Application of Overset Grid Methodology to Micro Rotor Simulations

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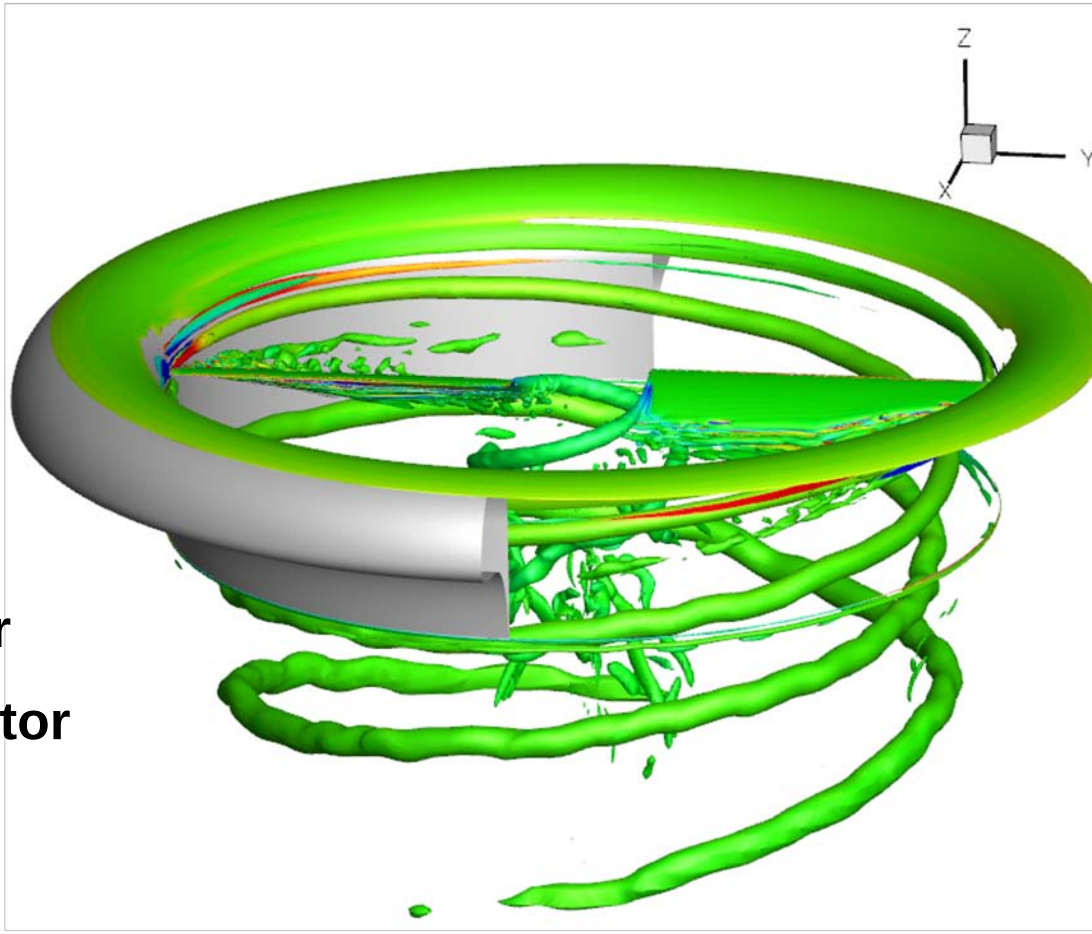
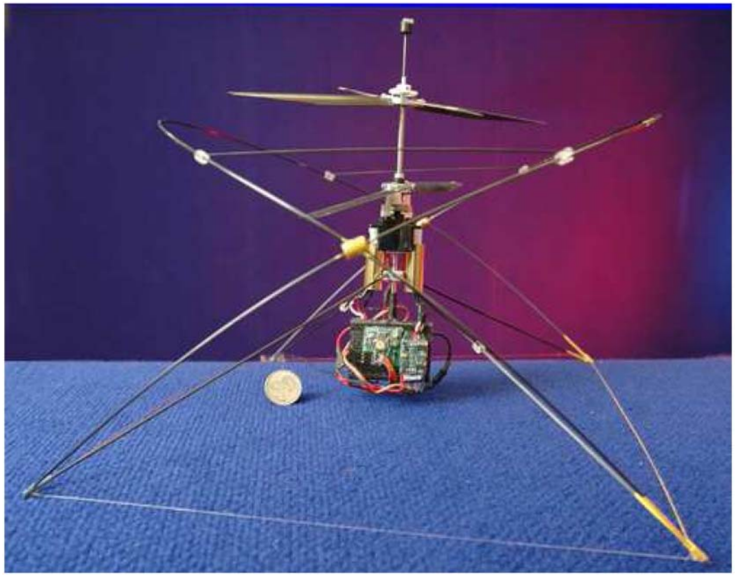
Outline

- Introduction
- Methodology
- Results
  - Micro-Scale Single Rotor
    - ➔ Out of ground effect
    - ➔ In ground effect
  - Micro-Scale Coaxial Rotor
  - Micro-Scale Shrouded Rotor
- Summary



Micro Air Vehicles

- **Micro Air Vehicles (MAVs) as defined by DARPA**
  - ➔ Dimension < 6 inches
  - ➔ Weight < 100g
  - ➔ Endurance > 1 hour
- **Can be used for variety of civilian and military operations**
- **Most current day MAVs lack capabilities demanded by various operations**
- **Apart from aerodynamic improvements, variety of unconventional configurations being studied**
  - ➔ Coaxial rotor, Shrouded rotor, Cycloidal rotor etc.



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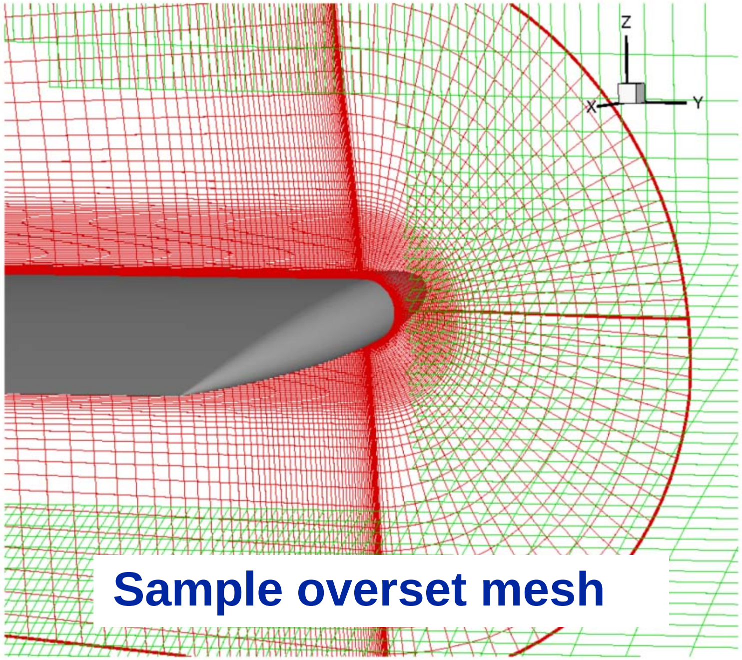
Overset methodology make it feasible to study complex geometries

Overset Methodology

- **Ability to use fine smoothly spaced meshes in regions of interest**
- **Involves:**
  - ➔ **Identifying overlap regions**
  - ➔ **Generate connectivity information**
  - ➔ **Exchange information across meshes at every time-step**
- **Issues:**
  - ➔ **Additional work**
  - ➔ **Loss of conservation property and accuracy**
    - → **Minimized if mesh sizes are similar in interpolation region**



Sample overset mesh

Hole points → iblank = 0

Field points → iblank = 1

Fringe points → iblank = 0 or 1

Traditional Methodology

- **'Hole-cut' in regions of solid surface**
  - ➔ **Hole points blanked to avoid contamination**
- **Holes expanded to find optimum hole**

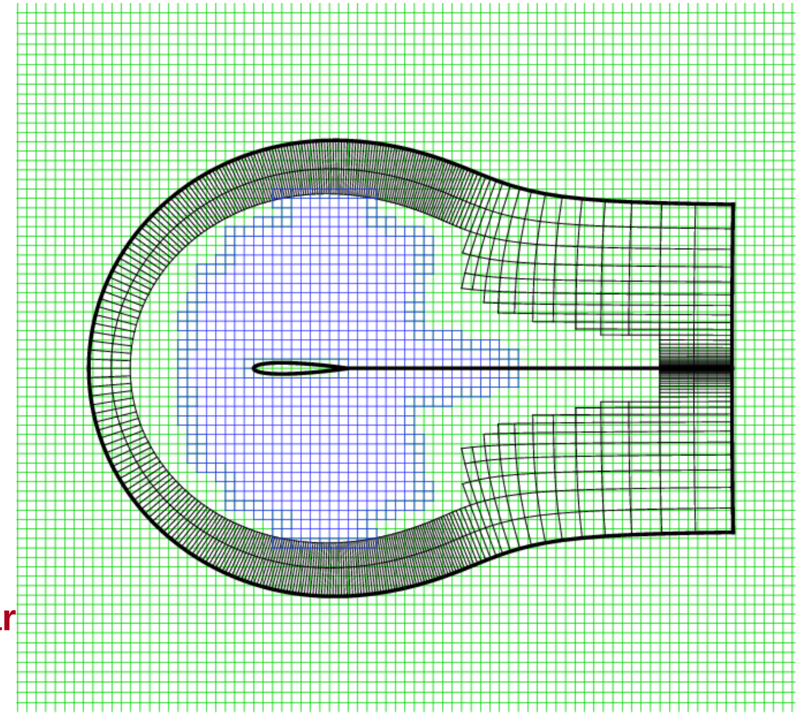
Implicit Hole-Cutting Method

- Alternative approach developed by Lee & Baeder, 2008

- Why is it called Implicit Hole-cutting?
  - ➔ No explicit hole involved (no hole points)
    - → Points are either field or fringe points
  - ➔ Based on cell volume comparison
    - → Solution obtained on mesh with smallest cell volume and interpolated to overlapping meshes
  - ➔ Presence of hole felt by mesh refinement
    - → E.g. Blade mesh points chosen as field point near blade surface due to near-wall refinement
  - ➔ Interpolation region is implicitly optimum

- No iblanking involved

- Larger number of fringe points compared to traditional method



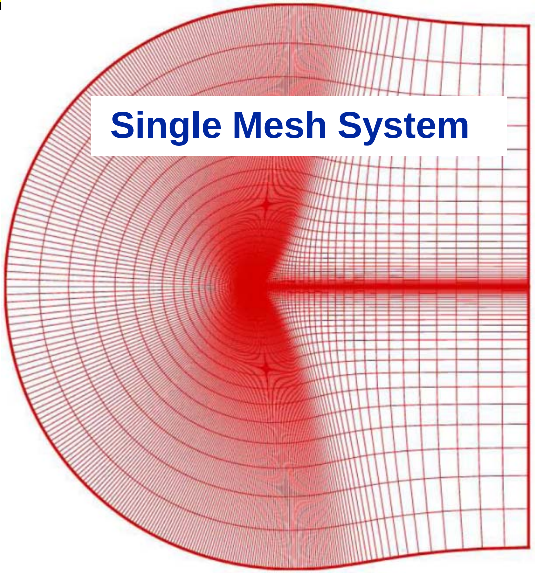
- Blue: Fringe points in background mesh
- Black: Fringe points in airfoil mesh
- Green: Field points in background mesh

