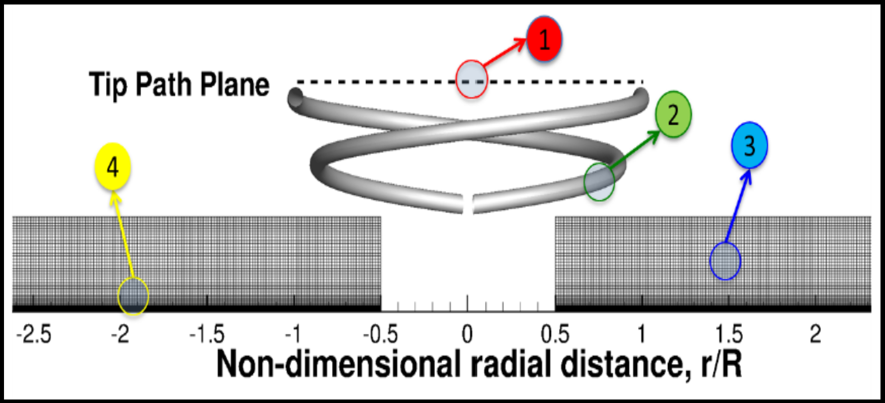


Figure courtesy: Thomas et. al

Need for RANS – based CFD that resolves vortices near ground without empiricism

Objectives

- Simplify problem to look at rotor in-ground-effect (IGE) in hover
- Simulate tip vortex formation
- Maintaining tip vortex until it reaches ground
- Provide detailed understanding of flow physics near ground
  - Unsteady boundary layer flow
  - Intensification / diffusion of tip vortices IGE
  - Turbulence levels near the ground
- Investigate effect of scaling parameters - number of blades, Re, tip changes
- Validate computational results with experimental data

Computational Methodology

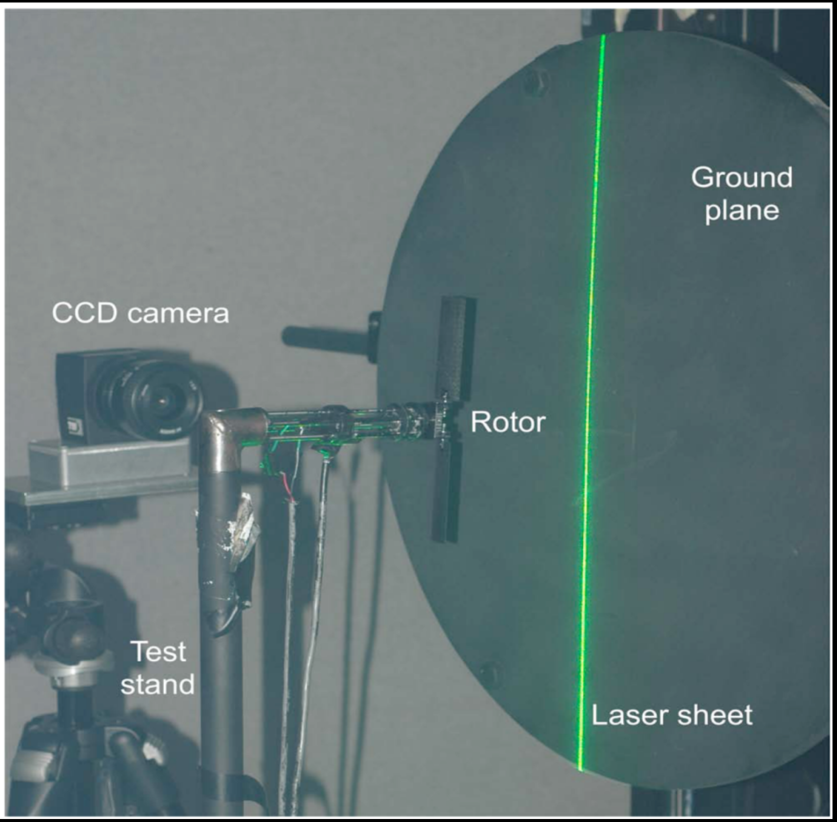
OVERTURNS: Overset Transonic Unsteady Reynolds Navier Stokes Solver

Compressible overset structured RANS

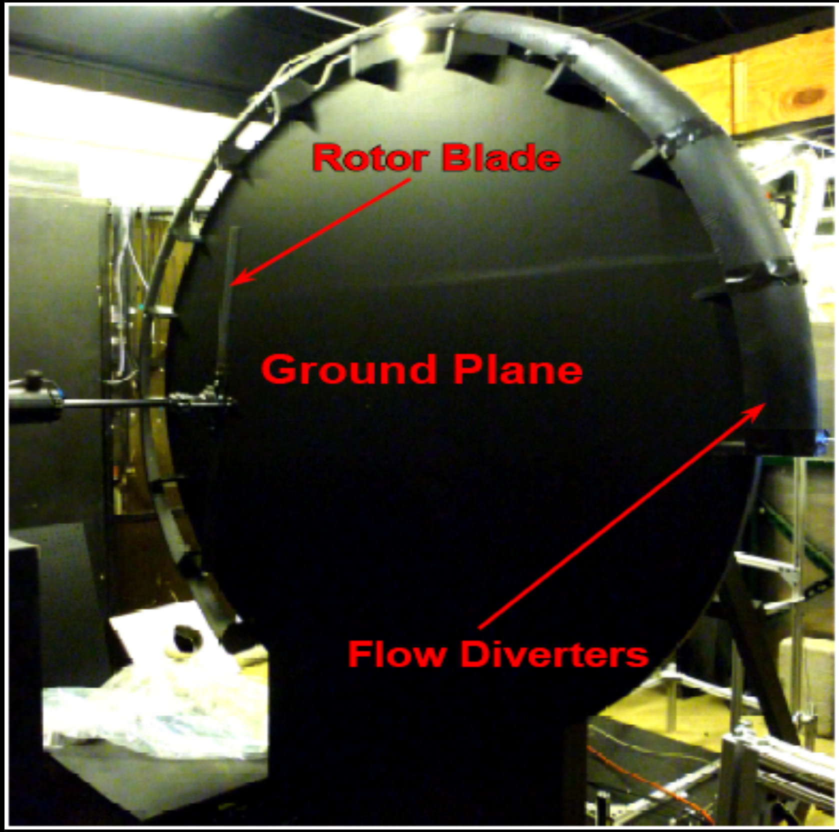
- **Spatial discretization**
  - Flux calculation done using Roe's Flux Difference splitting
  - Inviscid terms: 3rd order MUSCL scheme utilizing Koren's limiter and 5th order WENO scheme
  - Viscous terms: 2nd order central
- **Temporal discretization**
  - 2nd order backwards differencing
  - Implicit approximate factorization developed by Pulliam and Chaussee
  - Lower Upper Symmetric Gauss Seidel (LUSGS)
  - Turkel Preconditioning for Low Mach numbers
- **Spalart-Allmaras turbulence model with rotational correction**
  - Physical reduction of turbulence levels in vortices
- **Connectivity using Implicit Hole cutting (IHC) technique**
  - Automates transfer of information between meshes

Experiments Used for CFD Validation

- 2 bladed micro-scale rotor experiments, radius = 0.086 m
- 1 bladed sub-scale experiments, radius = 0.5 m



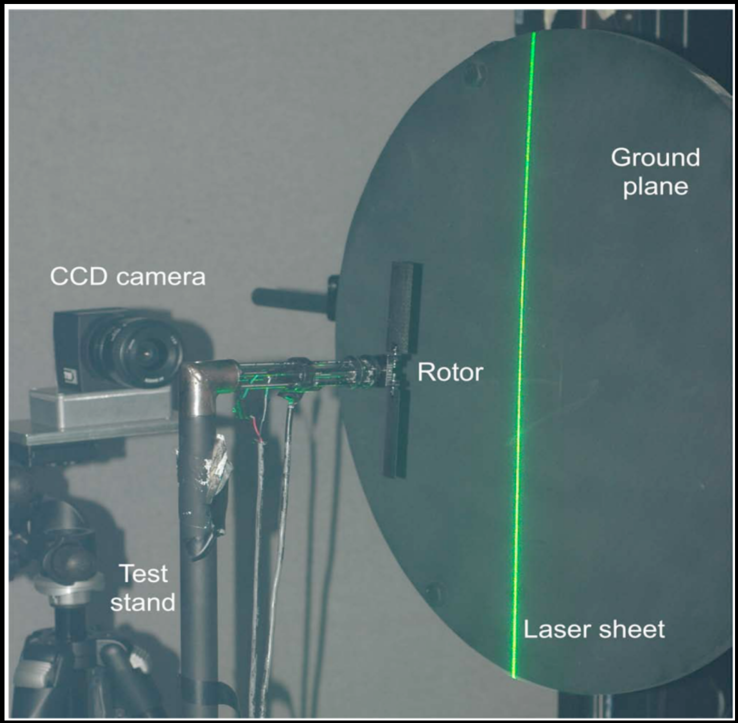
Experimental Setup, Lee et al. (2008) at University of Maryland



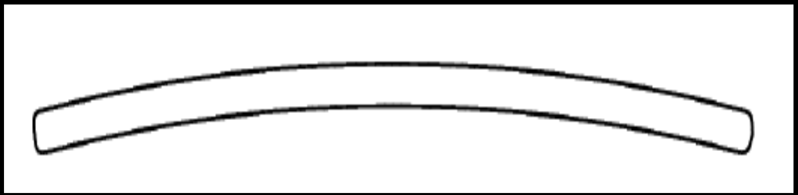
Experimental Setup, Milluzzo et al. (2010) at University of Maryland

2-Bladed Micro-Scale Rotor Setup

- **2-bladed rotor setup of Lee et al.**
  - Untwisted rectangular
  - Radius = 0.086 m
  - Chord = 0.019 m
  - Collective setting of 12°
- **Airfoil profile**
  - Blunt Leading and trailing edge
- **Flow conditions**
  - Re_{tip} = 32,400, Re_{root} = 6480
  - M_{tip} = 0.08
- **Ground plane distances**
  - h/R = 0.5, 1.0 and 1.5

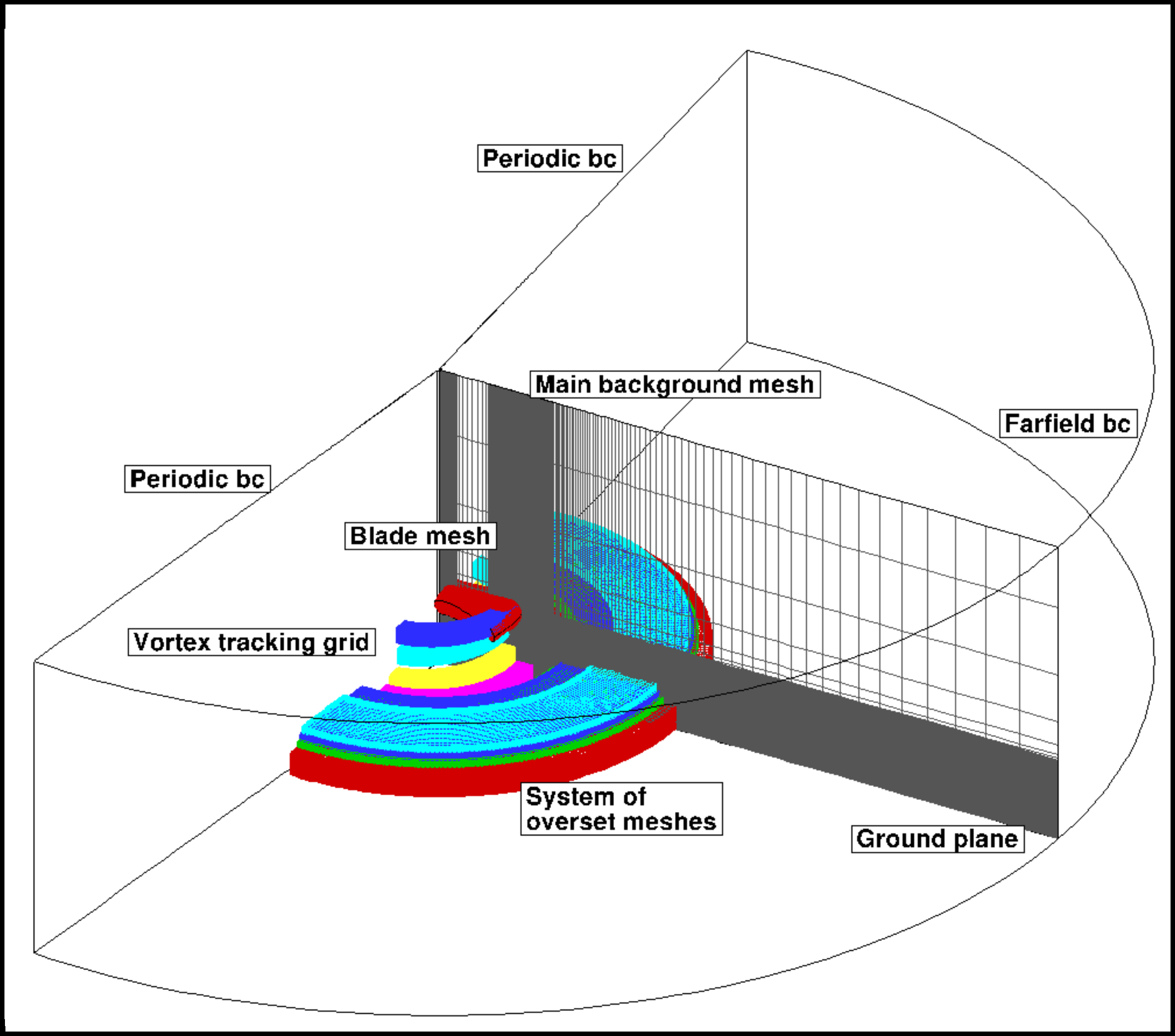


Experimental Setup, Lee et al. at University of Maryland



Airfoil profile

CFD Mesh Setup



Quiescent flow at far-field boundaries of the computational domain

Simulation done on one blade assuming spatial periodicity (model only 180 degrees of azimuth)

Low free-stream turbulence in all meshes (eddy viscosity ~ 0.1)