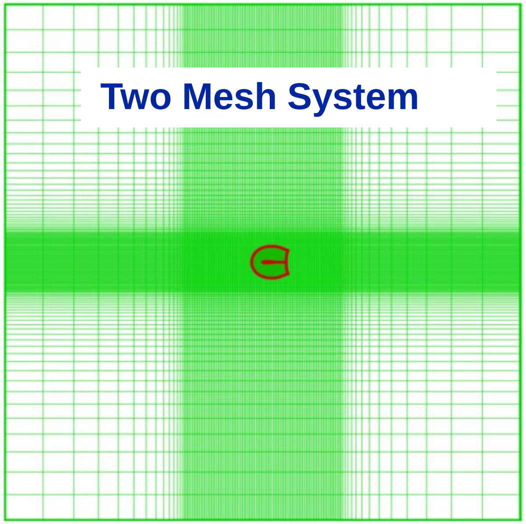
Connectivity done using IHC

Validation of IHC

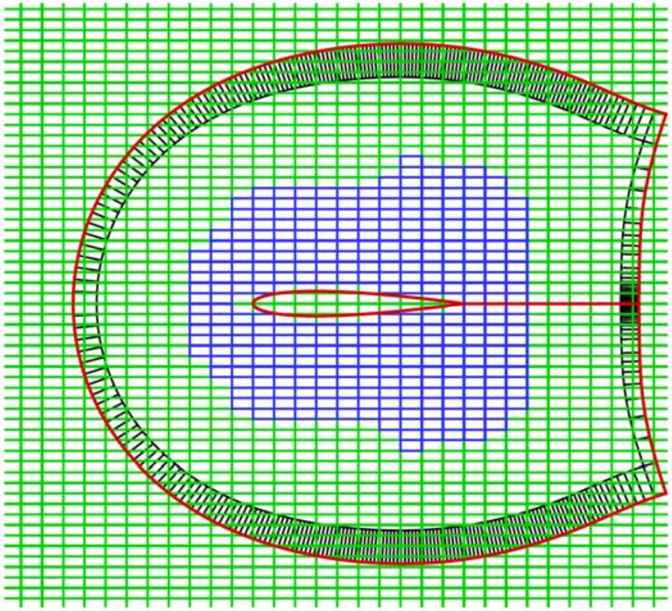
- **Steady 2D flow**
  - ➔ NACA 0012 airfoil
  - ➔ Angle of attack → 10°
  - ➔ Mach Number → 0.3
  - ➔ Reynolds Number → 3 X10^6

- **Modeled with**
  - ➔ Single mesh (327 X 85)
  - ➔ Two mesh
    - → Airfoil mesh (267 X 65)
    - → Background mesh (151 X 151)
    - → Connectivity using implicit hole-cutting



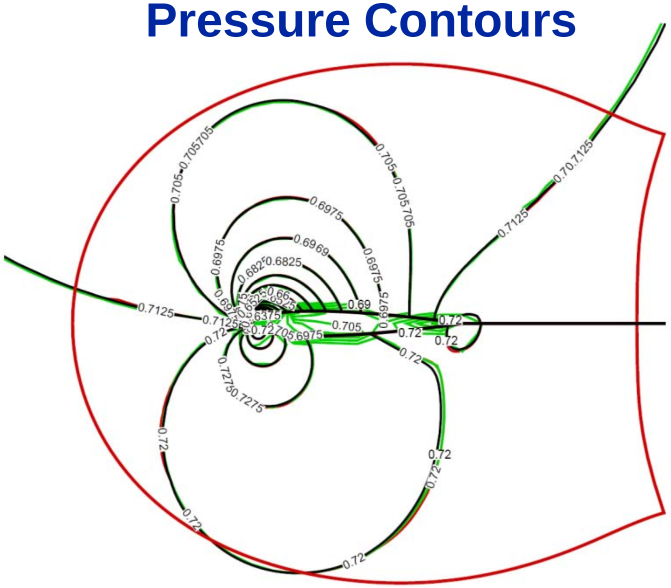


Baseline Implicit Hole-Cutting



- Blue: Fringe points in background mesh
- Black: Fringe points in airfoil mesh
- Green: Field points in background mesh

Pressure Contours



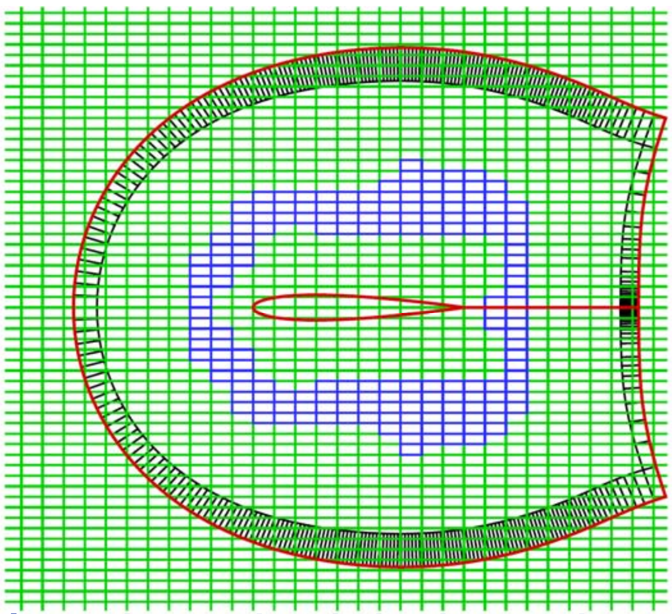
- Black: Contours on single mesh
- Red: Contours on airfoil mesh
- Green: Contours on background mesh

Contours fairly comparable

- **Issues with baseline IHC**
  - ➔ **Requires thick fringe layers to prevent contamination from invalid points**
    - → **Not guaranteed in all circumstances**
    - → **Increased communication time for parallel computation in 3D**

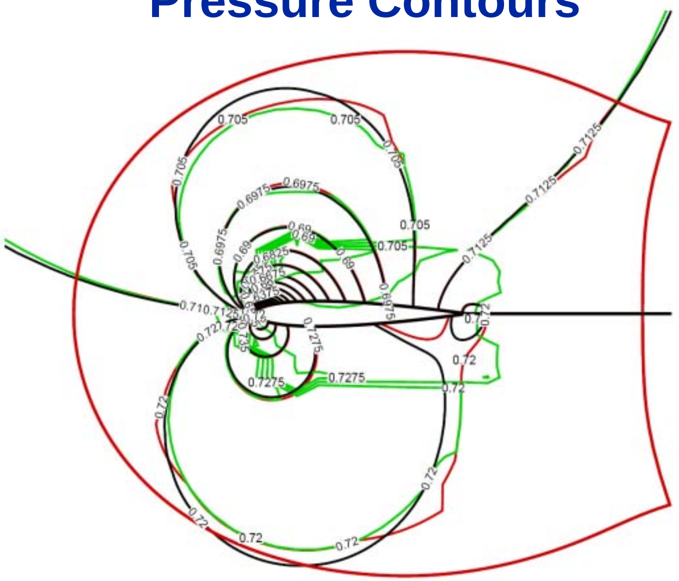
Modified Implicit Hole-Cutting

- Fringe layer thickness reduced manually



- Blue: Fringe points in background mesh
- Black: Fringe points in airfoil mesh
- Green: Field points in background mesh

Pressure Contours



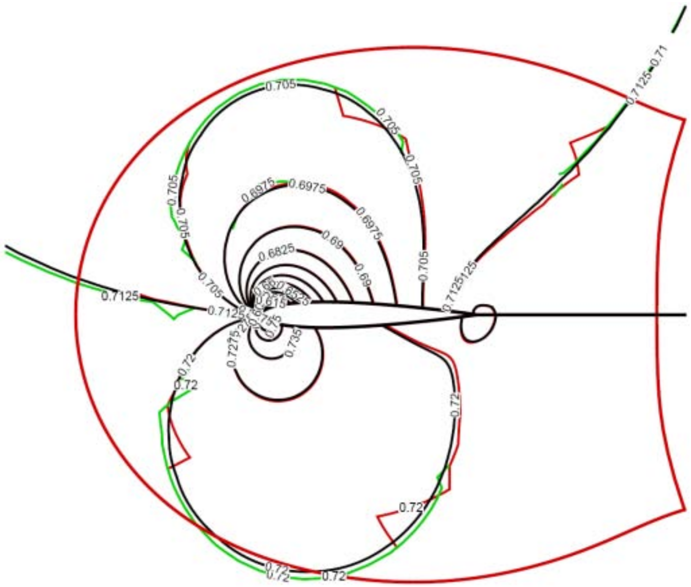
- Black: Contours on single mesh
- Red: Contours on airfoil mesh
- Green: Contours on background mesh

- Inaccuracies and discontinuities in two mesh system

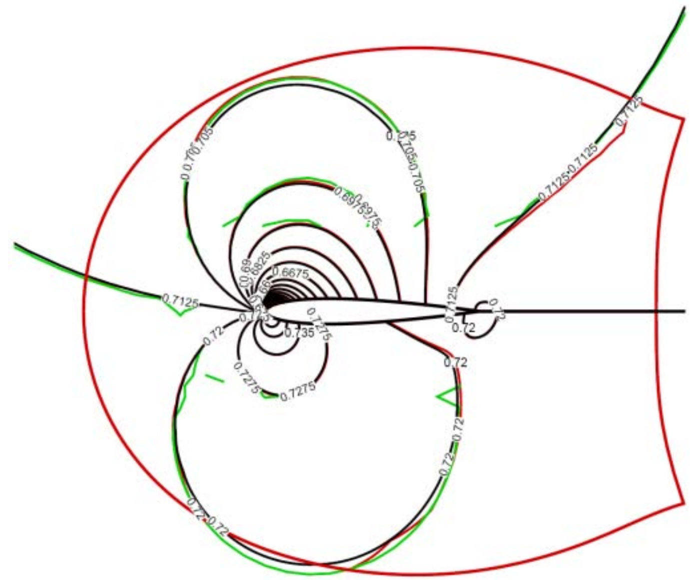
Can be resolved by adopting blanking technique from traditional methodology

Need for Improved Iblanking

IHC with reduced fringe layer and using iblanking



Hole points → iblank = 0
Field points → iblank = 1
Fringe points → iblank = 0



Hole points → iblank = 0
Field points → iblank = 1
Fringe points → iblank = 1

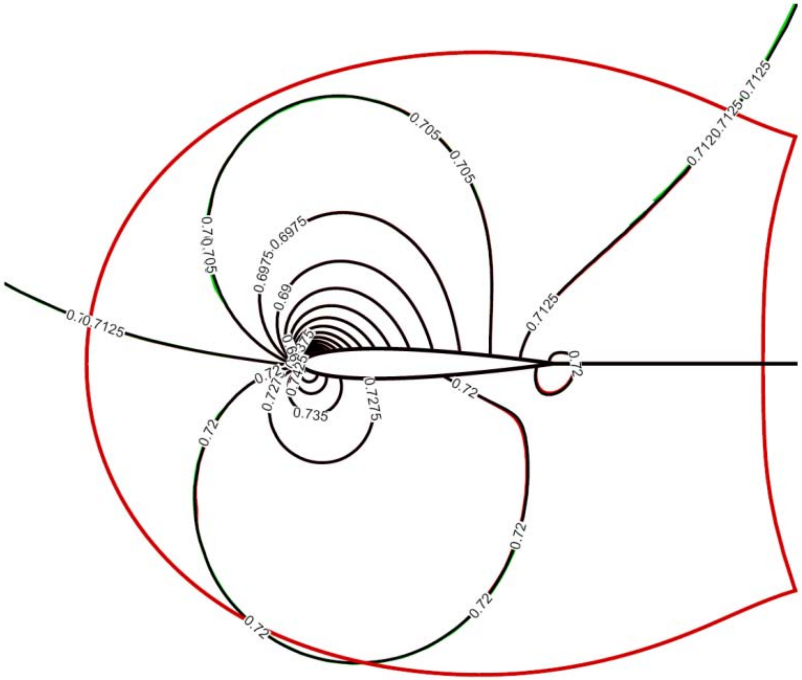
- **Improves solution**
- **Inaccuracies and discontinuity still present**

  → Applicable to even baseline hole-cutting methodology

Improved Iblanking

- Inconsistency in the treatment of fringe points
- Solution at fringe points are valid
  - ➔ Should be utilized for calculating fluxes
  - ➔ Suggests iblank = 1 for the RHS of the solver
- Updates at fringe points invalid during implicit inversion
  - ➔ Can result in contamination
  - ➔ Suggest iblank = 0 for the LHS of the solver
- Define *iblank = -1* for fringe points
- Use *abs(iblank)* in the RHS
- Use *max(iblank,0)* in the LHS

Results from Improved Iblanking



Method	C_l	C_d	C_m
Single mesh	1.123	0.0172	0.00726
Baseline implicit hole-cutting (IHC)	1.129	0.0176	0.00686
IHC with less fringe points (IHCfr)	1.132	0.0194	0.00562
IHCfr with iblanking			
$iblank = 0$ for fringe points	1.127	0.0186	0.00570
$iblank = 1$ for fringe points	1.129	0.0178	0.00634
$iblank = -1$ for fringe points	1.125	0.0169	0.00722

- **Black: Contours on single mesh**
- **Red: Contours on airfoil mesh**
- **Green: Contours on background mesh**

- **Contours compare excellently with new iblanking**

Results from Micro-Rotor Simulations

Flow Solver Methodology

OVERTURNS: Compressible overset structured RANS solver

- **Standard discretization**
  - ➔ Inviscid terms: 3rd order MUSCL scheme utilizing Koren's limiter, Roe's flux difference
  - ➔ Viscous terms: 2nd order central
- **Time-accurate computation using preconditioned dual-time scheme in diagonalized approximate factorization framework**
  - ➔ Implicit approximate factorization developed by Pulliam and Chaussee
  - ➔ Turkel Preconditioning for Low Mach numbers
- **Spalart-Allmaras turbulence model with rotational correction**
- **Point-sink boundary condition at far-field boundaries**
- **Connectivity using Implicit Hole cutting (IHC) technique**

Micro-Scale Single Rotor

Hovering Micro-Rotor

2-bladed rotor setup of Ramasamy et al.

- ➔ Untwisted rectangular
- ➔ Aspect Ratio of 4.39

Airfoil profile

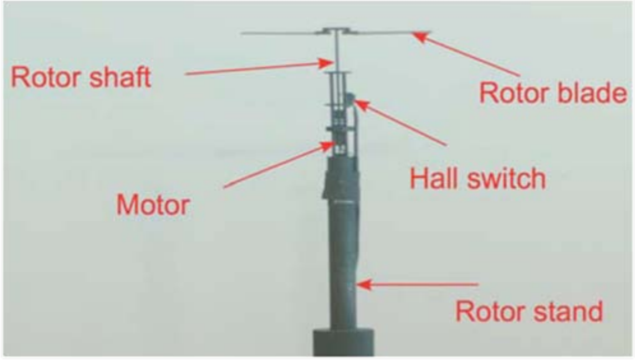
- ➔ Circular arc
- ➔ 3.7% Thickness
- ➔ 3.3% Camber

Flow conditions

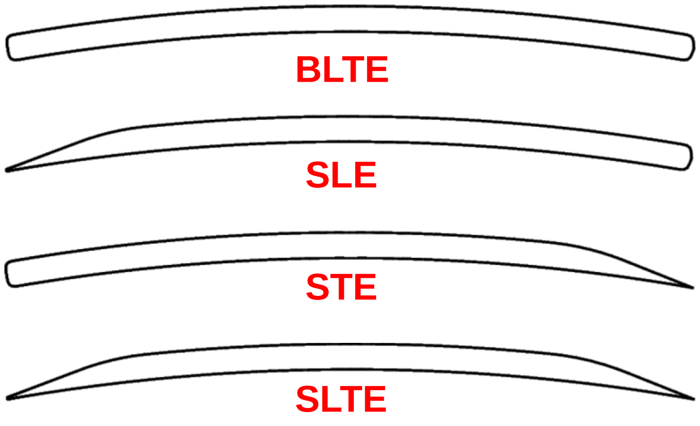
- ➔ Re_{tip} = 32,400, Re_{root} = 6480
- ➔ M_{tip} = 0.08

Modeled geometry has:

1. Blunt LE and blunt TE **(baseline/BLTE)**
2. Sharp LE and blunt TE **(SLE)**
3. Blunt LE and sharp TE **(STE)**
4. Sharp LE and sharp TE **(SLTE)**

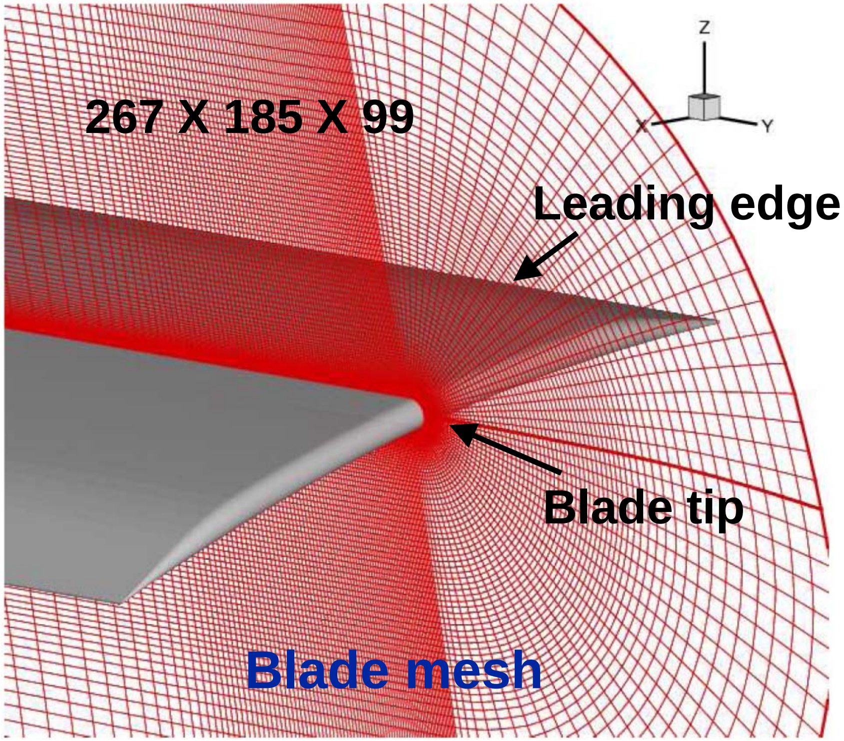


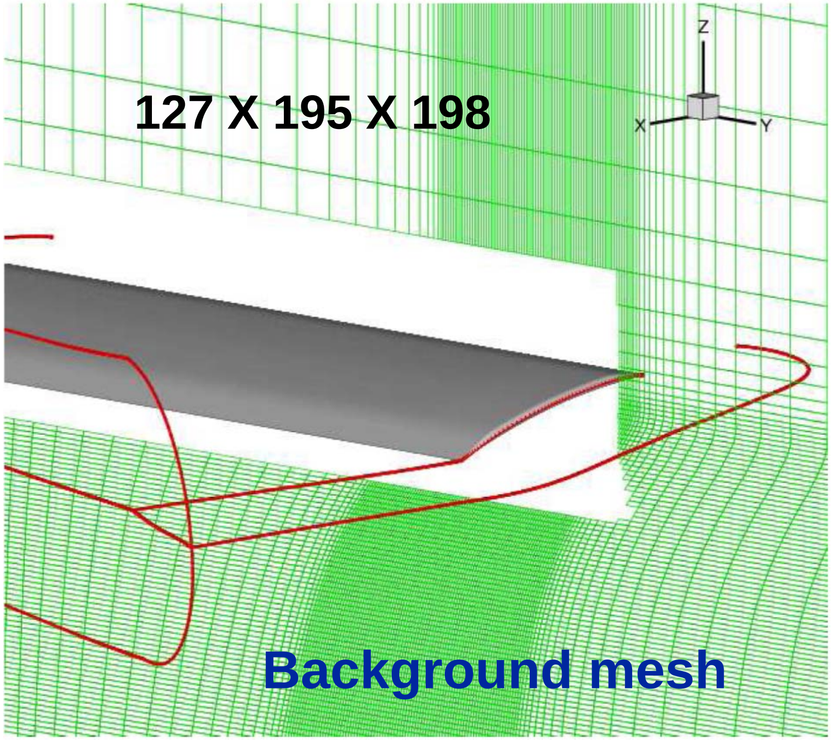
Experimental setup
Ramasamy et al.