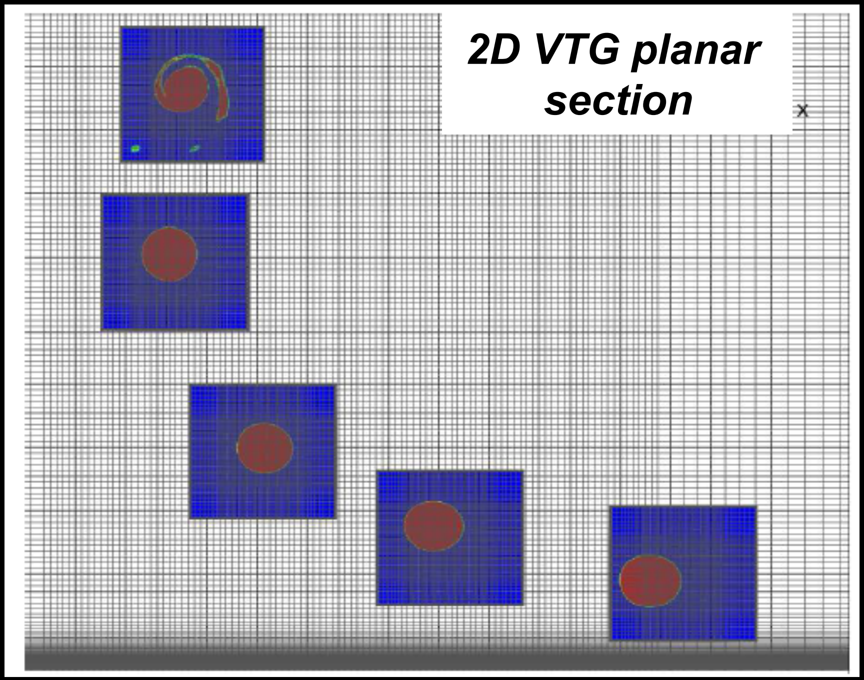
Rigid blade assumed

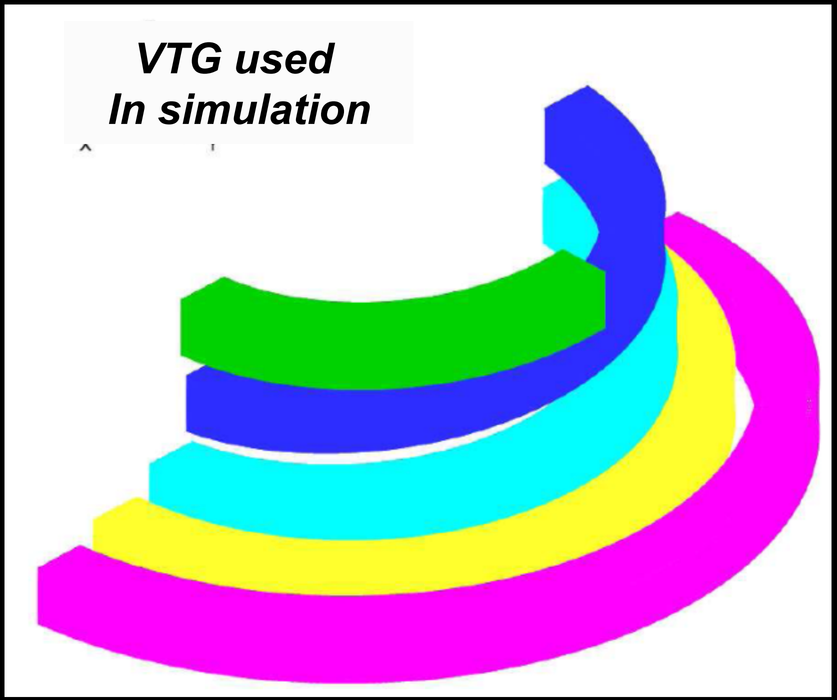
Rotor hub not modeled

Added vortex tracking grids

Added overset meshes close to ground

Added Vortex Tracking Grids

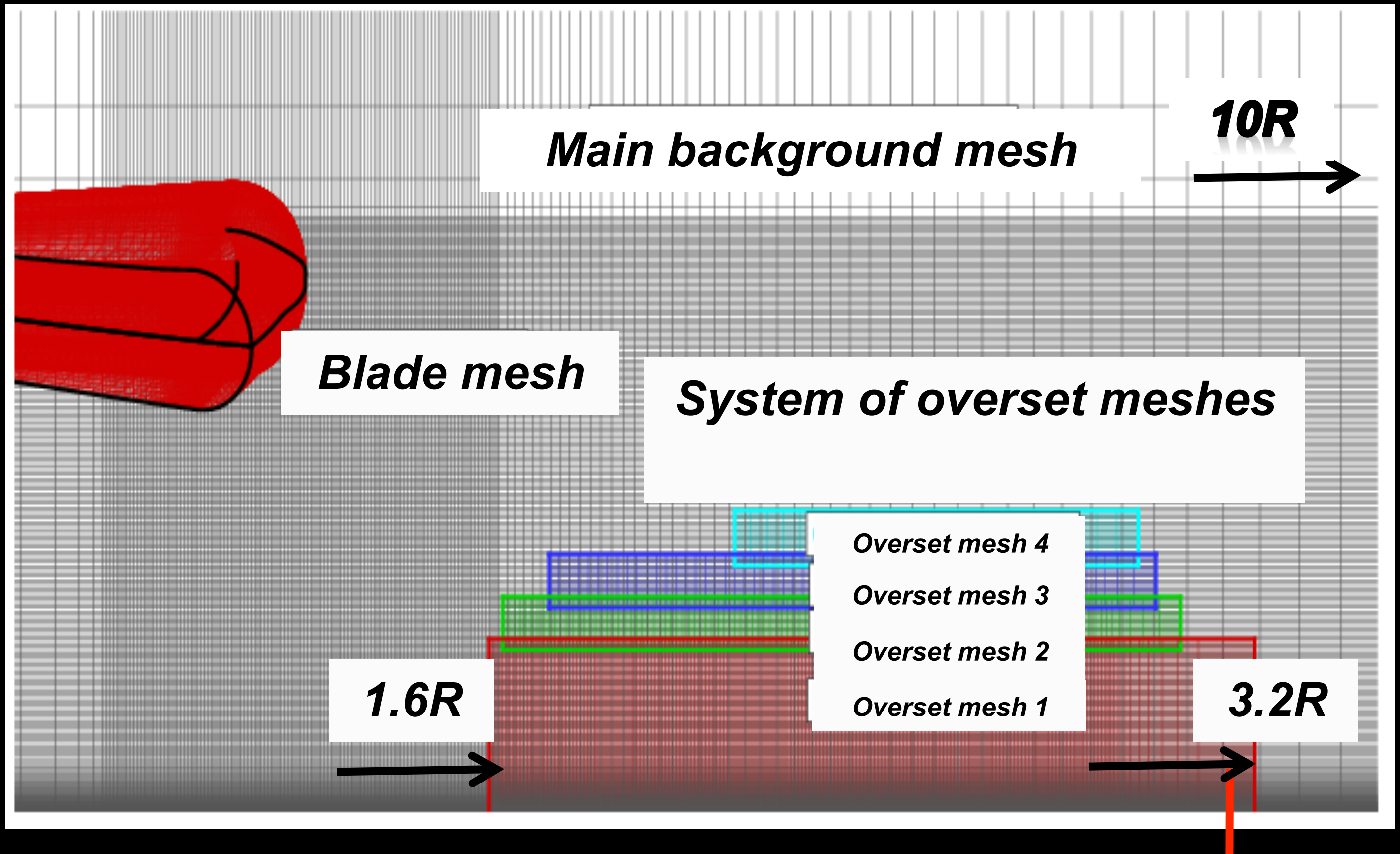




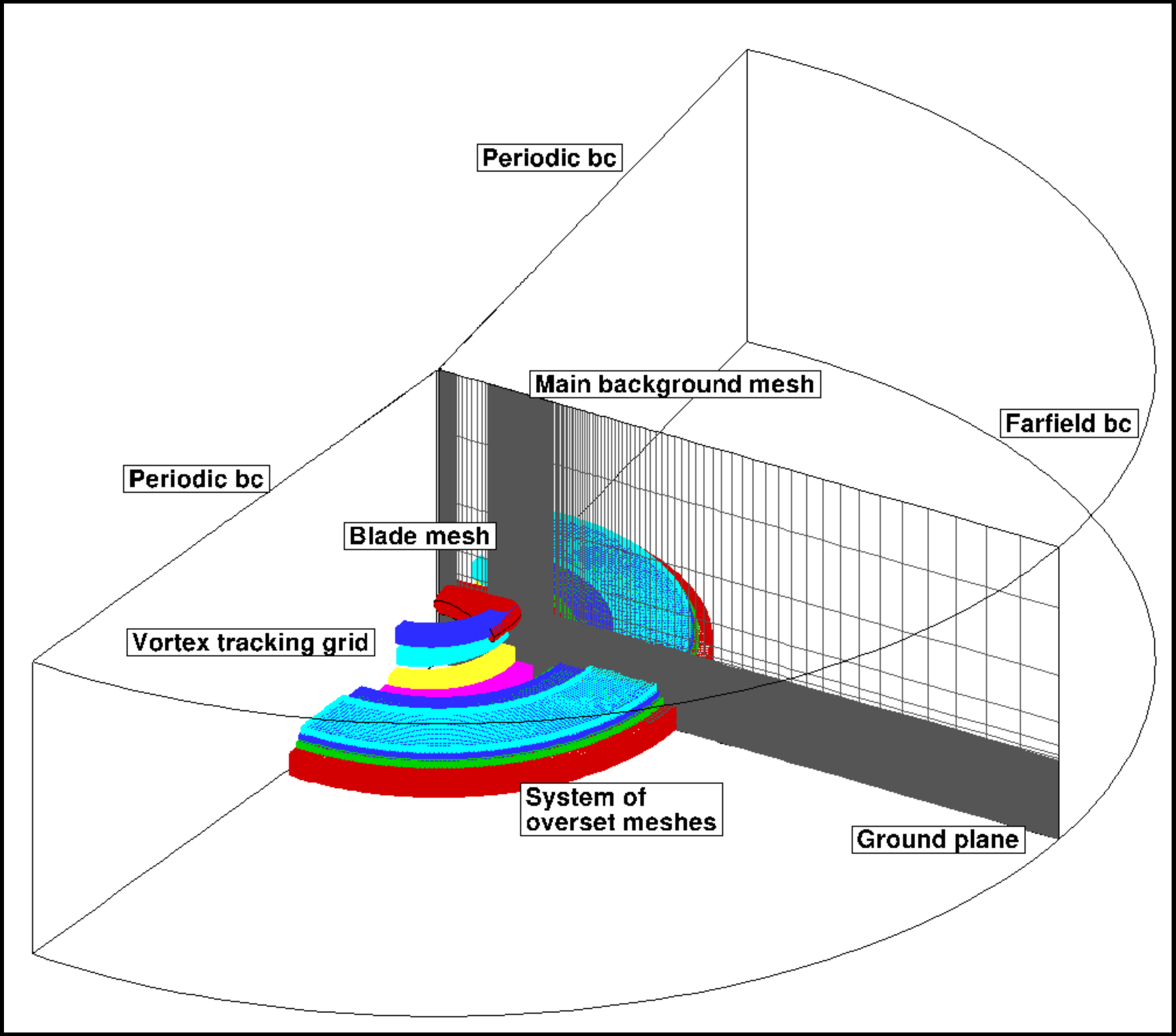
- 3-D helical shaped meshes
- Vortex trajectory extracted based on maximum vorticity magnitude
- 2-D planar Cartesian meshes placed at 0.75 deg of azimuth
- VTG adapted every 3 revolutions until tip vortex position are converged

Added Overset Meshes

- Added system of overset meshes in stair – step manner
- Limits cell size difference between consecutive overset meshes
- Overset mesh refined to 3.2R to accurately resolve tip vortices

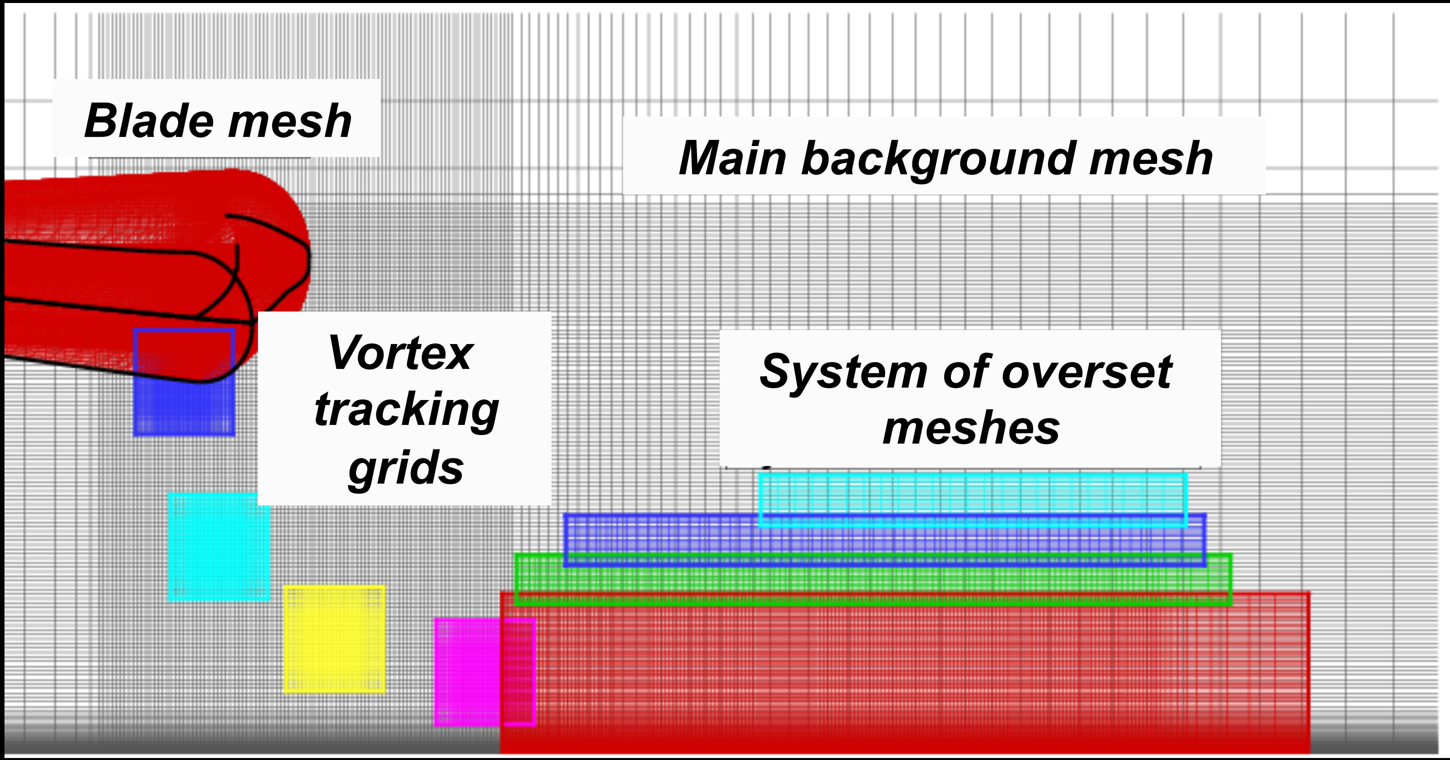


Converged Mesh System



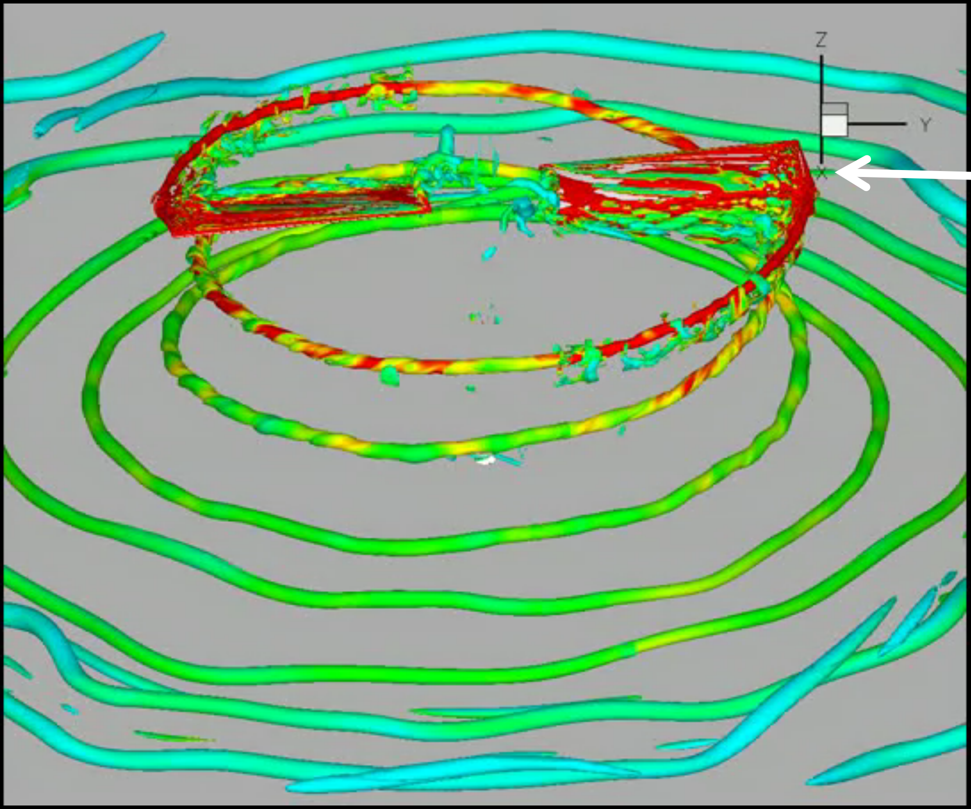
Converged Mesh System

- Reiterating mesh evolution : (Total mesh points 17.8 million points for 1R case)
  - Step 1: Use of blade and background mesh
  - Step 2: Addition of overset meshes
  - Step 3: Adding vortex tracking grids
  - Step 4: Use of higher order scheme



Flow Visualization, h/R = 1.0

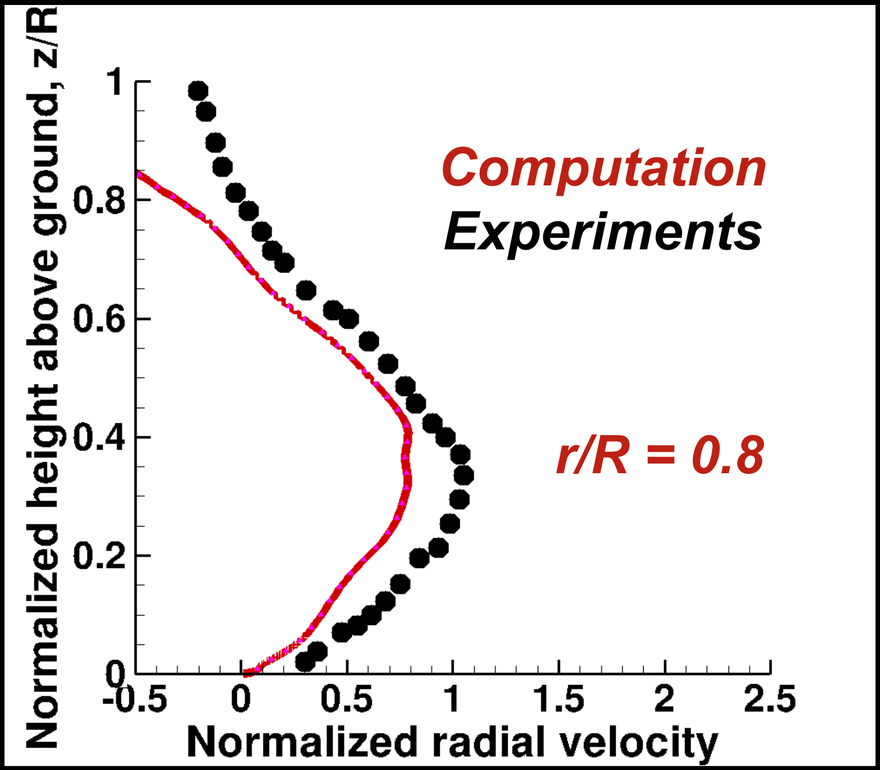
Iso surfaces of q criterion colored by vorticity magnitude

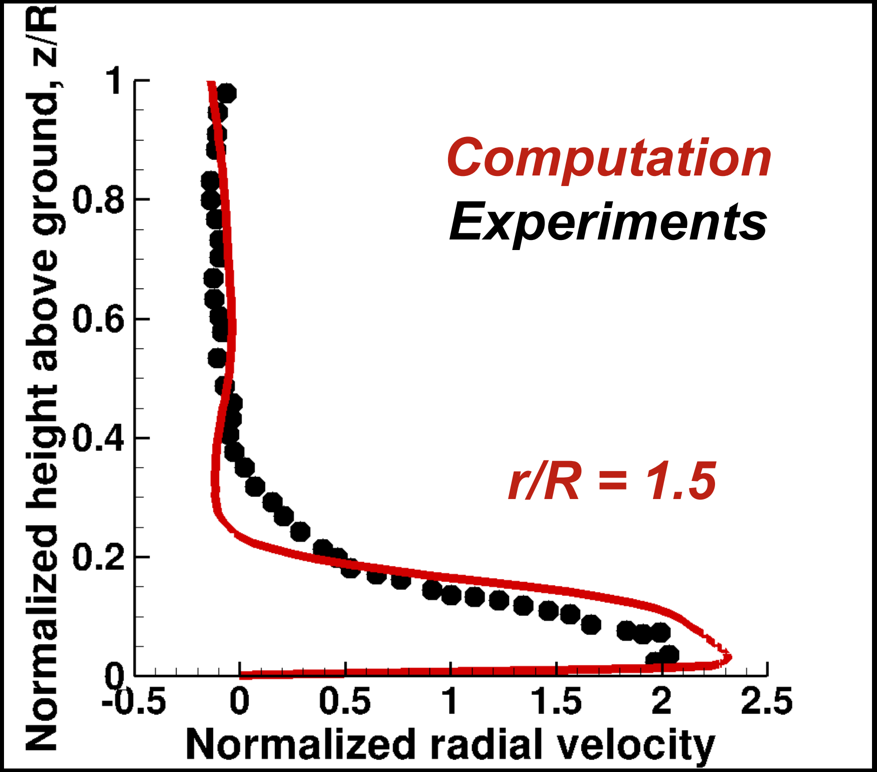


Rotor blade

- **Computations capture 3 – 3.5 rotor revolutions**
- **Finer structures captured at early wake ages**
- **Increase in aperiodicity as wake approaches close to ground**

Time-Averaged Radial Velocity, h/R = 1.0

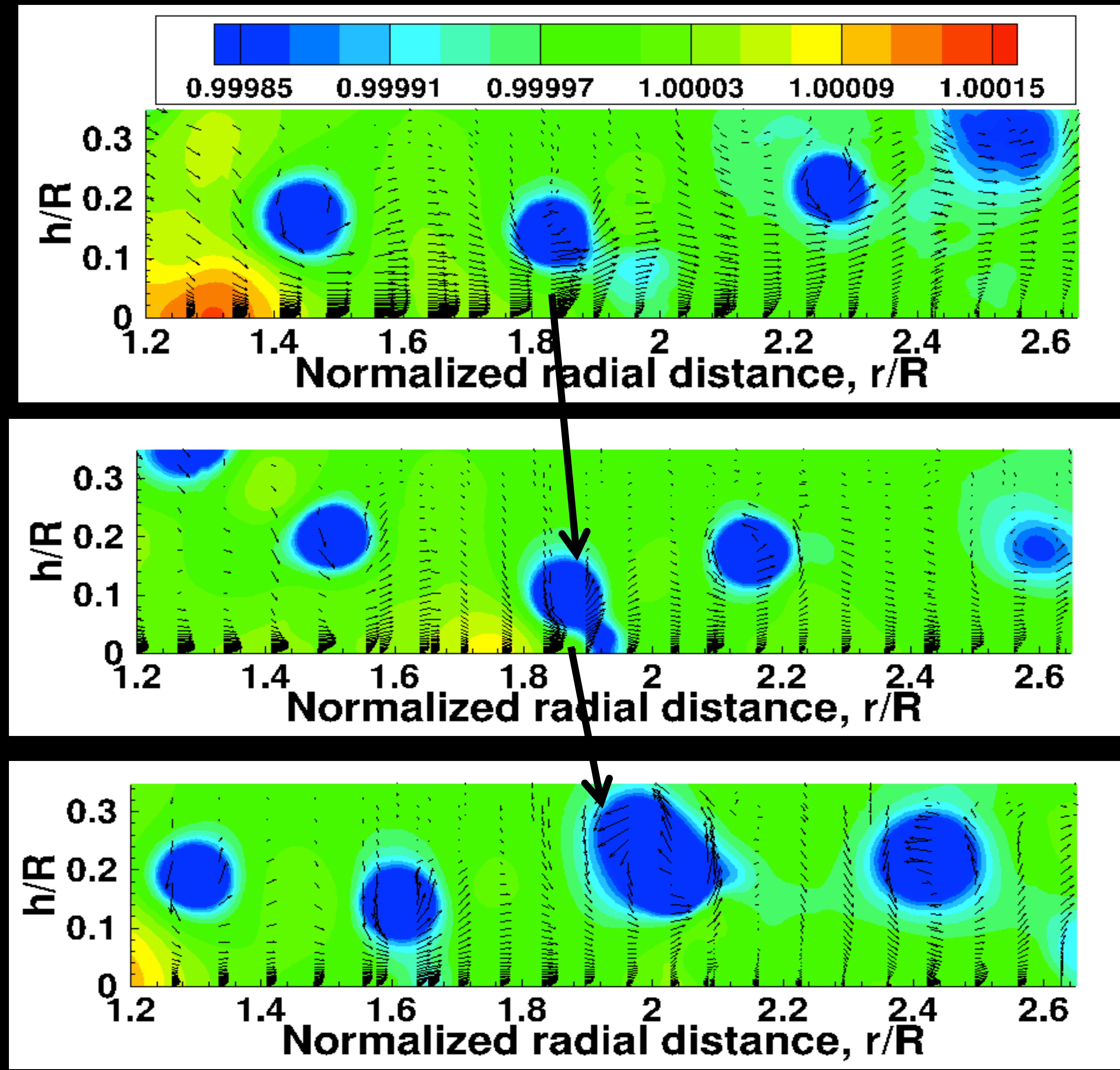




- **With time-averaging one sees wall jet forming at ground boundary**
- **At outboard sections wall jet becomes thin and radial velocities increase initially, but then decrease due to spreading**
- **CFD still predicts slightly higher maximum radial velocity and at slightly higher wall distance than that measured in experiment**

Pressure Contours (atmosphere units) with Velocity Vectors, h/R = 1.5

- Tip vortex gets close to ground
- Interaction of tip vortex with ground
- Large separation near region near ground
- Separation bubble detaches and gets carried away the other tip vortex
- Viscous vortex/ boundary layer interaction observed (Johnson et. al 2010)



Summary and Conclusions: Micro-scale Rotor Simulations

- **Hovering micro-scale rotor IGE studies resulted in:**
  - **Well resolved tip vortices**
  - **Ability to analyze rotor wake structure in details**
  - **CFD data couple to particle code enables in modeling of mechanisms involved in formation of brownout cloud**

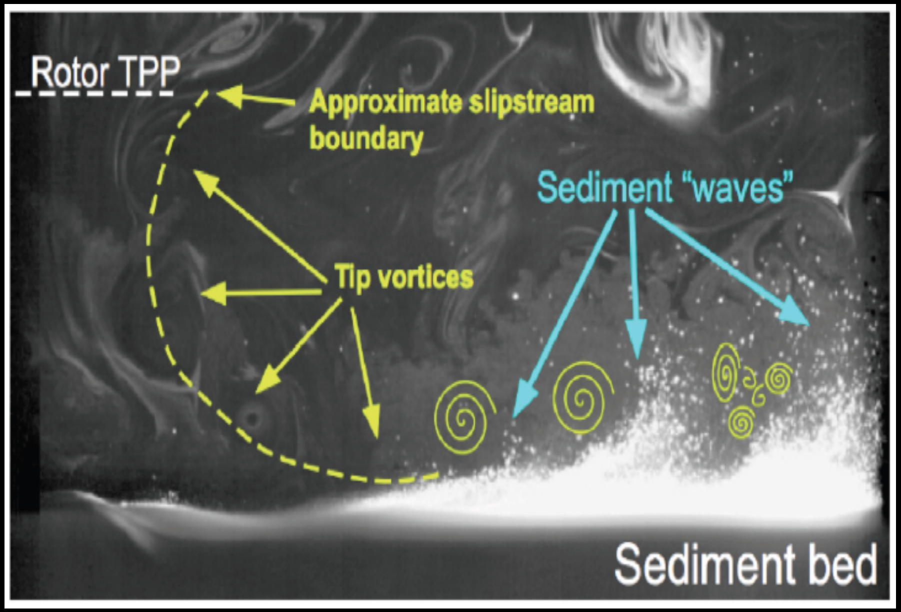


Figure courtesy. Sydney et al.

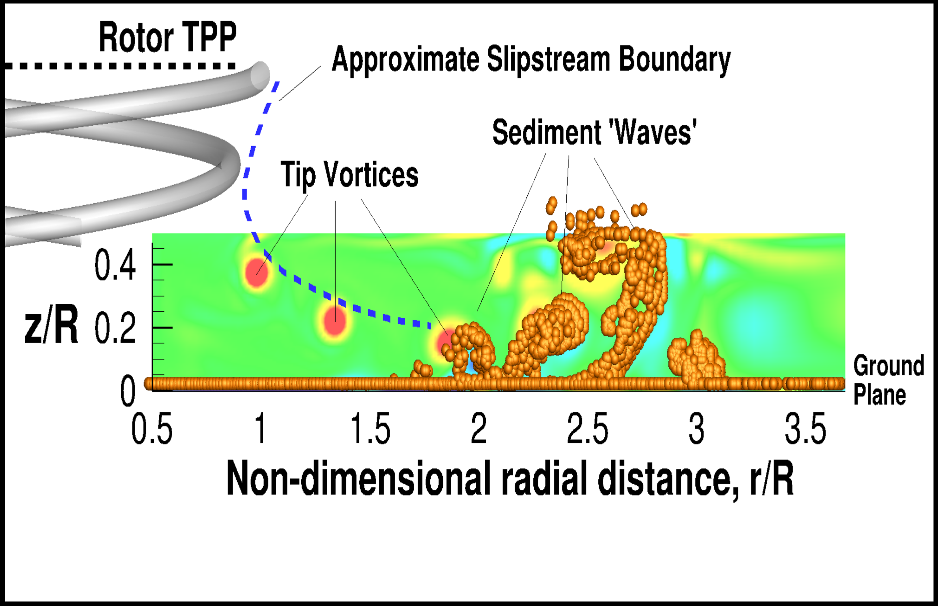
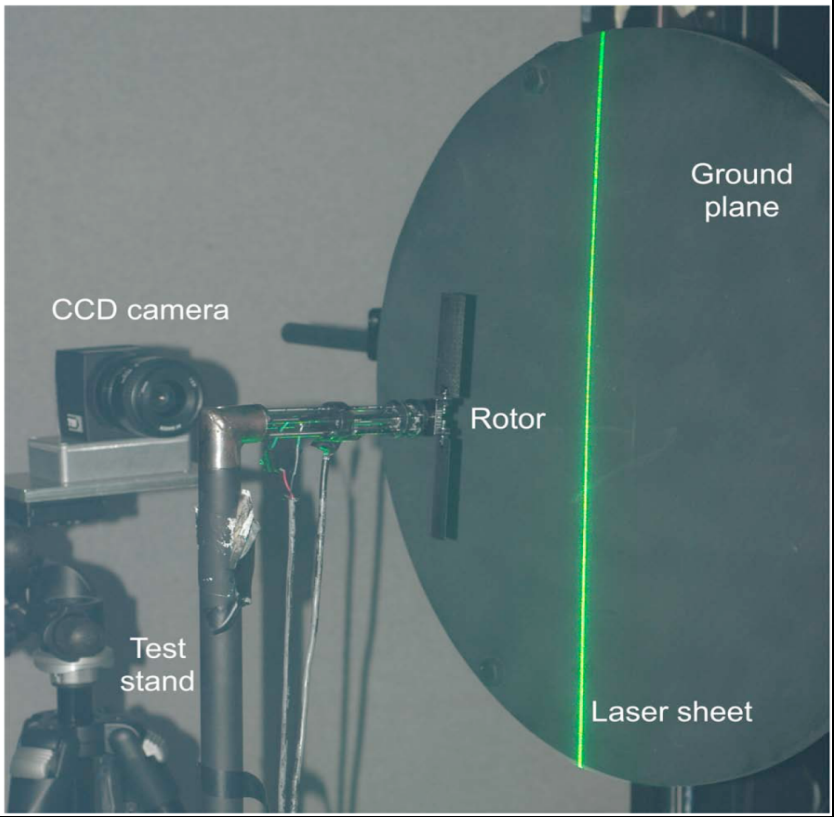


Figure courtesy. Thomas et al.