Modeled geometries

Mesh System – Fine
(12° collective setting – SLTE geometry)

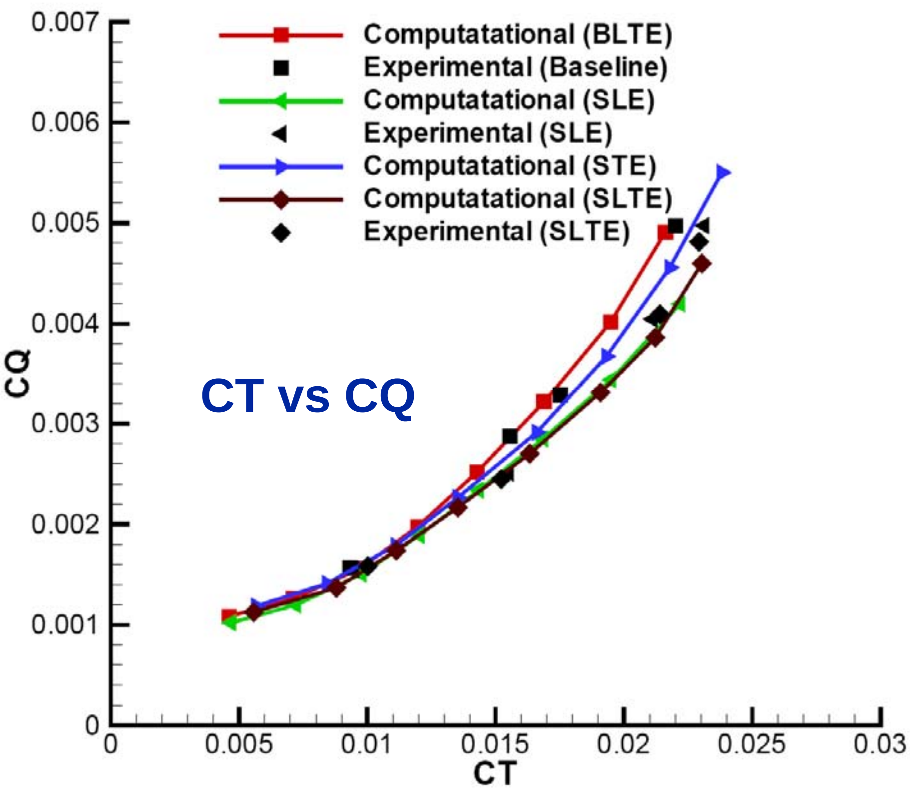


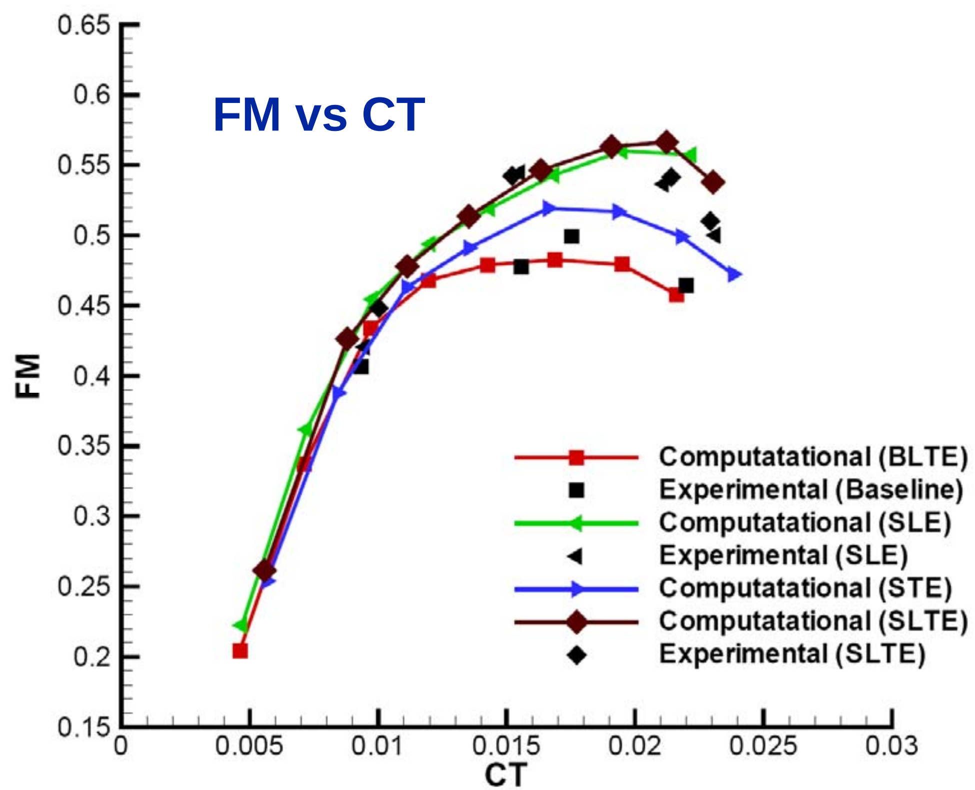


- **Total mesh points ~ 10 million**
- **In most refined regions**
  - ➔ $\Delta r = 0.02$ chords, $\Delta z = 0.02$ chords, $\Delta\psi = 1.5^o$, background