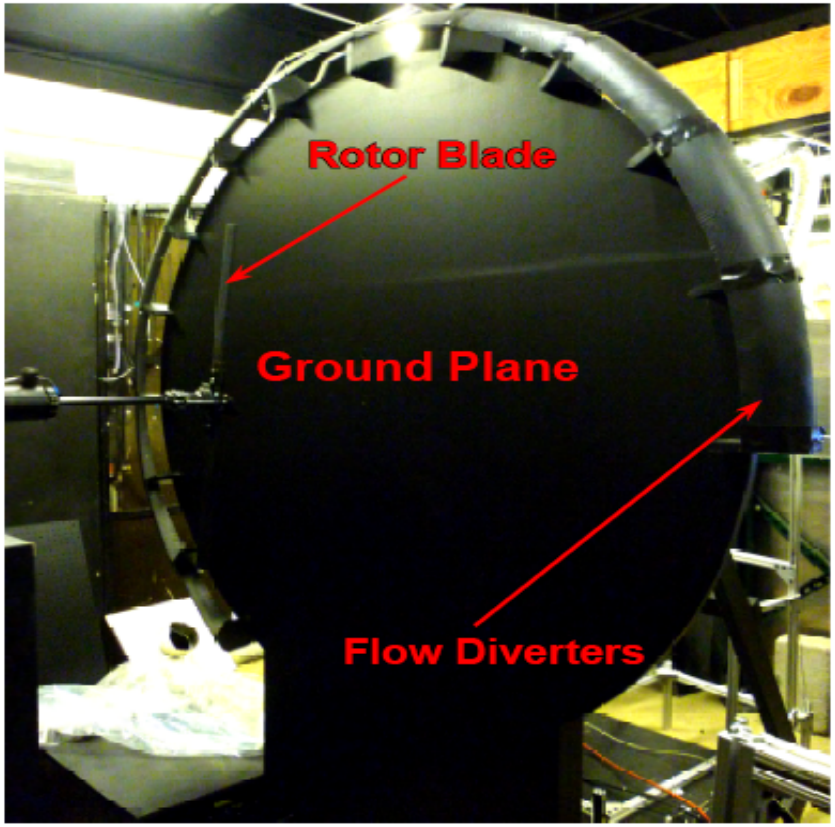
Provides framework for larger scale rotor simulations

Experiments Used for CFD Validation

- 2 bladed micro-scale rotor experiments, radius = 0.086 m
- 1 bladed sub-scale experiments, radius = 0.5 m



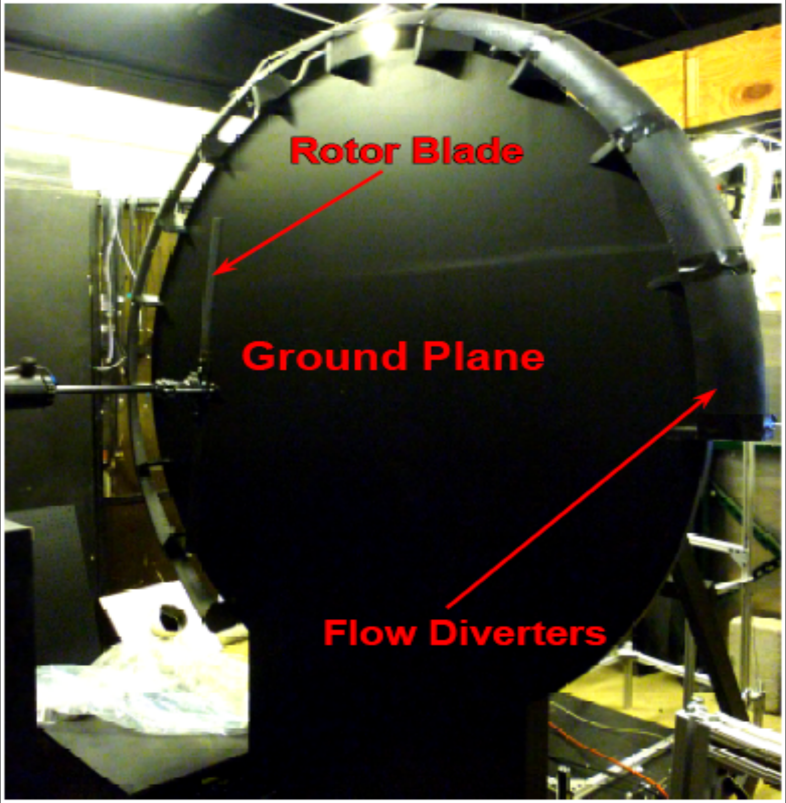
Experimental Setup, Lee et al. (2008) at University of Maryland



Experimental Setup, Milluzzo et al. (2010) at University of Maryland

1-Bladed Sub-Scale Rotor Setup

- **1-bladed rotor**
  - Baseline untwisted rectangular
  - Radius = 0.408 m
  - Chord = 0.0445 m
  - 4.5 deg Collective setting
- **Airfoil profile**
  - NACA 2415
- **Flow conditions**
  - Re_{tip} = 250,000
  - M_{tip} = 0.24
- **Ground plane distances**
  - h/R = 1.0

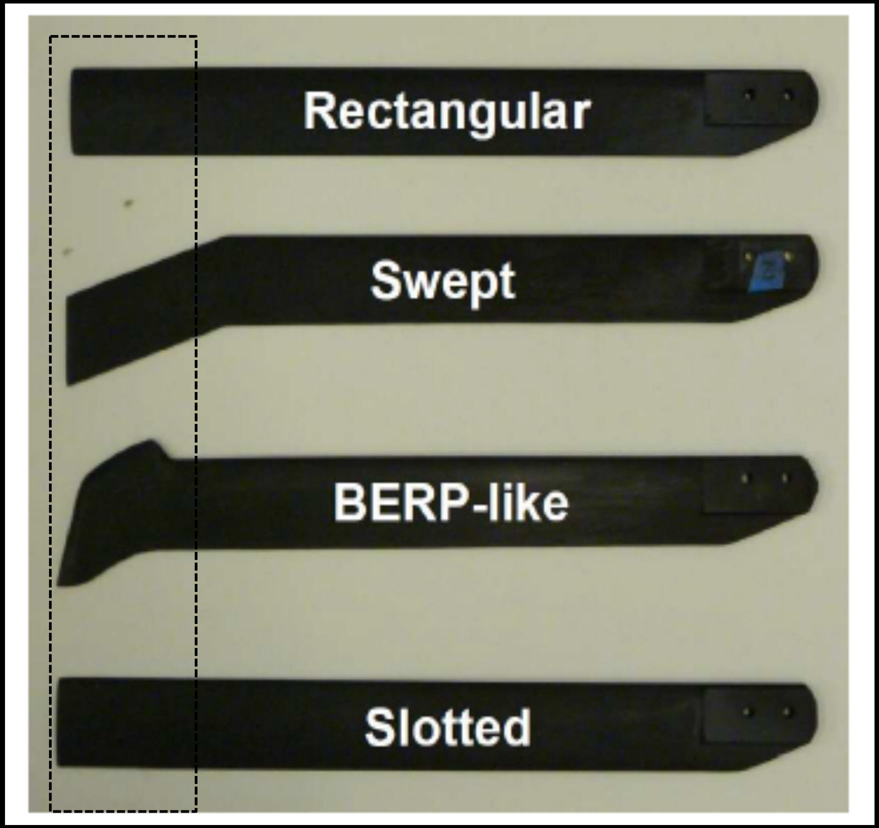


Experimental Setup, Milluzzo et al. (2010) at University of Maryland

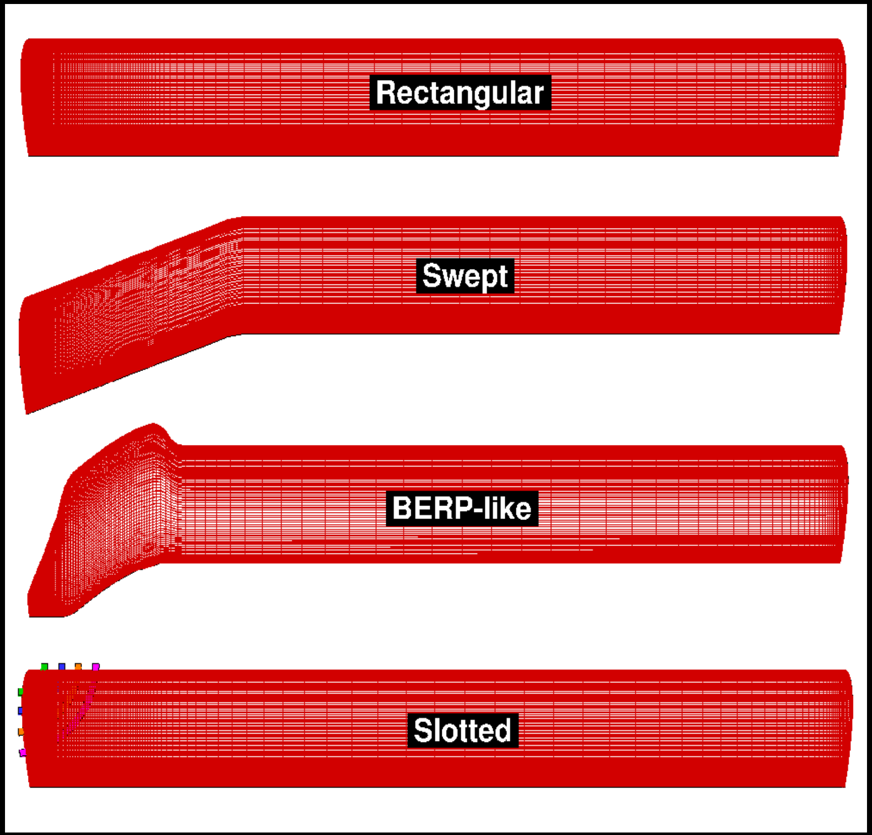
Experiments performed for four blade tip shapes: Rectangular, Swept, BERP-like and Slotted

Sub-Scale Rotor Blade Tips

Rotor tips

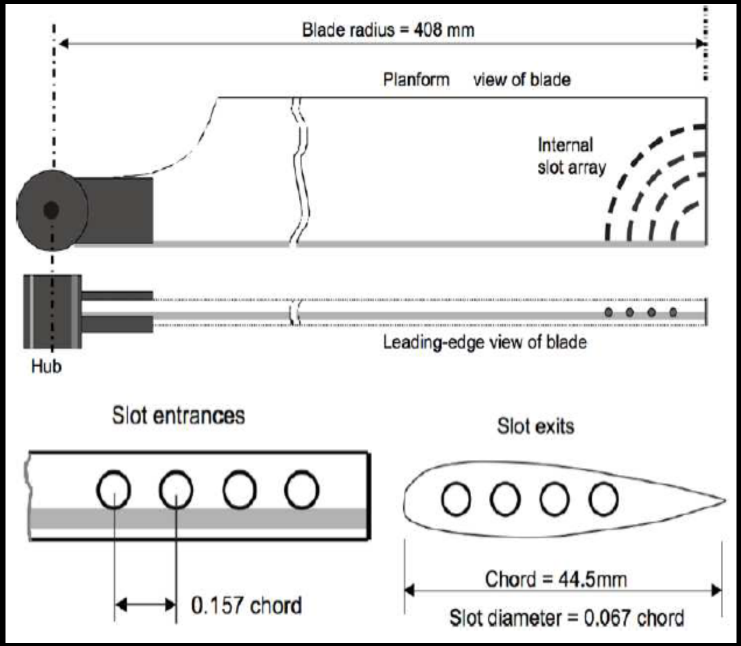


Experimental blade tips

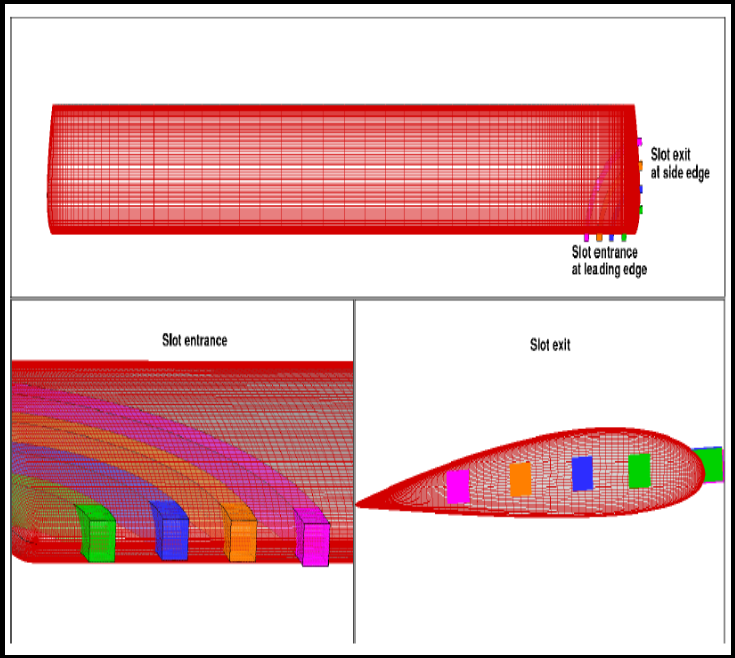


Computational blade tips

Slotted Mesh Details



Experimental slotted tip

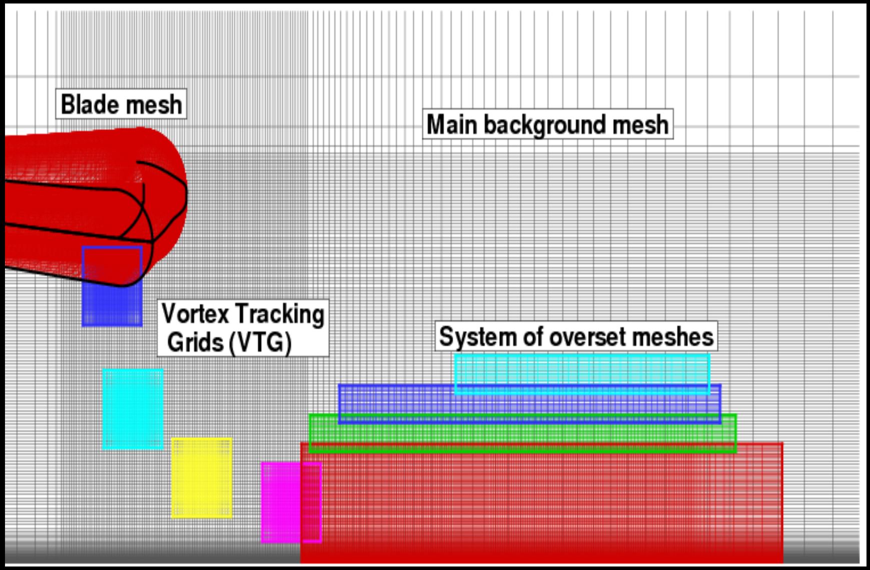


Computational slotted tip

- **Slots connect leading edge of the blade to the side edge**
- **Rectangular computational slots to avoid grid volumes from going to zero compared to circular slots of experiments**

Methodology Extension – Micro to Sub-scale rotor

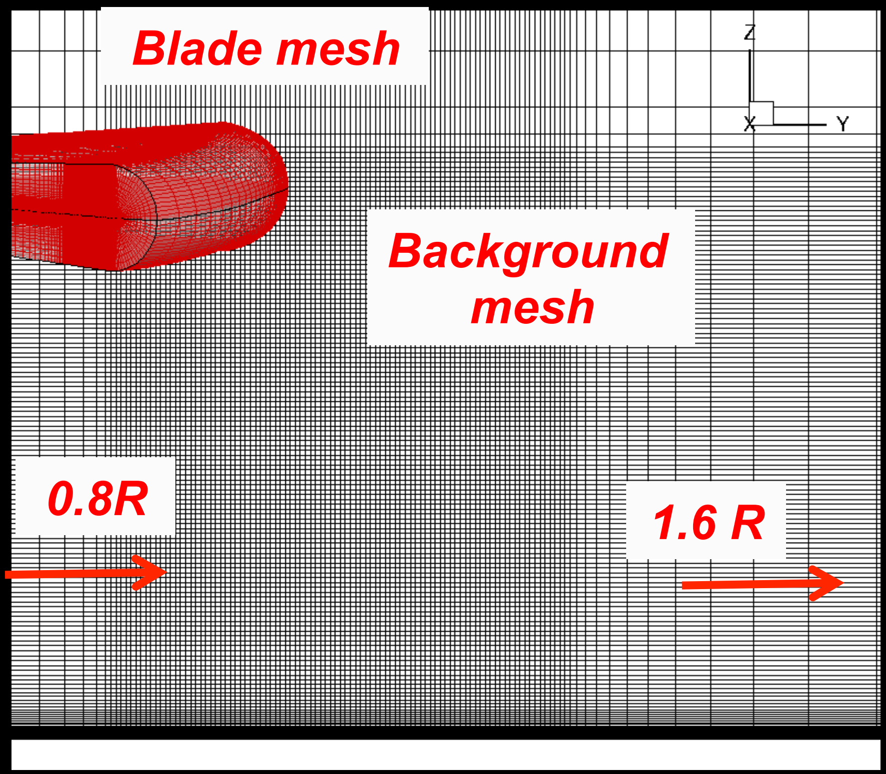
Micro-scale	Sub-scale
M = 0.085	M = 0.24
Re = 35,000	Re = 250,000
Aspect Ratio = 4.387	Aspect Ratio = 9.132

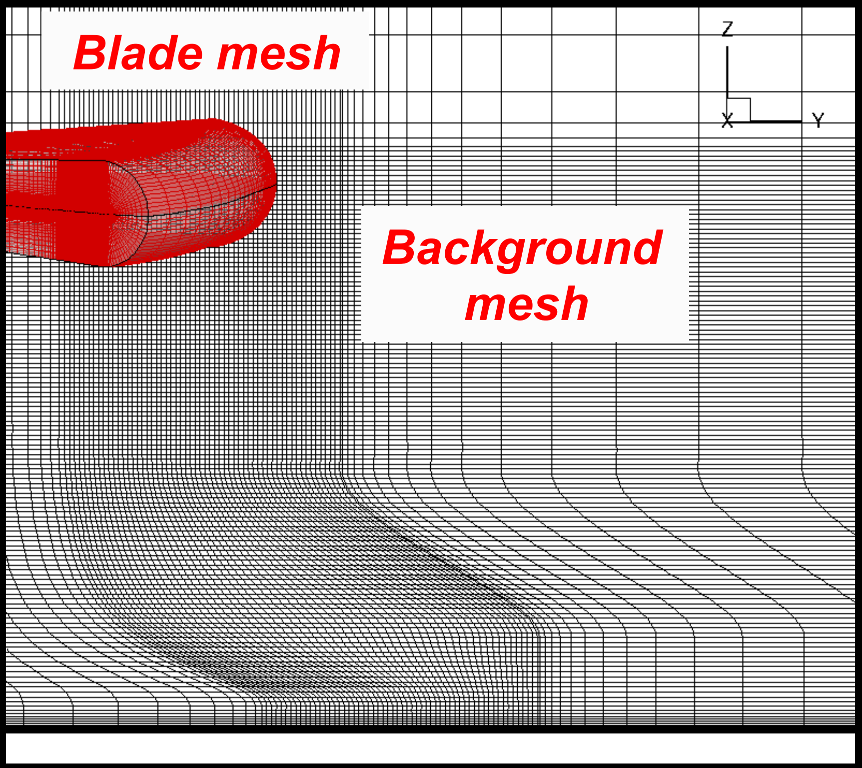


Micro-scale Rotor Mesh System

- **Micro-scale rotor simulation used 17.8 million mesh points, h/R = 1.0**
- **1-bladed rotor requires modeling of entire 360 degrees azimuth**
- **Similar mesh resolution for sub-scale rotor requires 120 million points (using 566 processors for optimum load distribution)**
- **Strategy is prohibitive with limited computational resources**

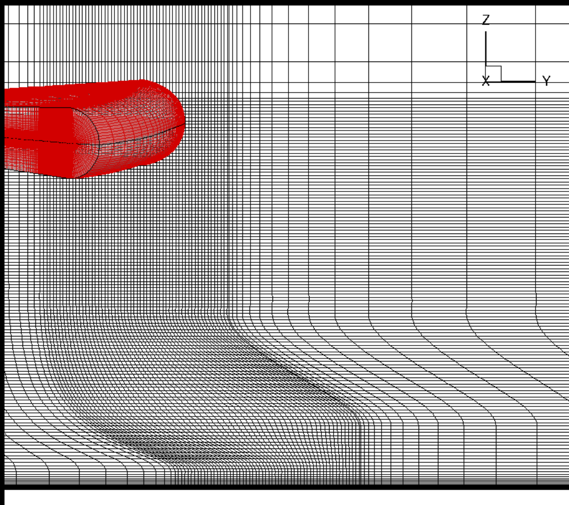
Mesh System : 1-bladed Sub-scale Rotor



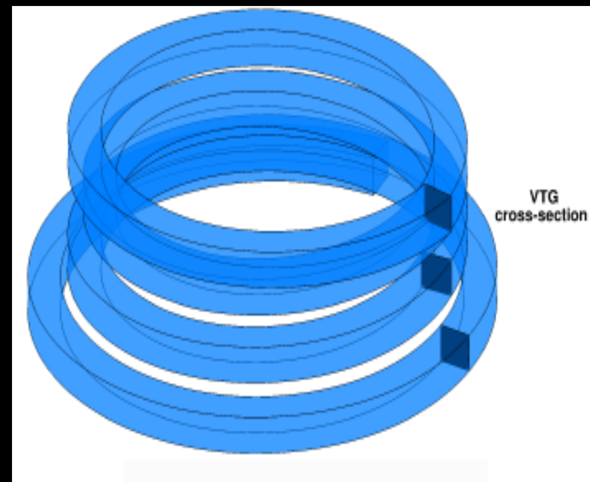


- Simulation performed for 15 revolutions
- Background mesh adapted to follow the path of rotor wake

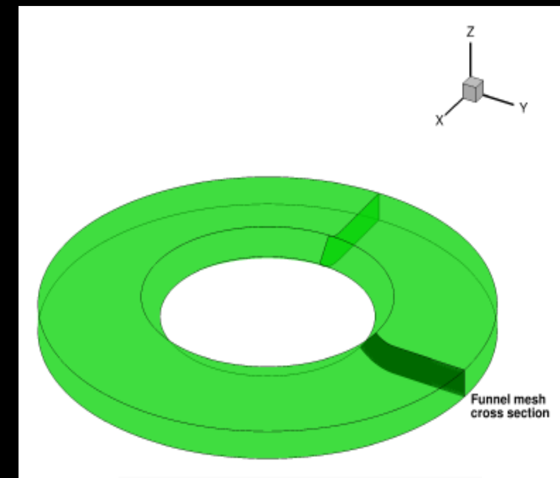
Mesh System : 1-bladed sub-scale rotor



Background mesh

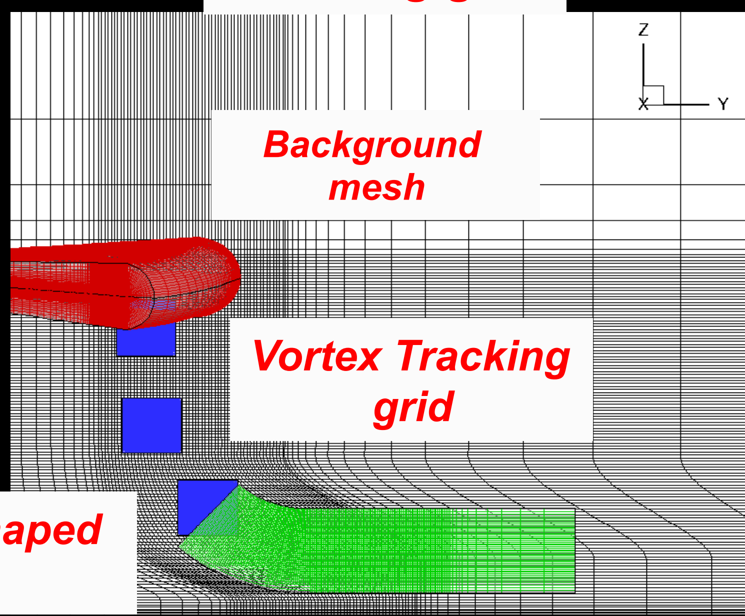


Vortex Tracking grid



Funnel shaped grid

- 61.82 million mesh points
- 240 processors on DOD's Copper system

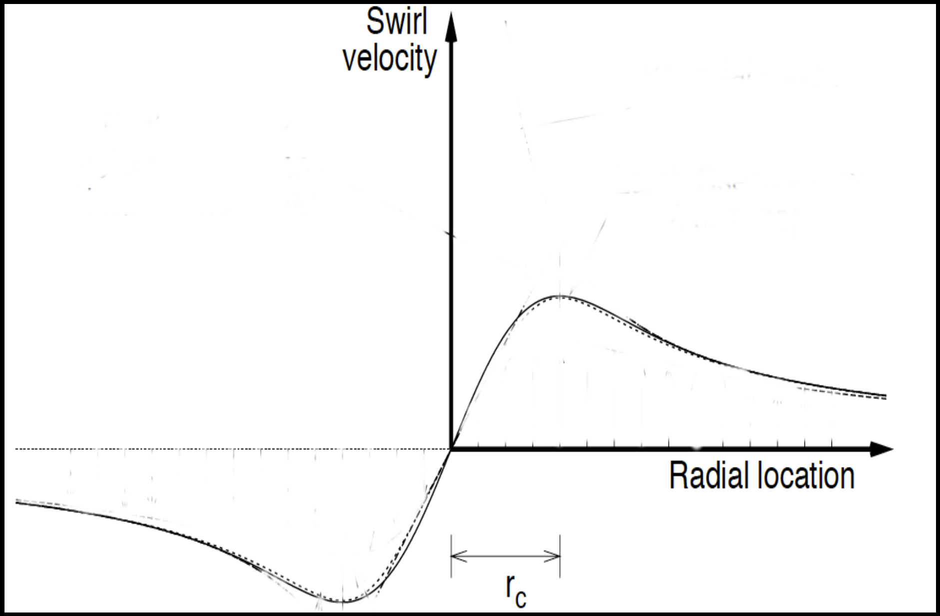


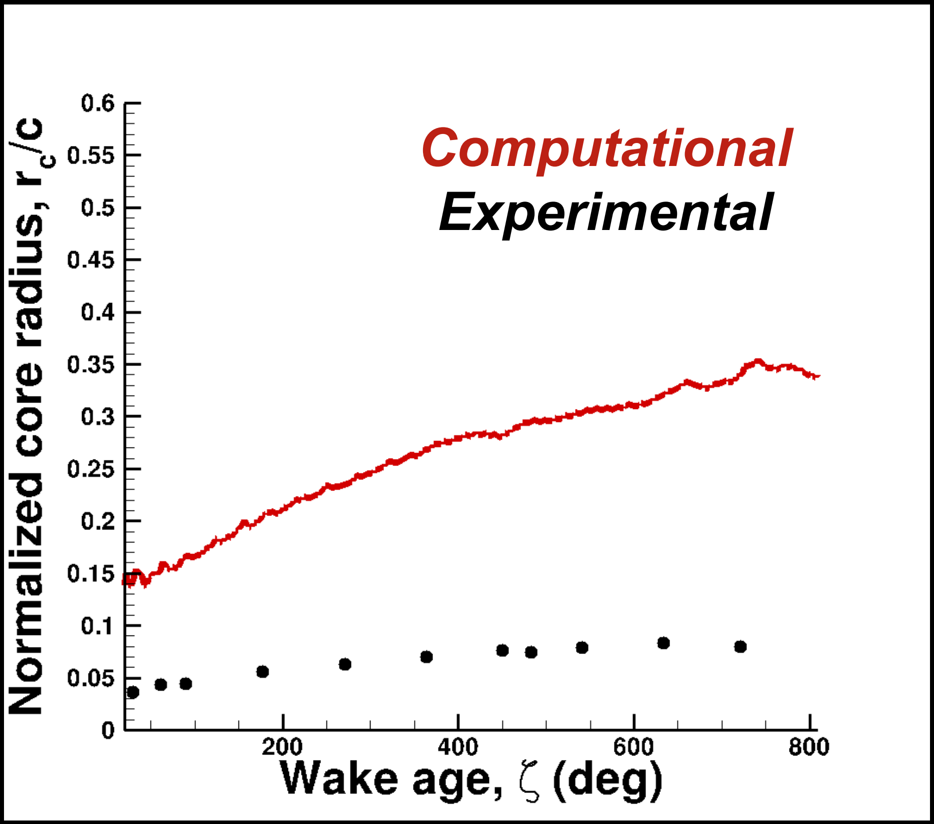
Funnel shaped grid

Cross sectional area of full mesh system

Modeling Difficulties for Sub-Scale Rotor

Core radius growth for rectangular tip

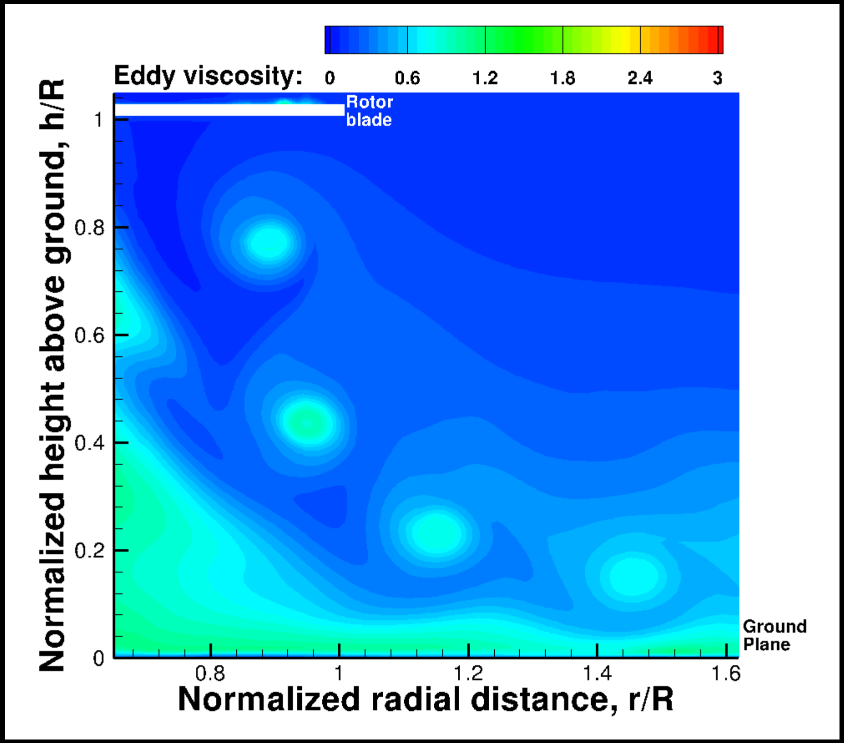




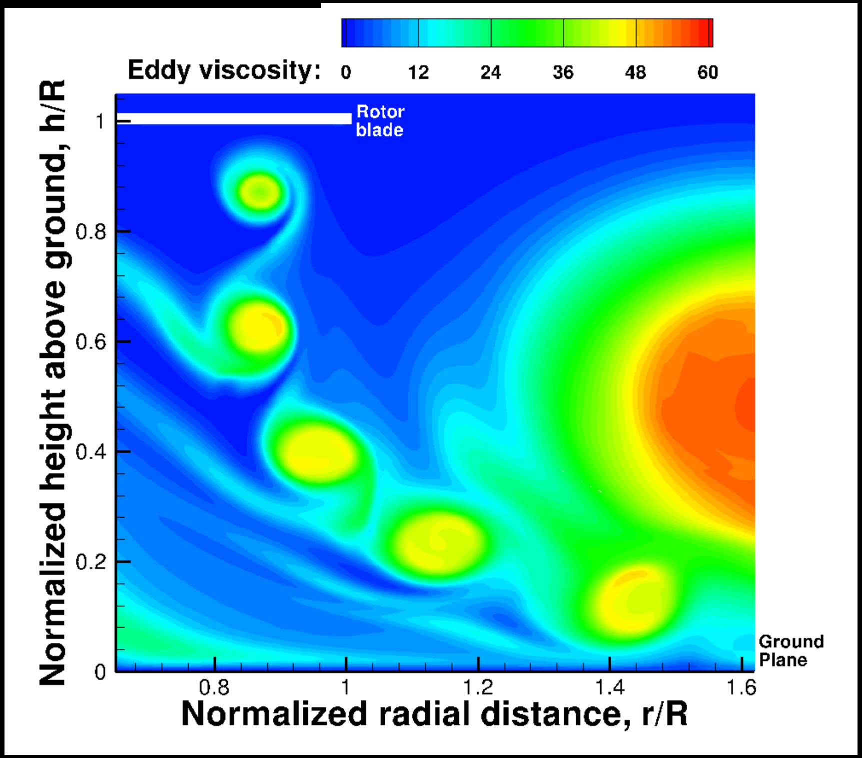
- Core radius grows to 0.3 chord by 400 degrees in RANS-SA computations compared to 0.075 chords in experiments
- RANS computations unable to predict core radius growth