Coarser mesh used for performance comparison

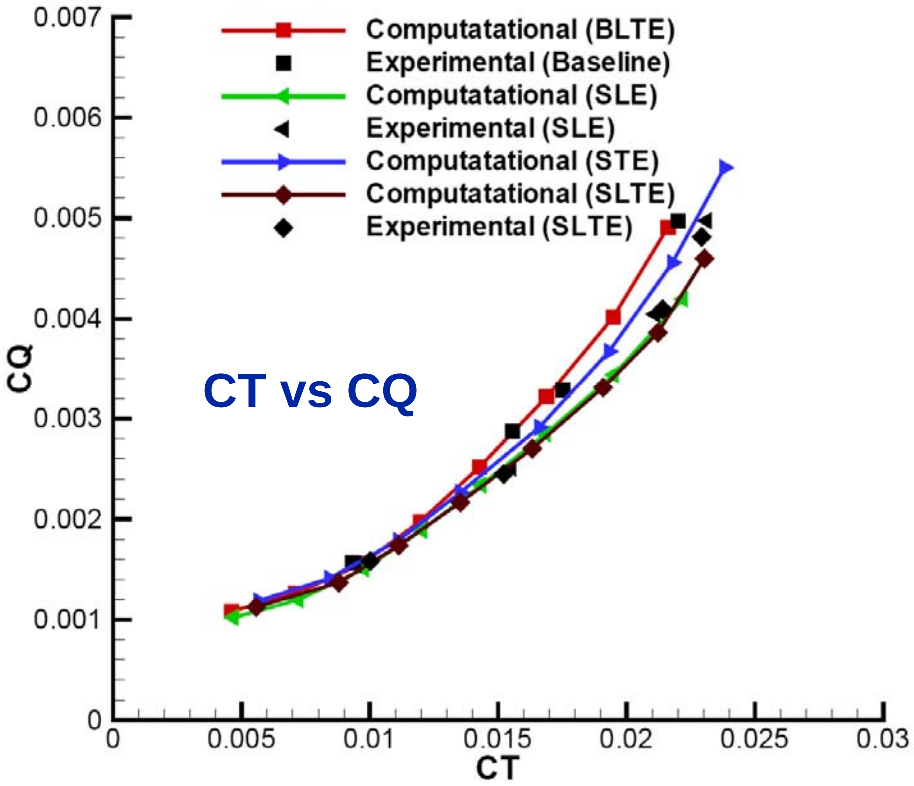
Performance Comparison

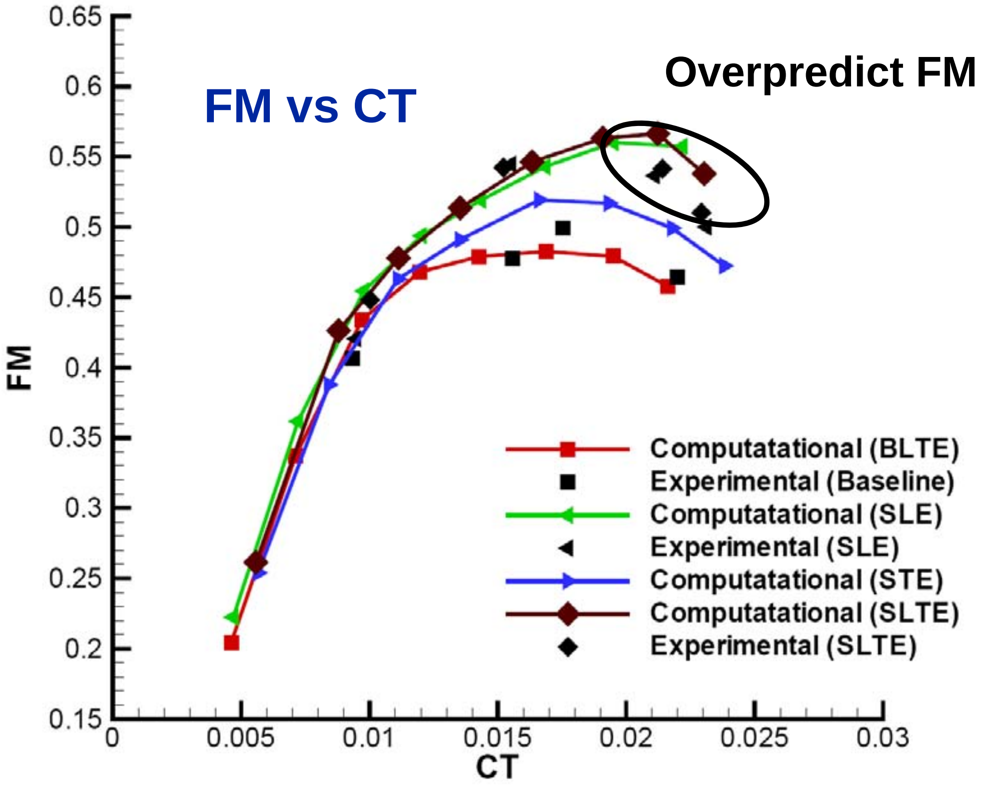




Reasonably good comparison between CFD and experiment

Performance Comparison





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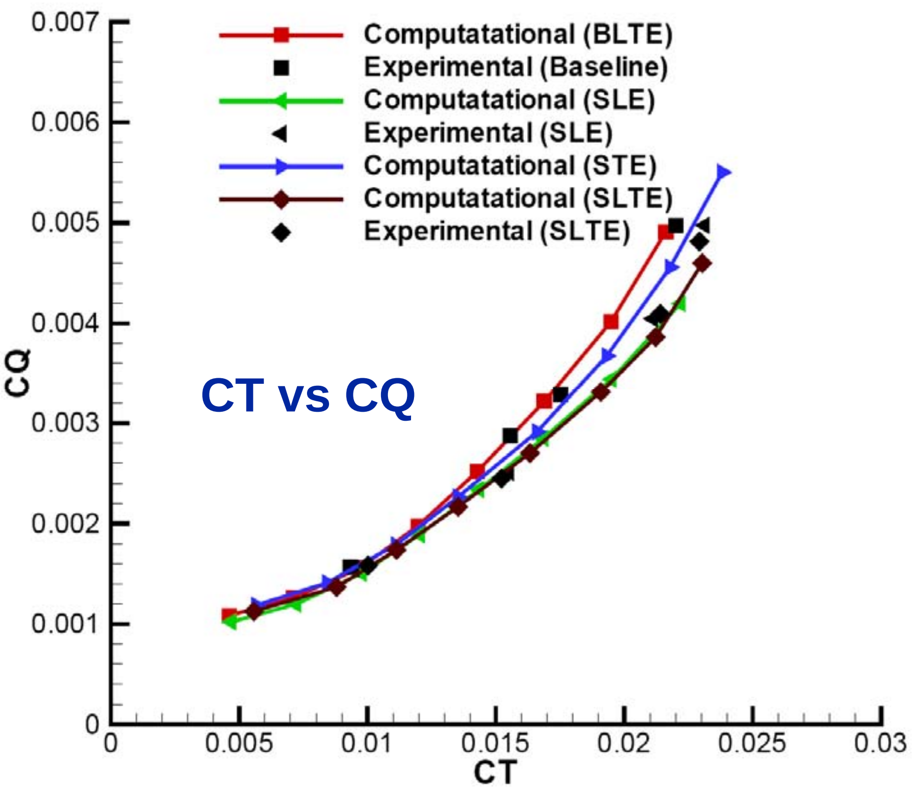
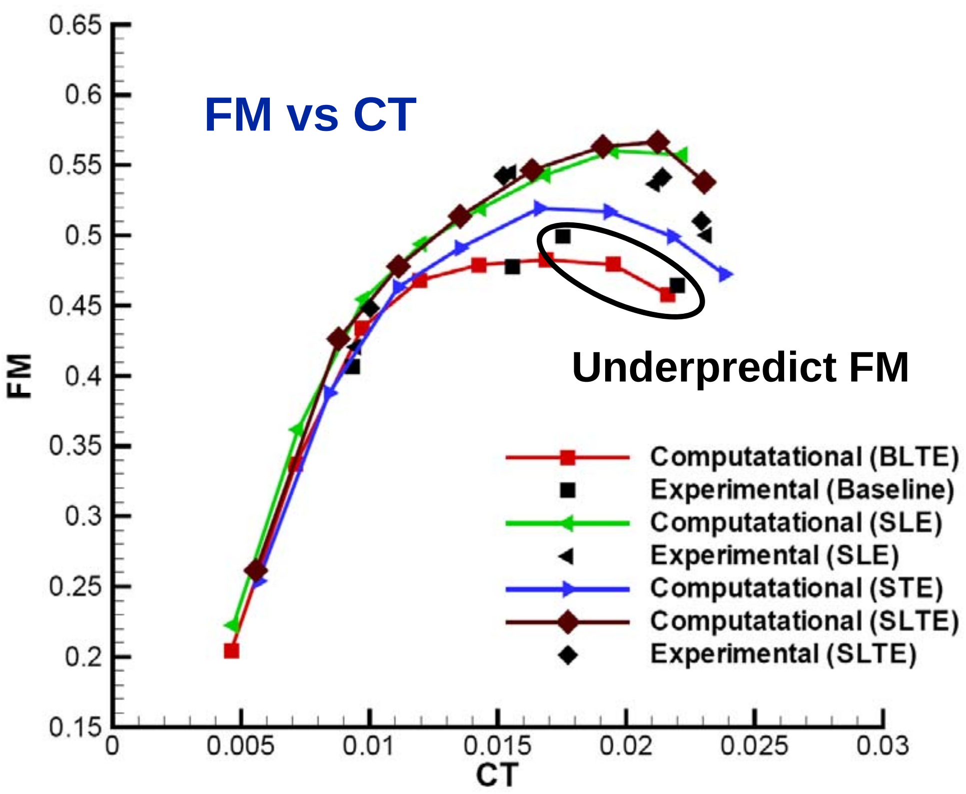
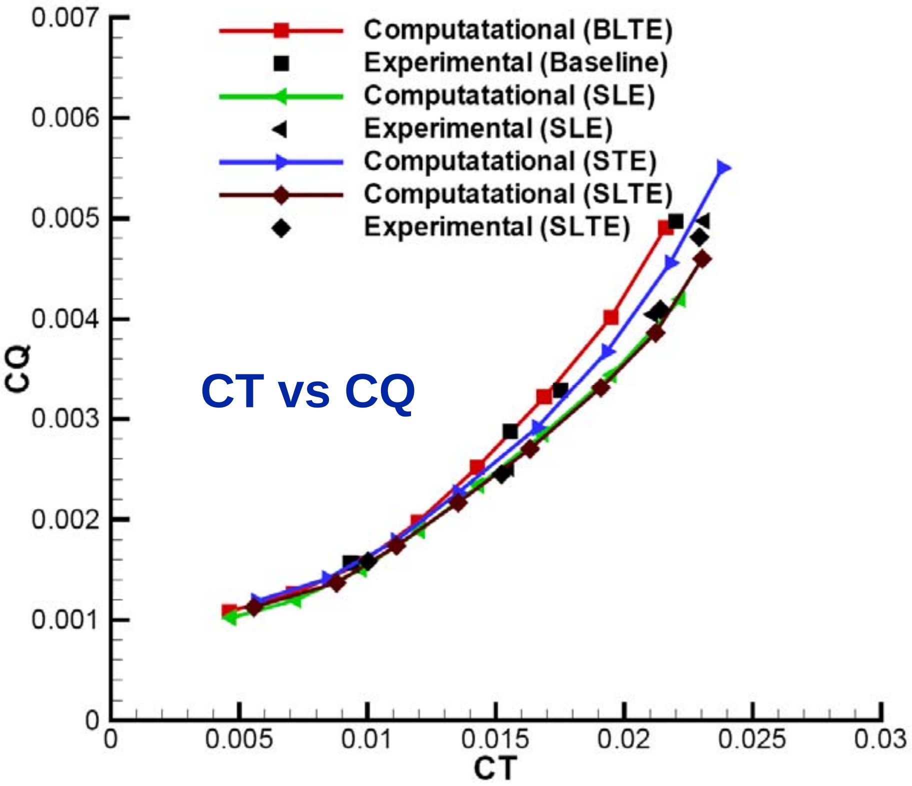
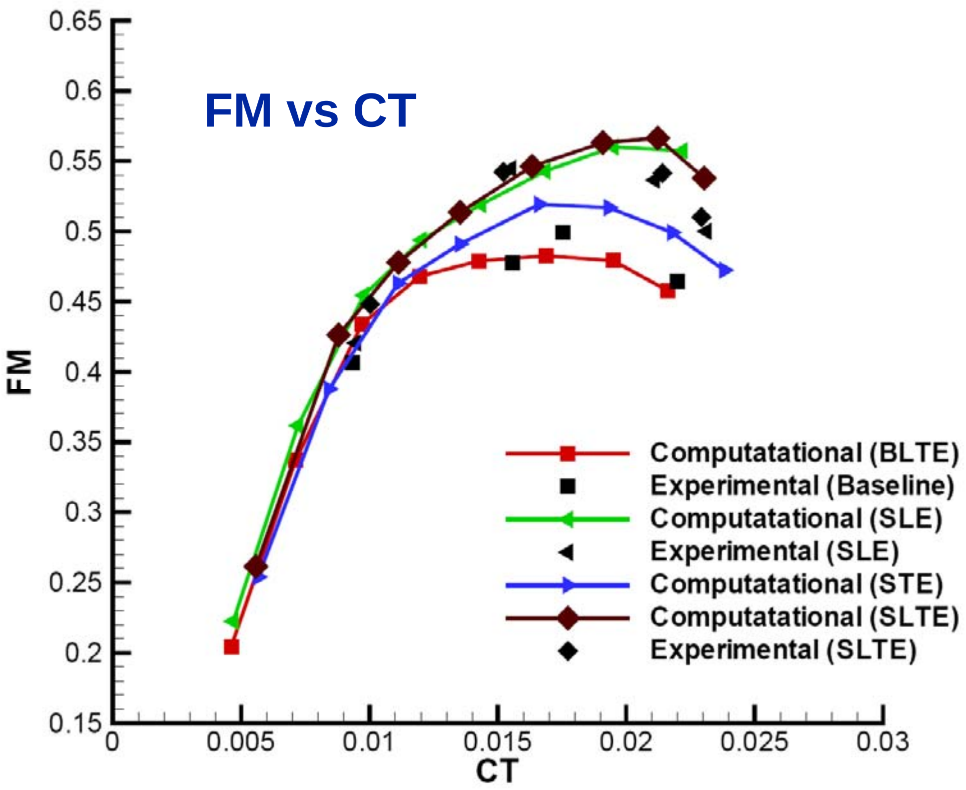