Compare Turbulence Levels of Both Rotor Regimes

Contour levels different for illustration



Micro-scale rotor



Sub-scale rotor

- **Micro-scale rotor shows laminar vortex cores; expected theoretically from sub-scale rotor**
- **Higher turbulence levels lead to excessive diffusion of vortices**
- **Need of exploring higher fidelity methods than RANS**

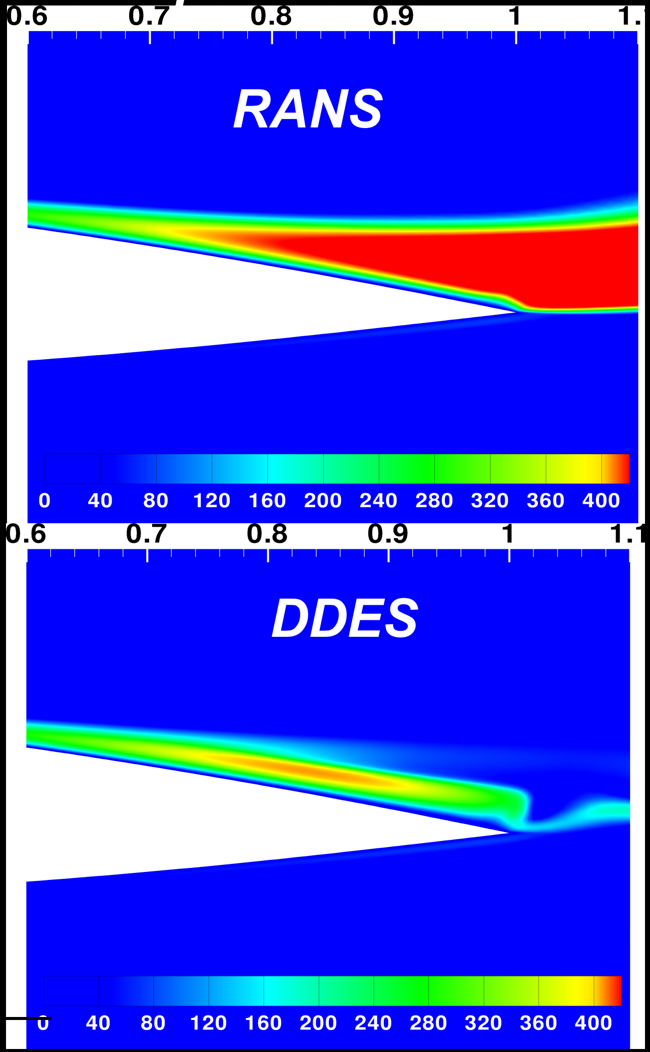
Delayed Detached Eddy Simulations (DDES)

- Use of hybrid RANS/LES models
- Near to the wall RANS mode is activated (turbulence levels are modeled)
- Away from the wall LES mode captures the large scale turbulence levels
- Technique used is DDES
- Implementation costs minimal (Distance function modified in Spalart Allamaras model
- Distance function modification

$$\tilde{d} = d - f_d \max(0, d - C_{DES}\Delta)$$

$$\Delta = \max(\Delta x, \Delta y, \Delta z)$$

Aerospatiale-A airfoil



DDES shows reduced eddy viscosity values compared to RANS (Medida et al., 2013)

Delayed Detached Eddy Simulations (DDES)

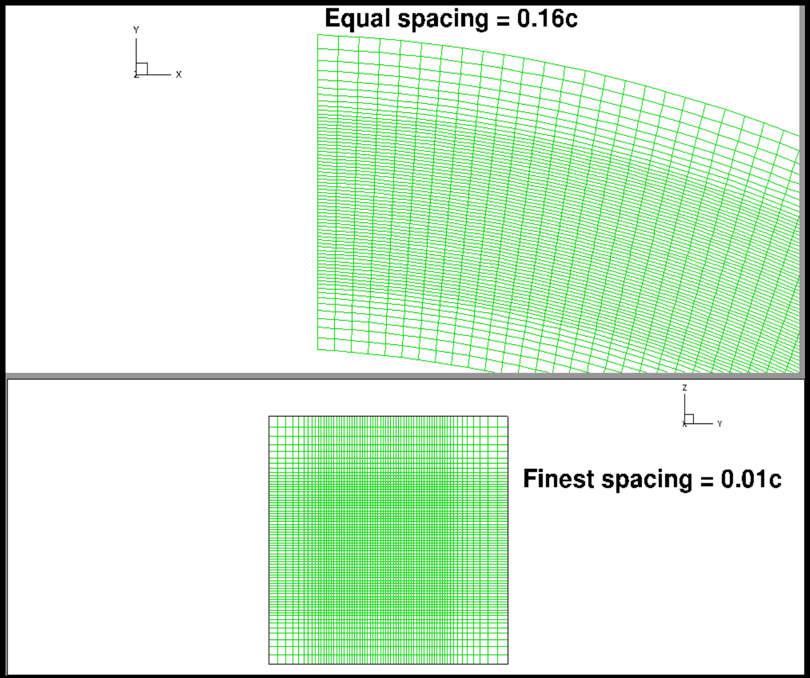
Length scale modification

- **DDES length scale modification based on isotropic grids**

$$\tilde{d} = d - f_d \max(0, d - C_{DES}\Delta)$$

$$\Delta = \max(\Delta x, \Delta y, \Delta z)$$

- **Length scale modification required for anistropic grids**
- **Azimuthal spacing = 0.16c, vertical And horizontal spacing = 0.01c**
- **Suggested by Scotti et al. (1993)**



Vortex Tracking Grid

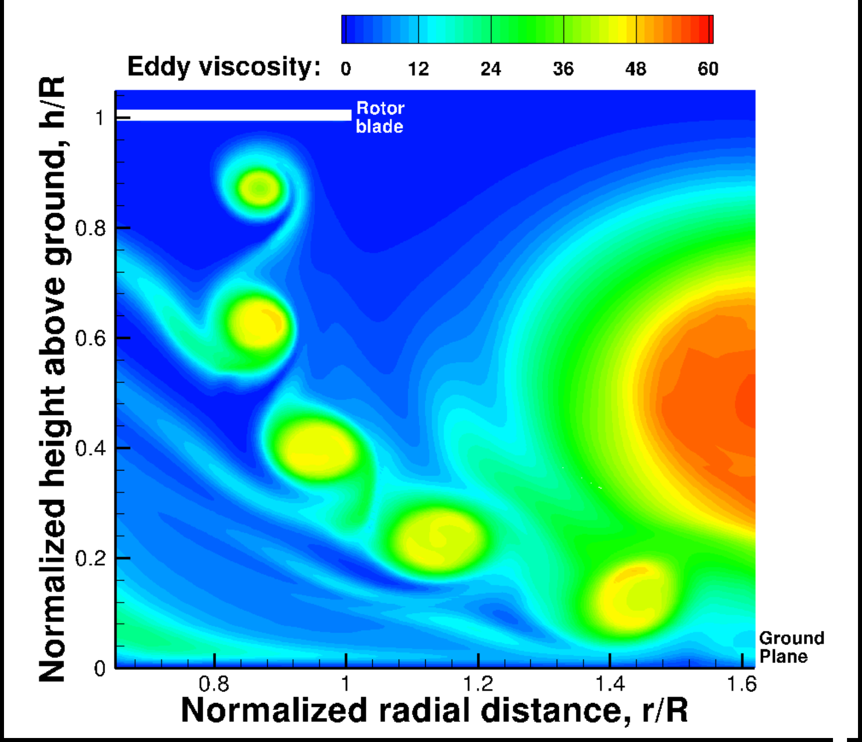
$$\Delta = f(a_1, a_2) \text{ x } \max(\Delta x, \Delta y, \Delta z)^{1/3}$$

$$f(a_1, a_2) \approx \cosh \sqrt{\frac{4}{27}[(\ln(a_1))^2 - \ln(a_1)\ln(a_2) + \ln(a_2)^2)]}$$

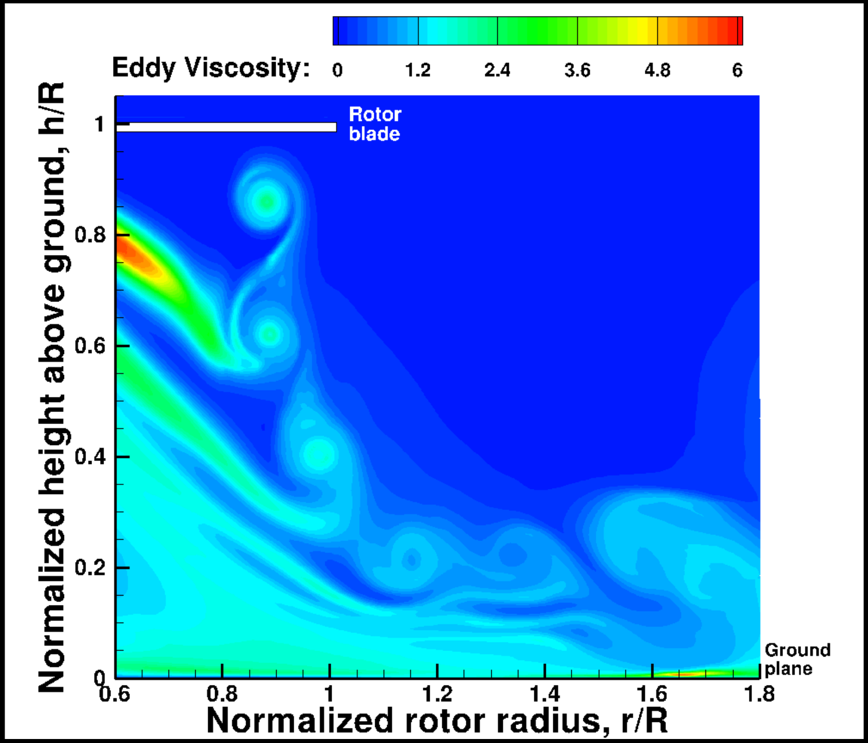
- **a_1,a_2 aspect ratio of grids**

SA-DDES Predicted Turbulence levels

Contour levels different for illustration



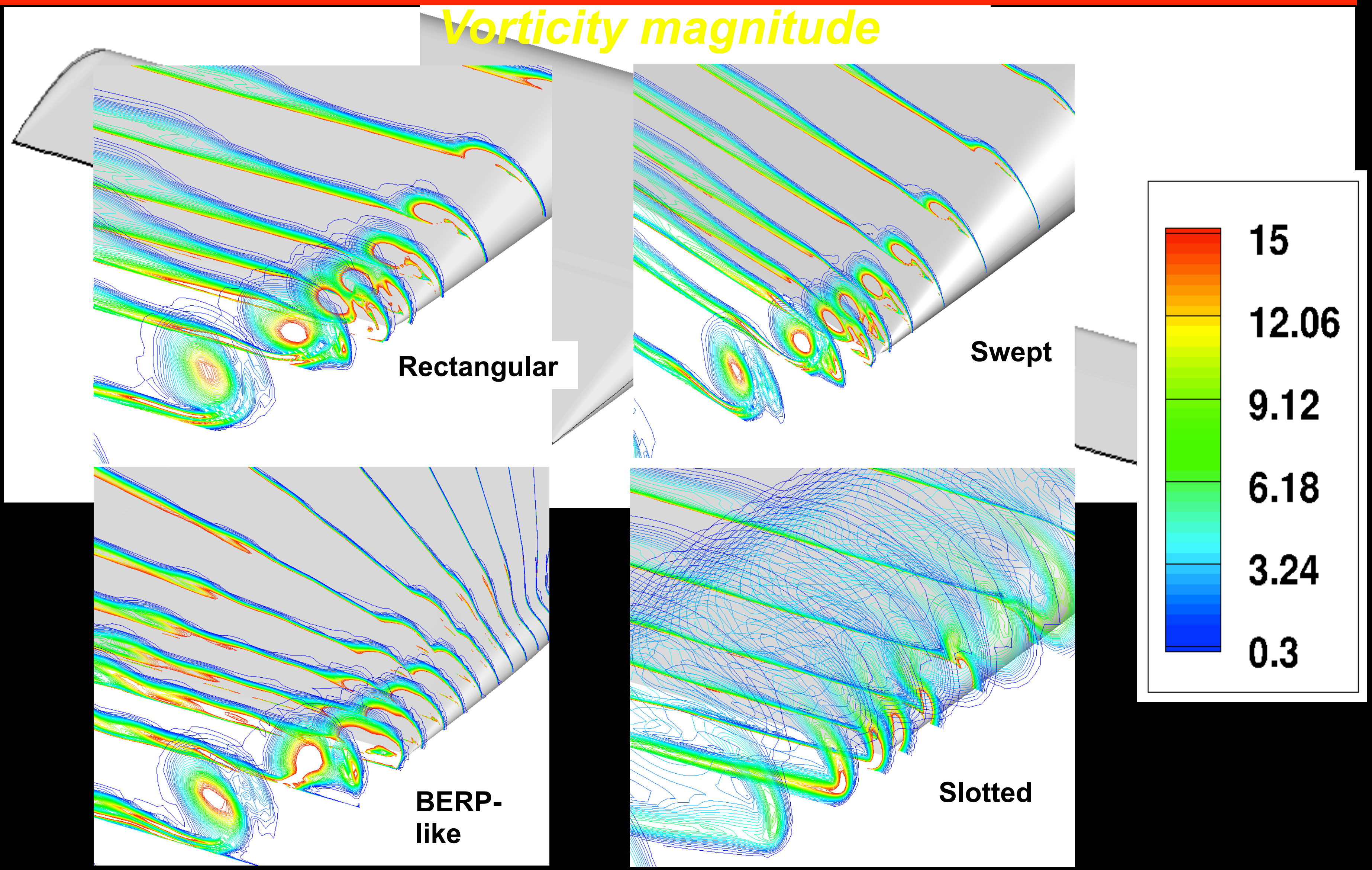
SA-RANS



SA-DDES (Hybrid RANS/LES)

- **SA-RANS shows order of magnitude higher levels compared to SA-DDES**
- **Vortex centers have laminar cores; theoretical expectation**

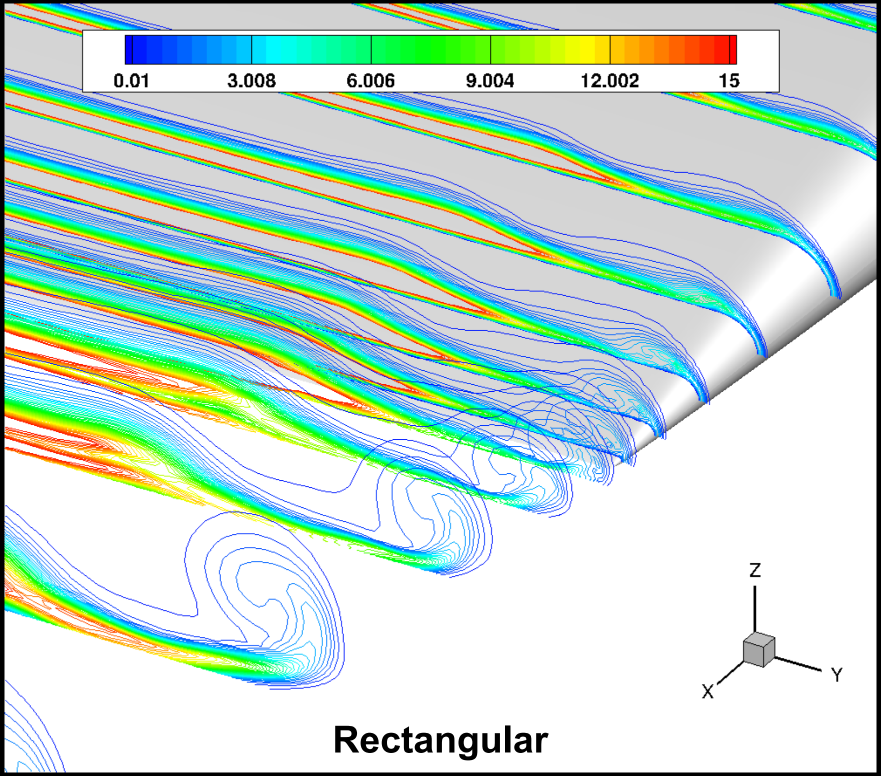
Flow field Visualization at the Blade Tips

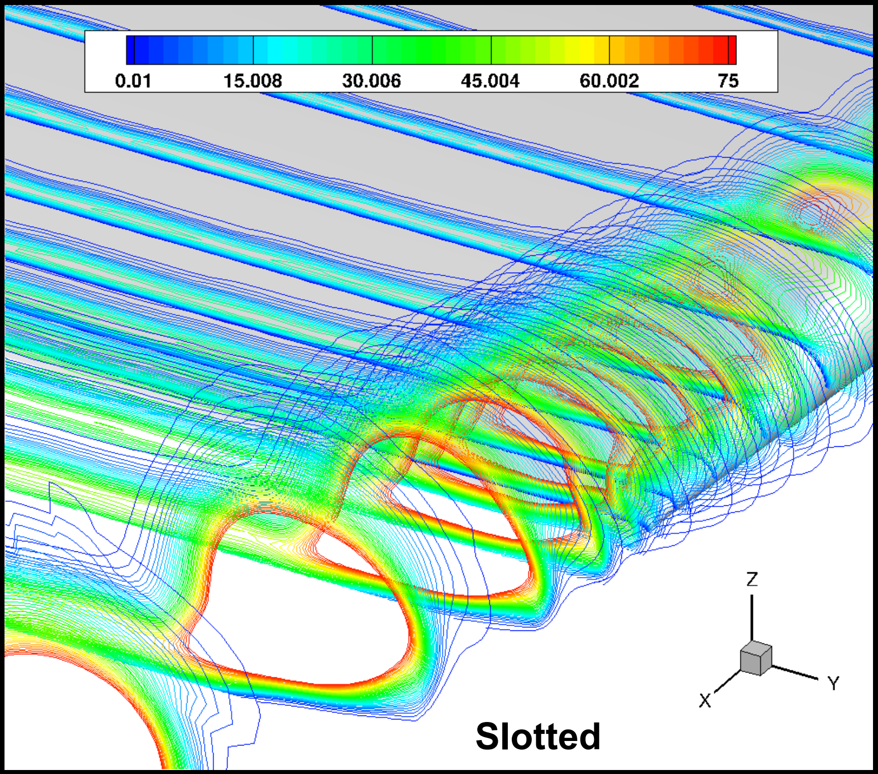


- **Slotted tip diffuses the tip vortex at early wake ages**

Flow field Visualization at the Blade Tips

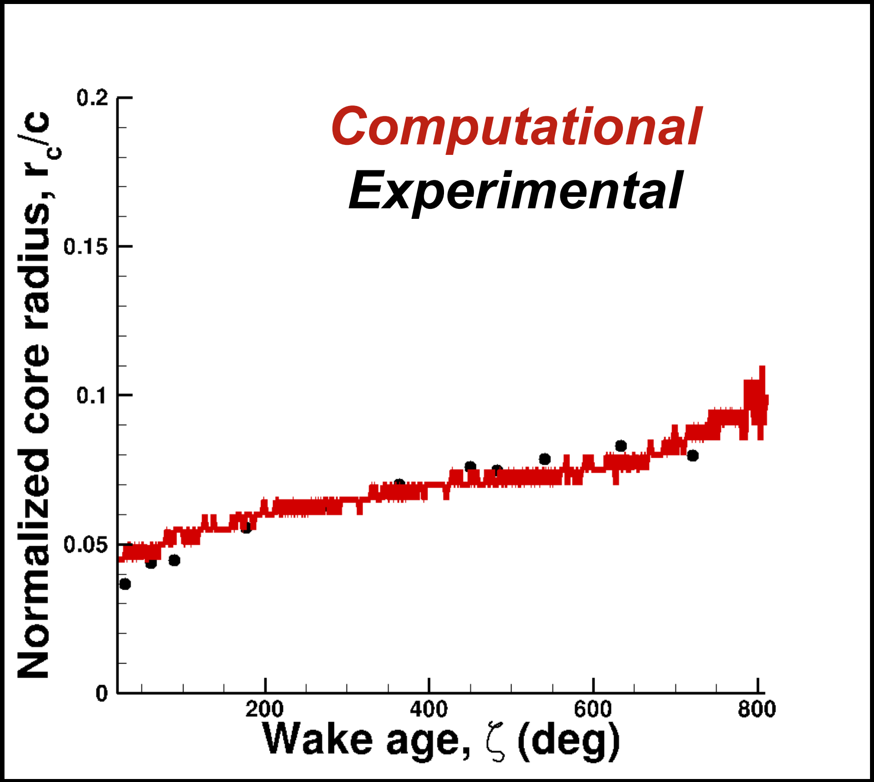
Turbulence levels near wake



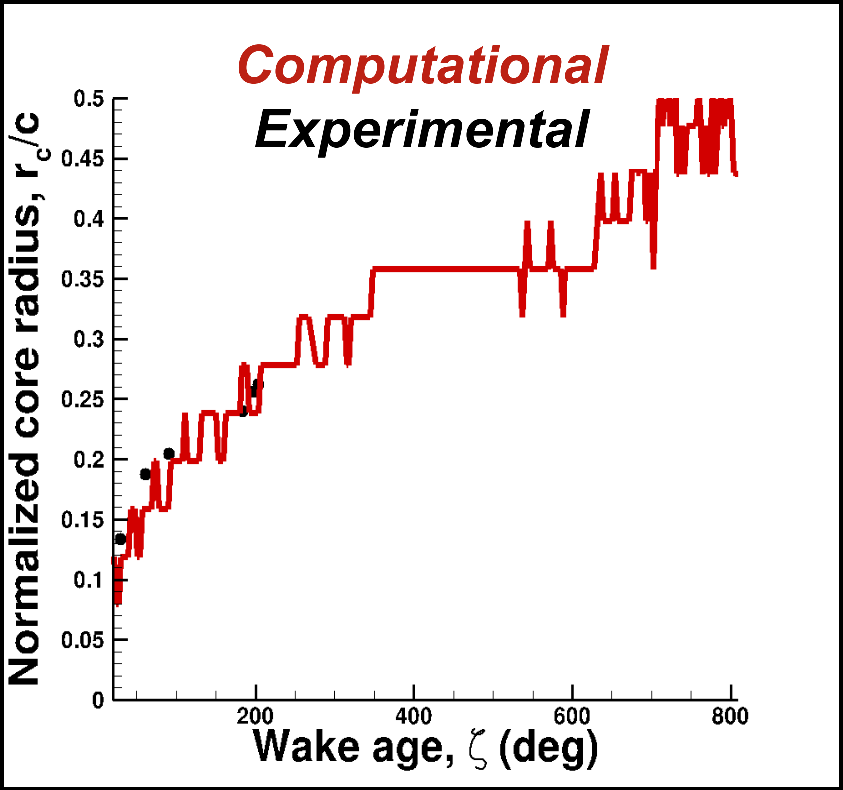


- **Higher turbulent levels in tip vortex for slotted tip**

Core Radius Growth with SA-DDES Method



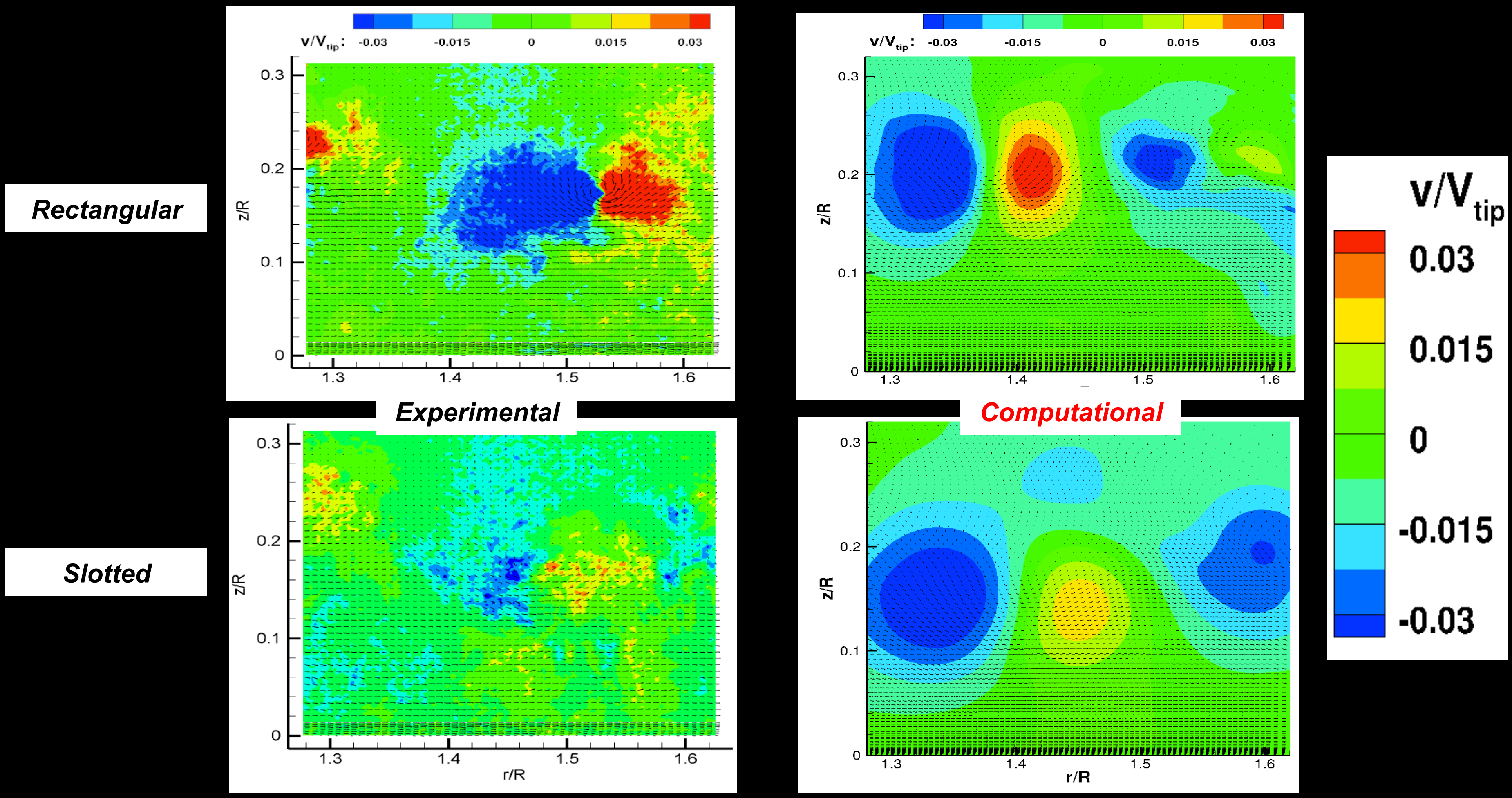
Rectangular



Slotted

- **Rectangular tip rotor shows similar trajectory of core radius**
- **Slotted tip shows diffusion of core radius (vortex strength decreases)**

Flow Field Close to the Ground



- Slotted tip rotor shows lesser upwash than rectangular tip

Summary and Conclusions: Sub-scale Rotor Simulations

- **Hovering Subscale Rotor IGE studies resulted in:**
  - **Important to intelligently cluster mesh system to avoid prohibitive costs at larger scales**
  - **High levels of turbulence in flow field lead to excessive diffusion**
  - **Use of hybrid SA-DDES methodology accurately captures rotor wake**
  - **Slotted tip shape shows diffusion of vortices at early wake ages**
  - **Close to the ground, flow field shows stronger upwash for three tips other than the slotted tip shape**
  - **Slotted tip might be an ideal candidate for brownout mitigation at the cost of power penalty**