Reasonably good comparison between CFD and experiment

Performance Comparison

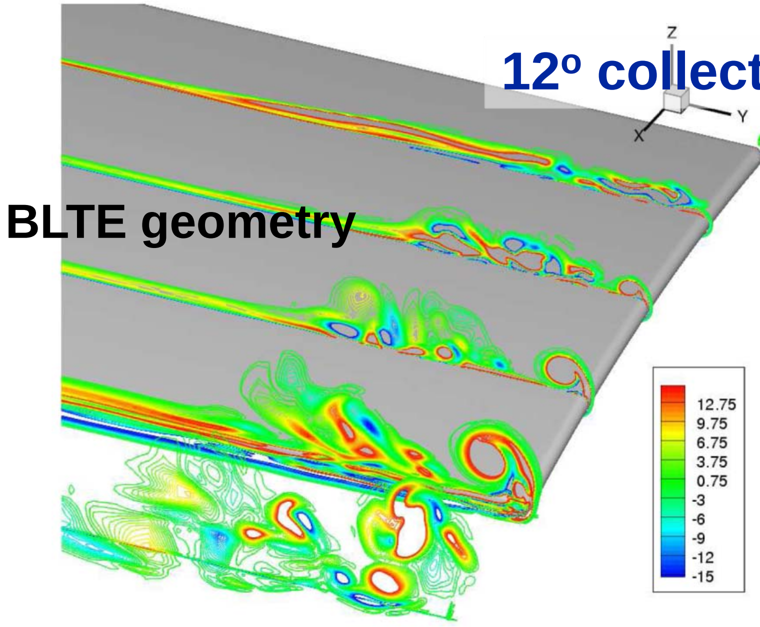


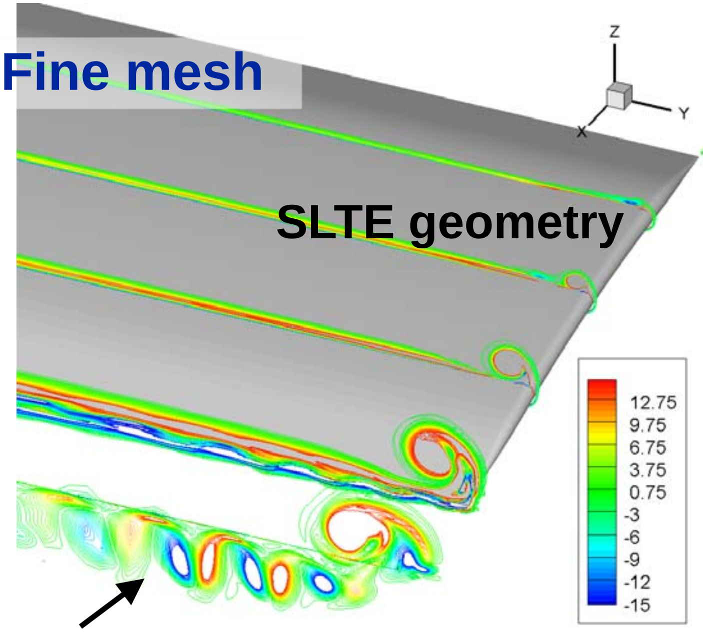


Reasonably good comparison between CFD and experiment

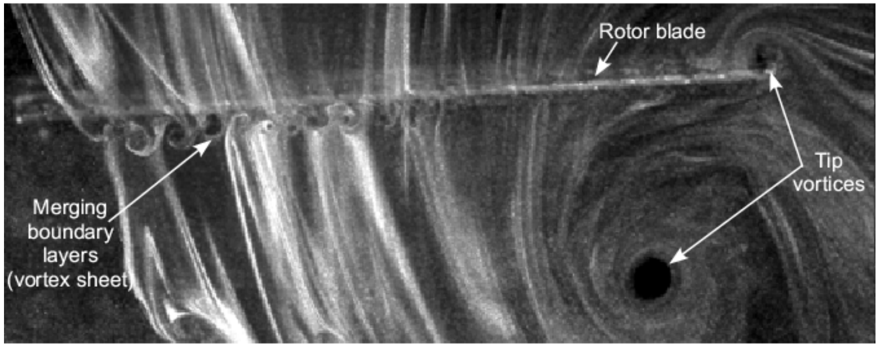
Streamwise Vorticity Contour

12° collective – Fine mesh





Taylor-Gortler vortices

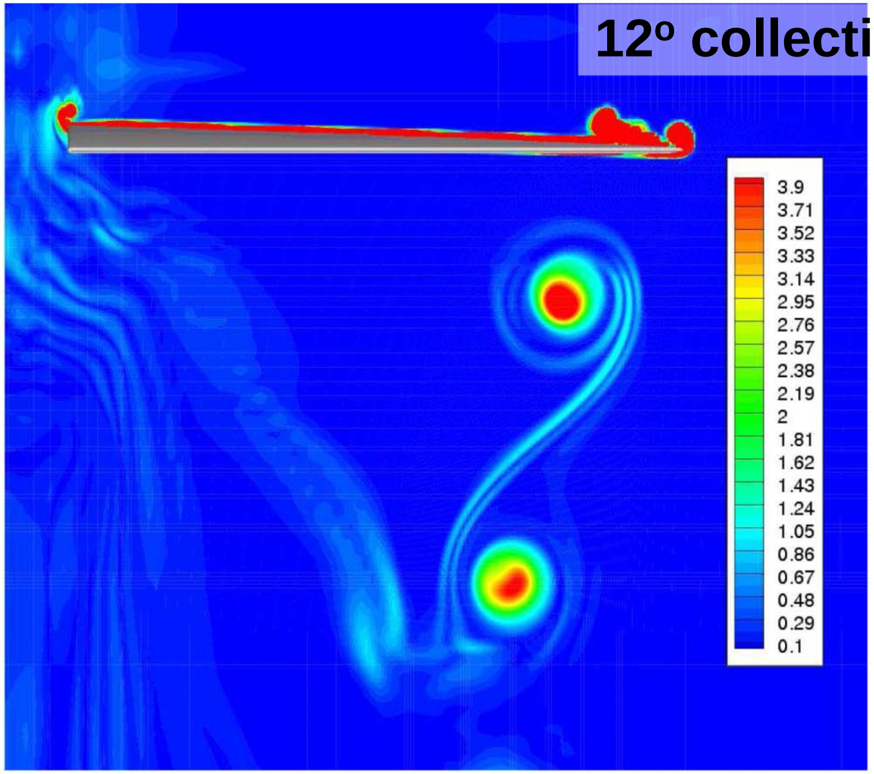


Experimental Flow Visualization.

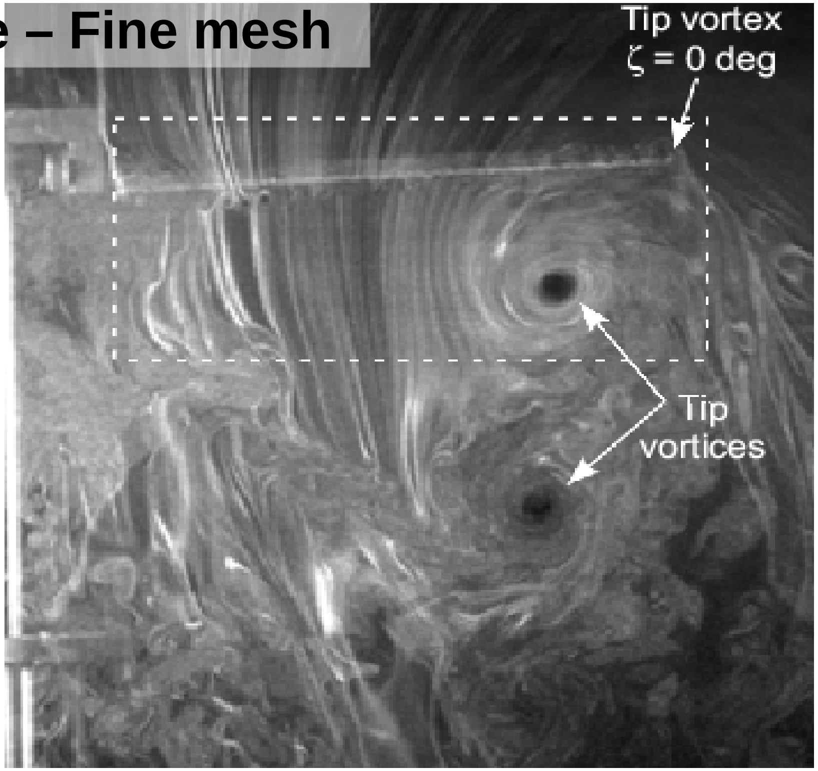
Courtesy: Ramasamy, Leishman and Lee

Flow-Field Visualization (BLTE geometry)

12º collective – Fine mesh



Vorticity magnitude contours, ψ=0º.
(Blunt leading edge geometry)

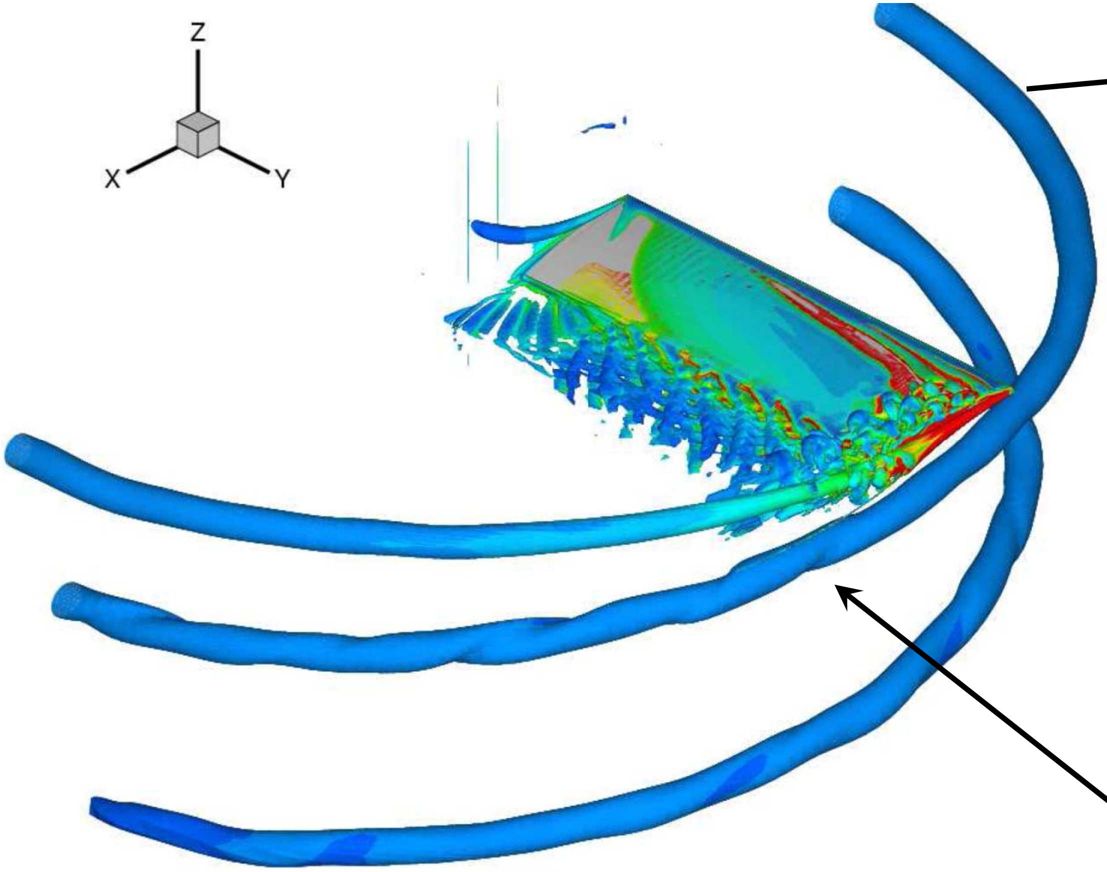


Experimental Flow Visualization.
Courtesy :Ramasamy, Leishman and Lee

- **Wake Structures are very similar**

Flow-Field Visualization (BLTE geometry)