Thank you

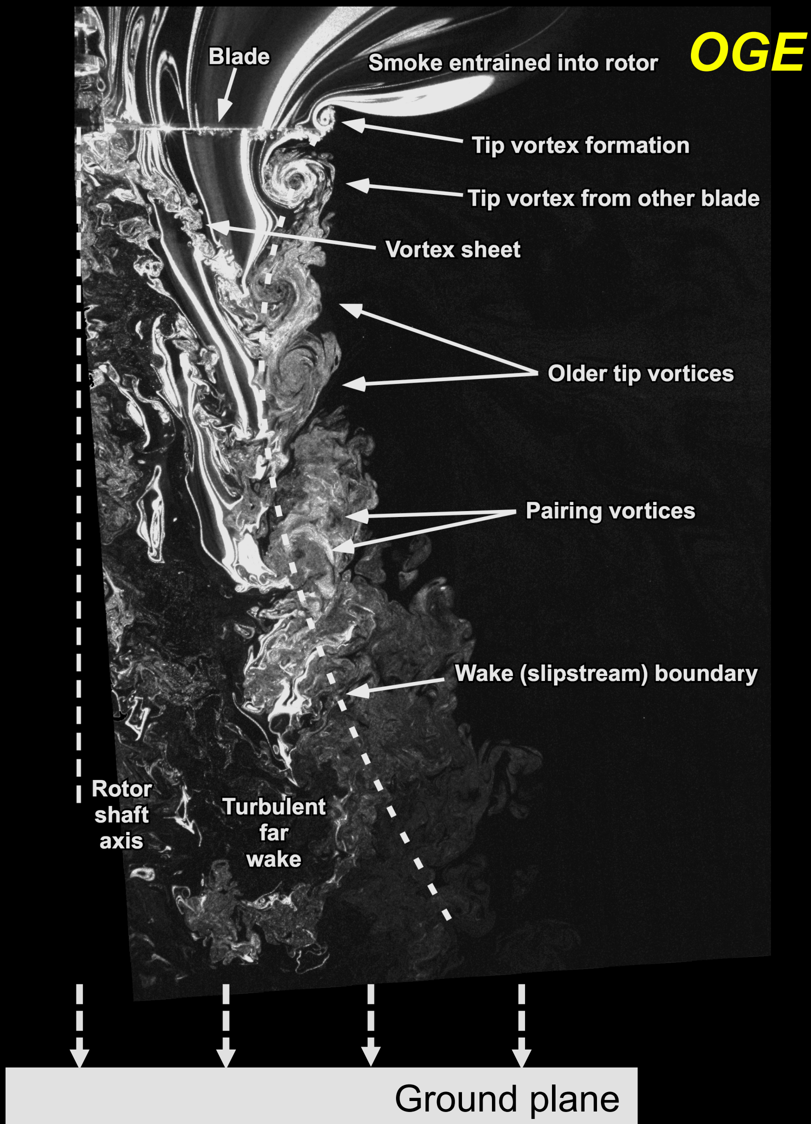
Computational Setup

- **Distribution of points different rotor heights**

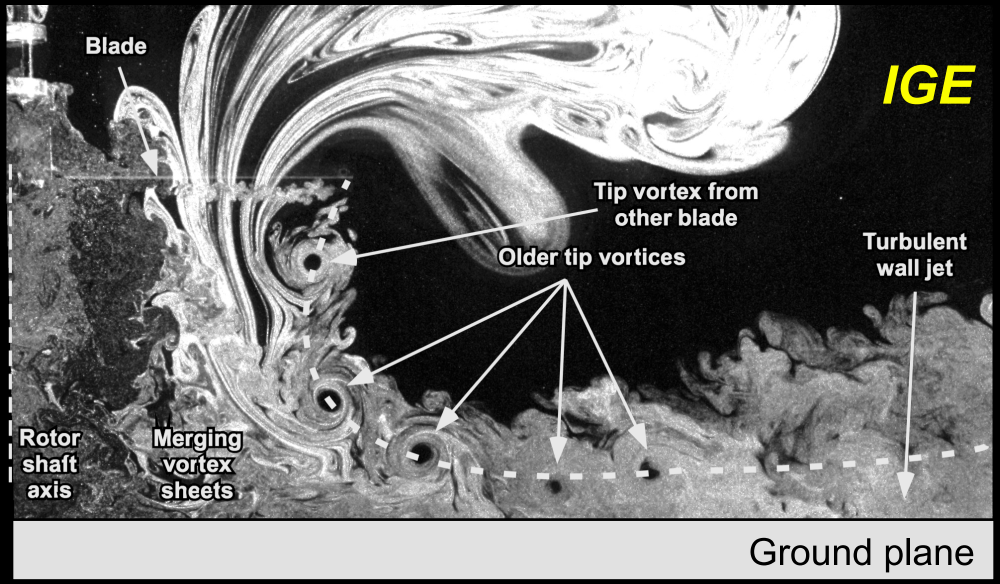
Rotor height above ground	Points (in millions)
1.5	21.4
1.0	17.8
0.5	18.7

- **18 rotor revs required for flow field to converge**
- **Time step size of 0.25 deg**
- **10 MBs per 300,000 points**
- **32 processors simulation use Intel Xeon 3.2 GHz processors**
- **24 hours for 1440 iterations**

Rotor Flows in Ground Effect Operation



Lee et al. (2010)

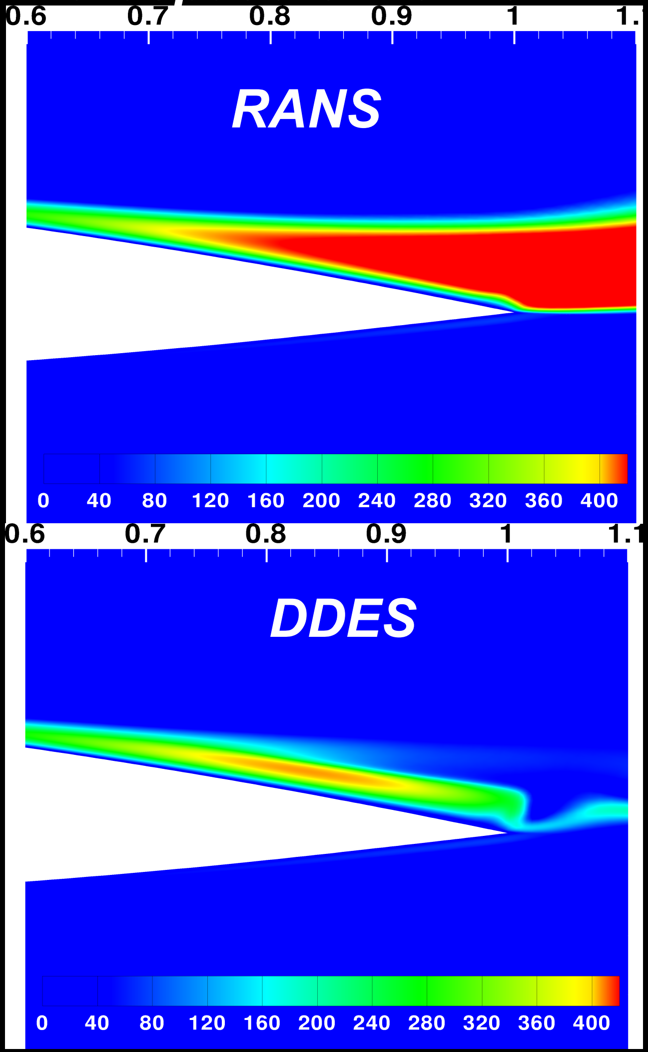


- Rotor in-ground-effect aerodynamics are unsteady and three-dimensional
- Vortices persist to older wake ages
- Vortices are responsible for strong induced velocities near the ground
- Near wall flow contains steeply embedded velocity gradients and vortex-vortex interactions

Delayed Detached Eddy Simulations (DDES)

- Use of hybrid RANS/LES models
- Near to the wall RANS mode is activated (turbulence levels are modeled)
- Away from the wall LES mode captures the large scale turbulence levels
- Technique used is DDES
- Implementation costs minimal (Distance function modified in Spalart Allamaras model)

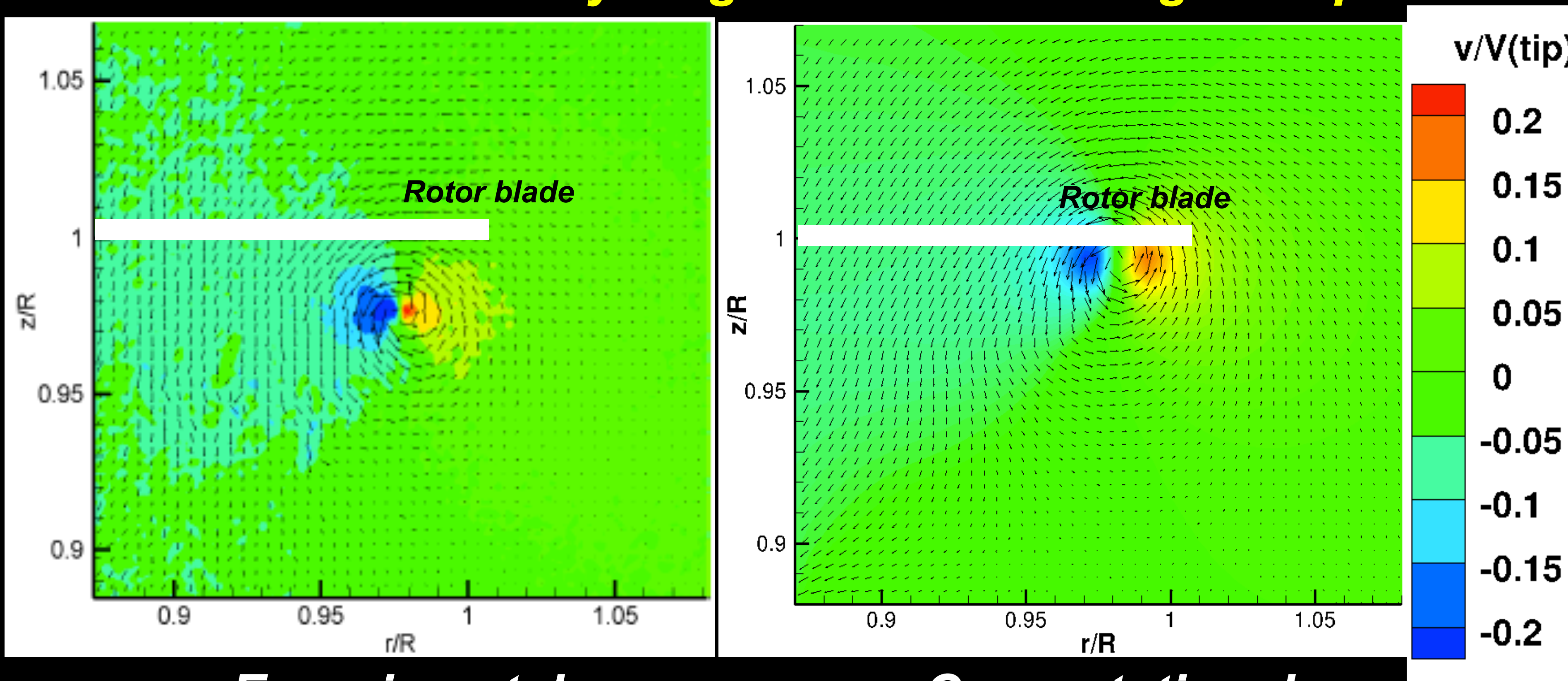
Aerospatiale-A airfoil



DDES shows reduced eddy viscosity values compared to RANS (Medida et al., 2013)

Modeling Difficulties for Sub-Scale Rotor

Vertical velocity magnitude for rectangular tips

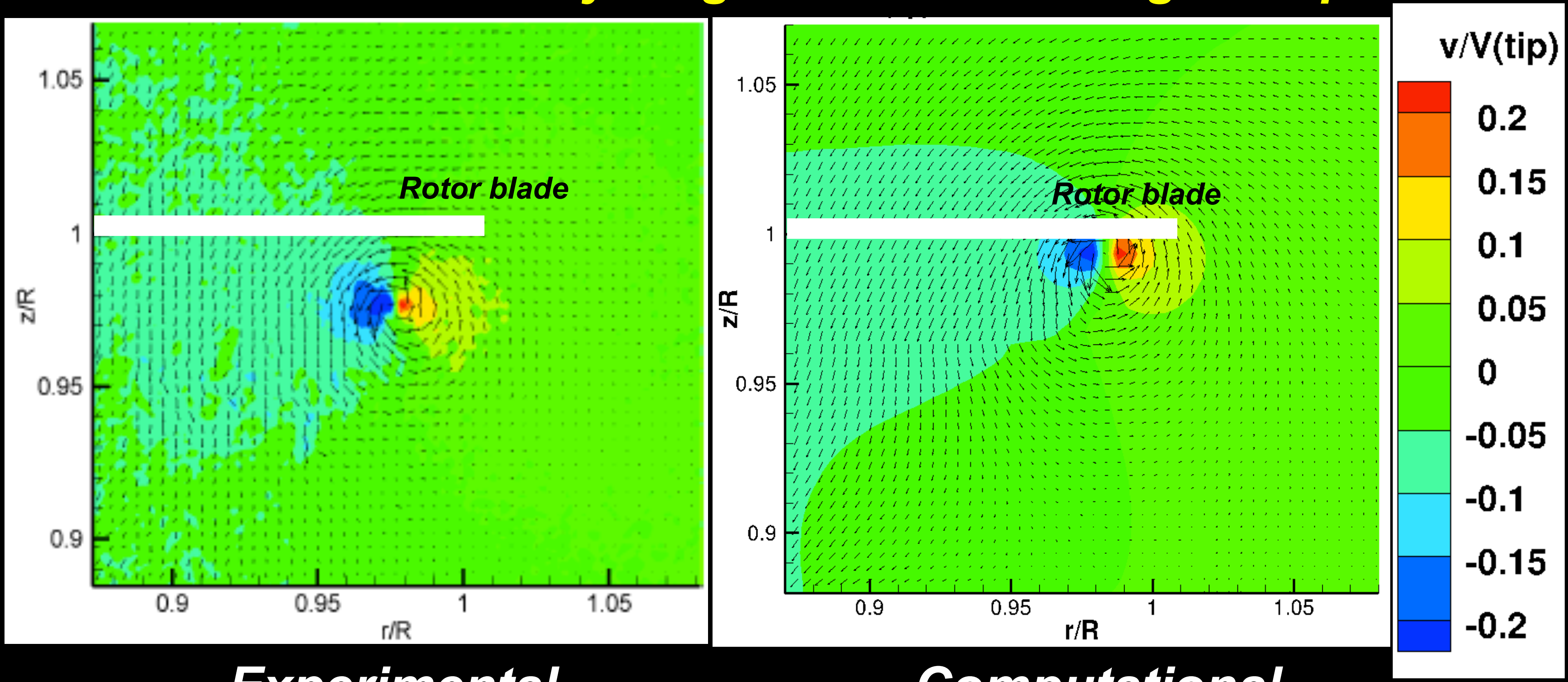


Experimental **Computational**

- **Vertical velocity magnitudes show weaker contours**
- **Difficulties in capturing vortex core size for subscale rotor**

Simulations with SA-DDES Methodology

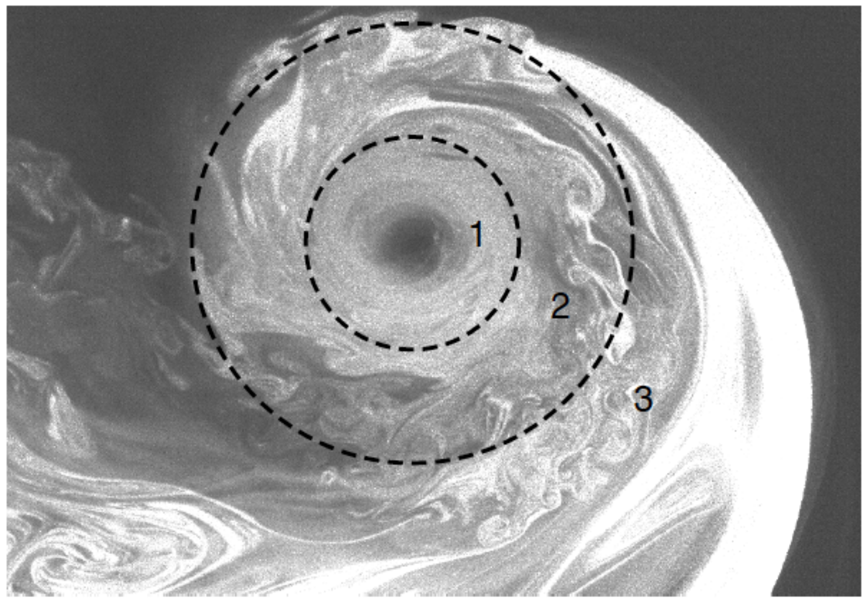
Vertical velocity magnitude for rectangular tips



Experimental *Computational*

- Vertical velocity magnitudes show comparable levels

Expected Vortex Structure (Ramasamy et al. 2004)



Region 1: Fully laminar
Region 2: Transitional
Region 3: Fully turbulent

- **Fully laminar: No interaction between adjacent layers of fluid**
- **Transitional region: Eddies of varying sizes**
- **Turbulent region**