12° collective – Fine mesh



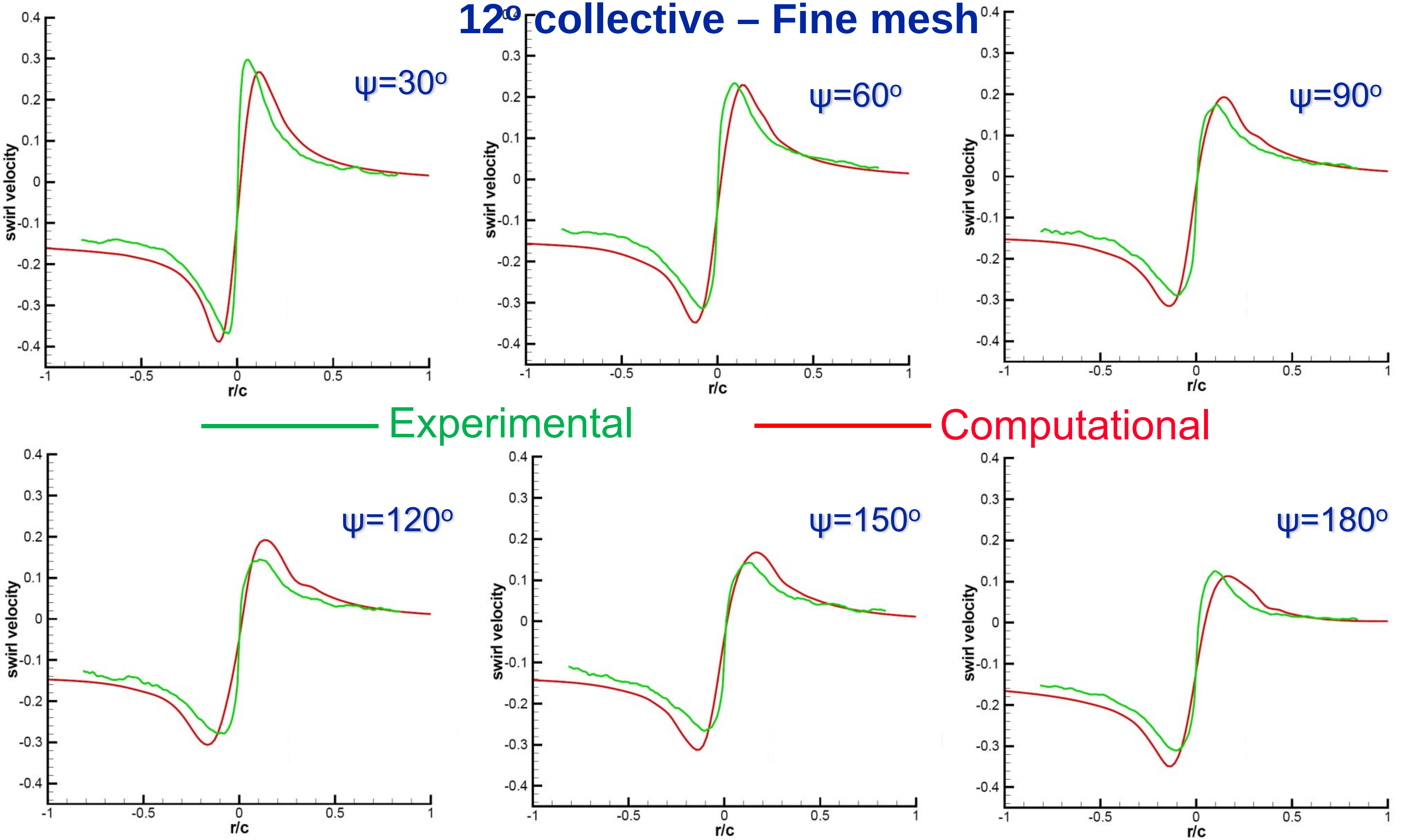
From second blade

Iso-surfaces of q-criterion, q = 1.0.

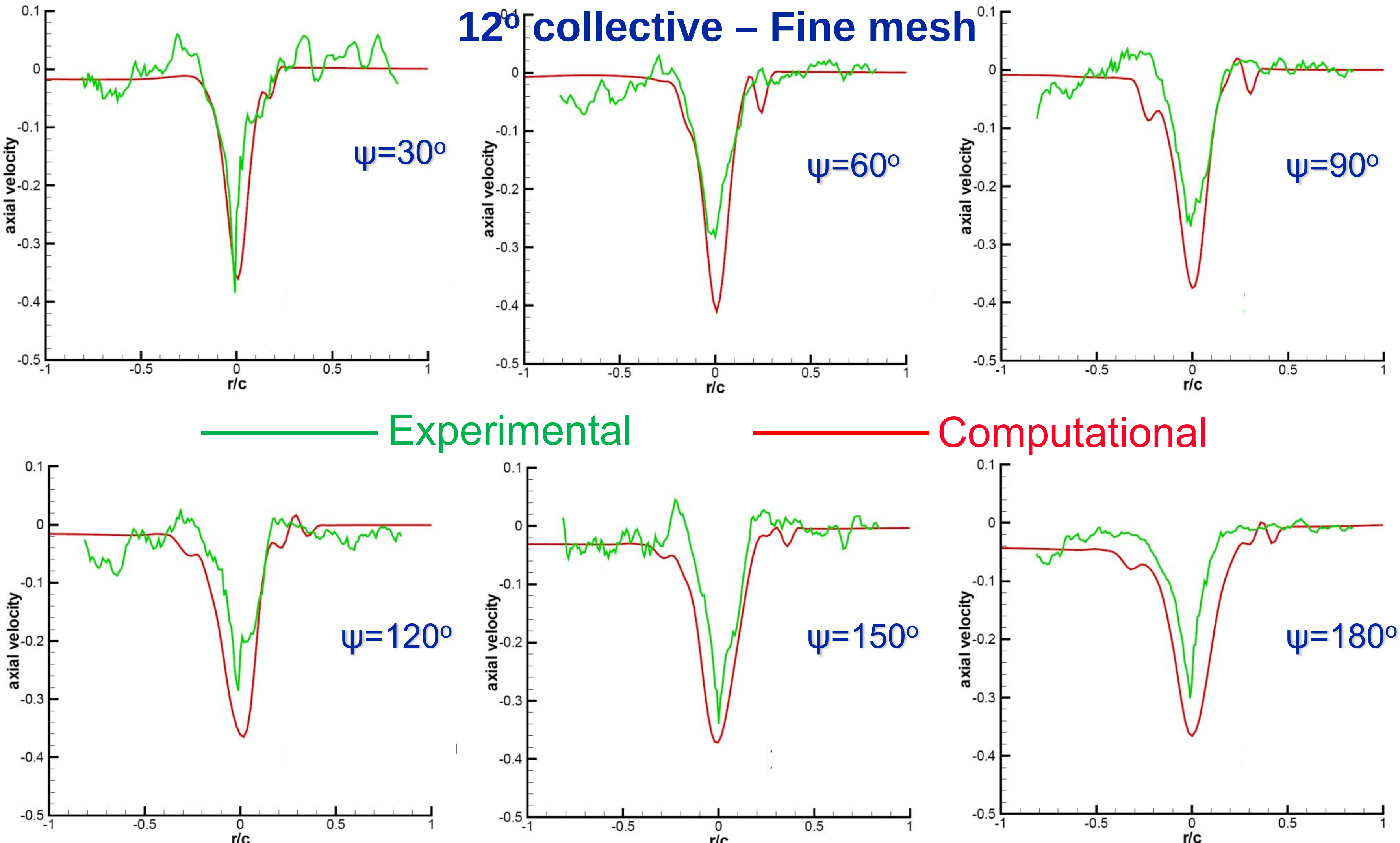
Twisting of vortices after blade passage

Vortex Structure – Swirl Velocity (BLTE geometry)

12° collective – Fine mesh



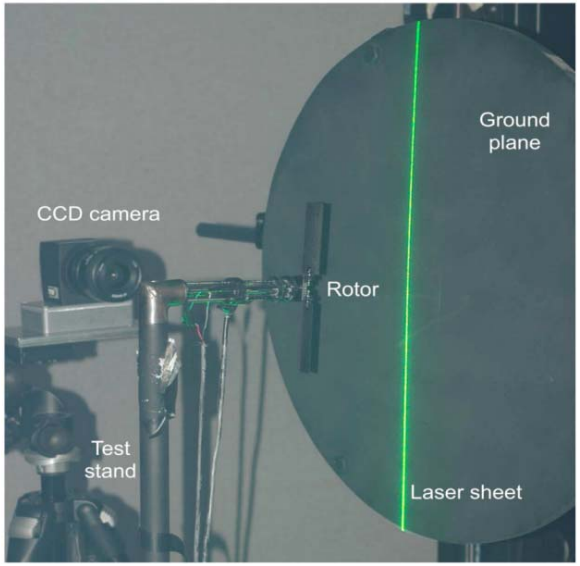
Vortex Structure – Axial Velocity (BLTE geometry)



Micro-Scale Single Rotor in Ground Effect

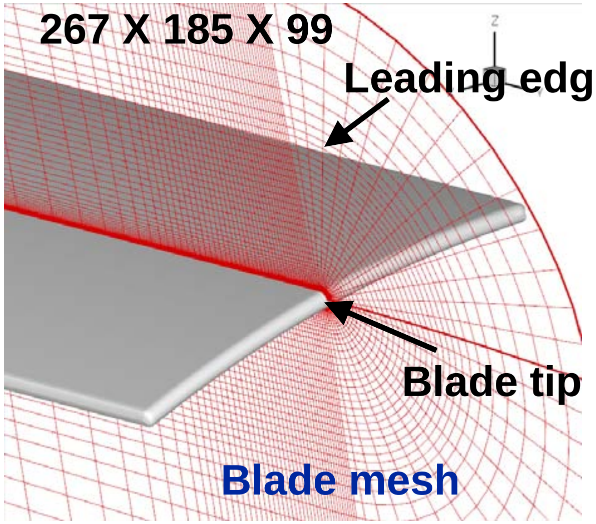
Experimental Setup for Validation

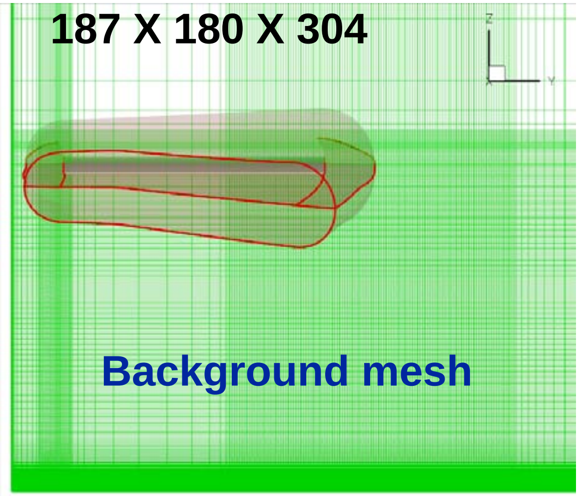
- **2-bladed rotor setup of Lee et al.**
  - ➔ BLTE rotor of Ramasamy et al.
  - ➔ Collective setting of 12^o
- **Ground plane distances**
  - ➔ h/R = 0.25 to 4.0



Experimental Setup, Lee et al.

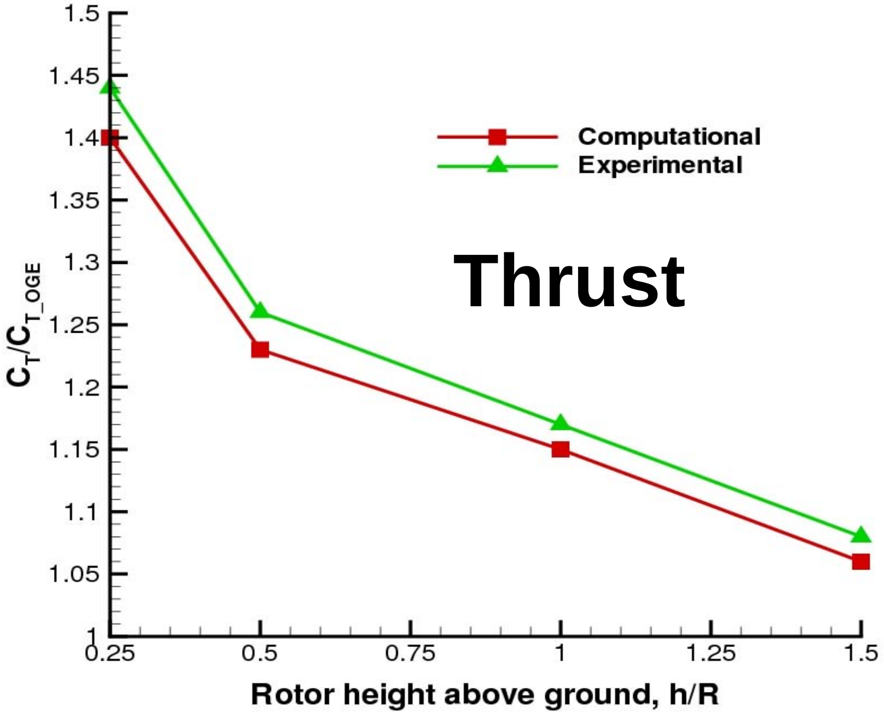
Mesh System

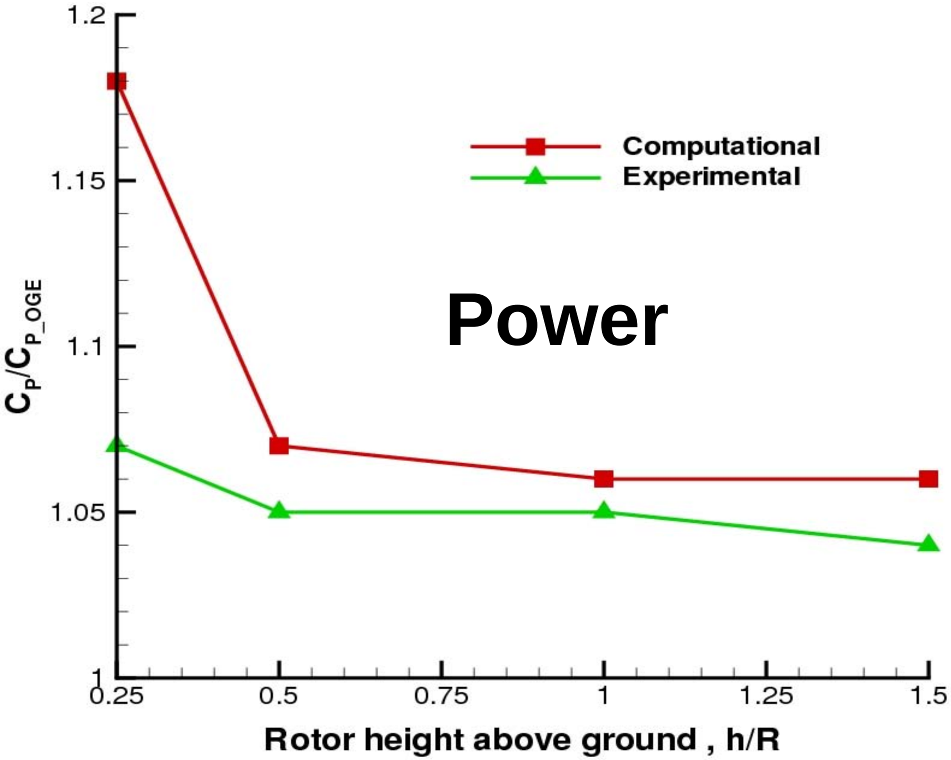




9.8 million mesh points

Performance Comparison





$C_{T(OGE),\ computational} = 0.0143$

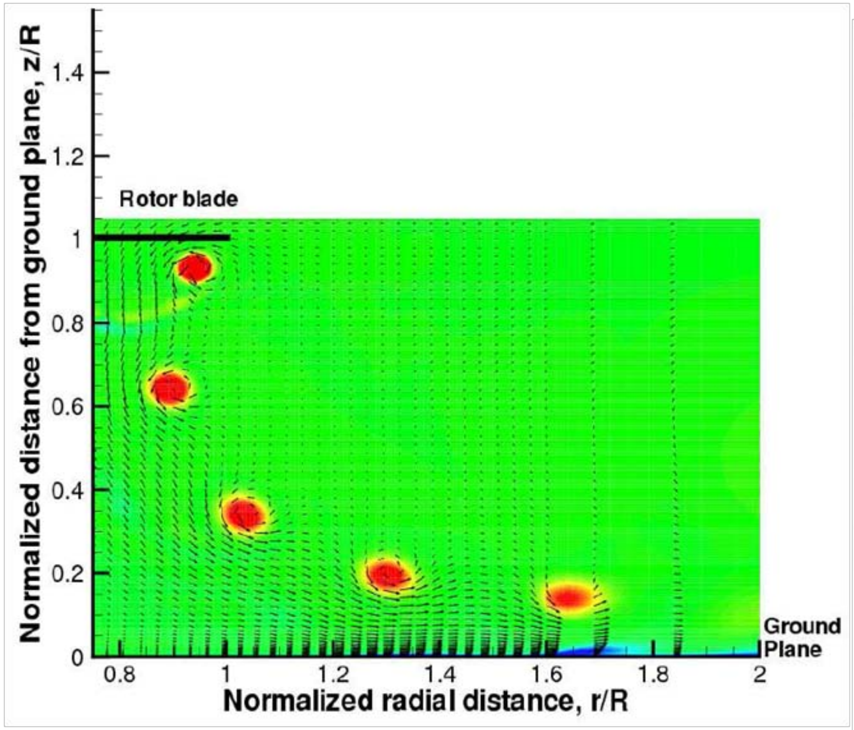
$C_{T(OGE),\ experimental} = 0.0133$

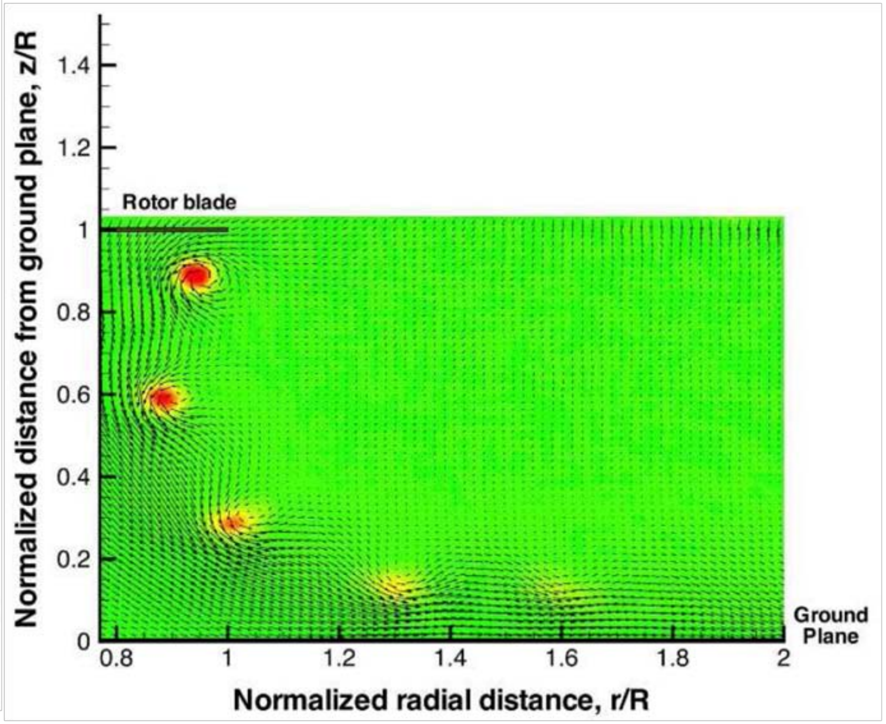
$C_{P(OGE),\ computational} = 0.00277$

$C_{P(OGE),\ experimental} = 0.00249$

- **Good agreement, except for power at h/R = 0.25**

Vortex Trajectory Comparison, h/R = 1.0

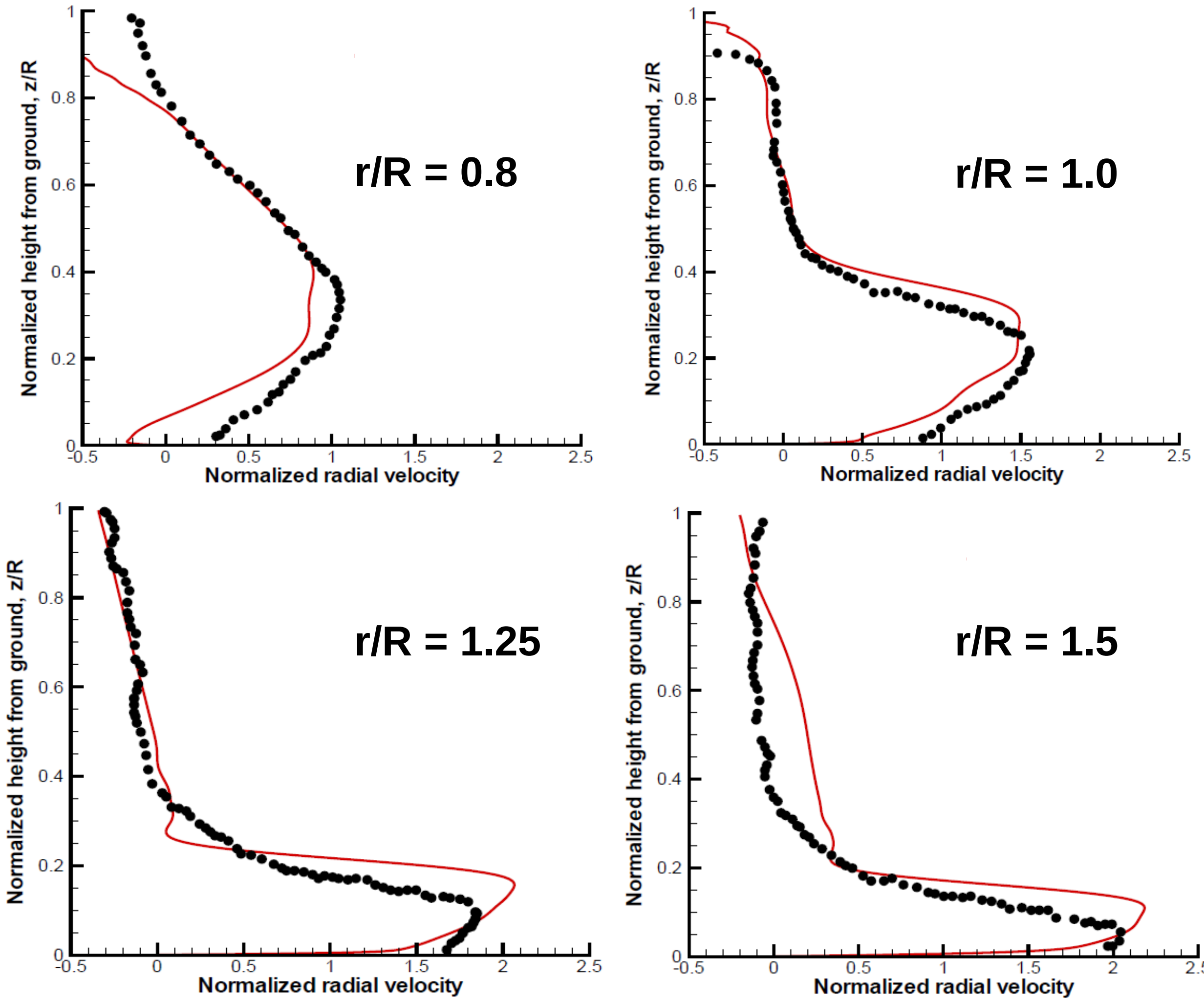




Computational, $\Psi = 60^o$ **Experimental, $\Psi = 60^o$**

- **Good agreement of vortex positions**
- **Increased wandering in experiment increases effective core size**

Time-Averaged Radial Velocity, h/R = 1.0



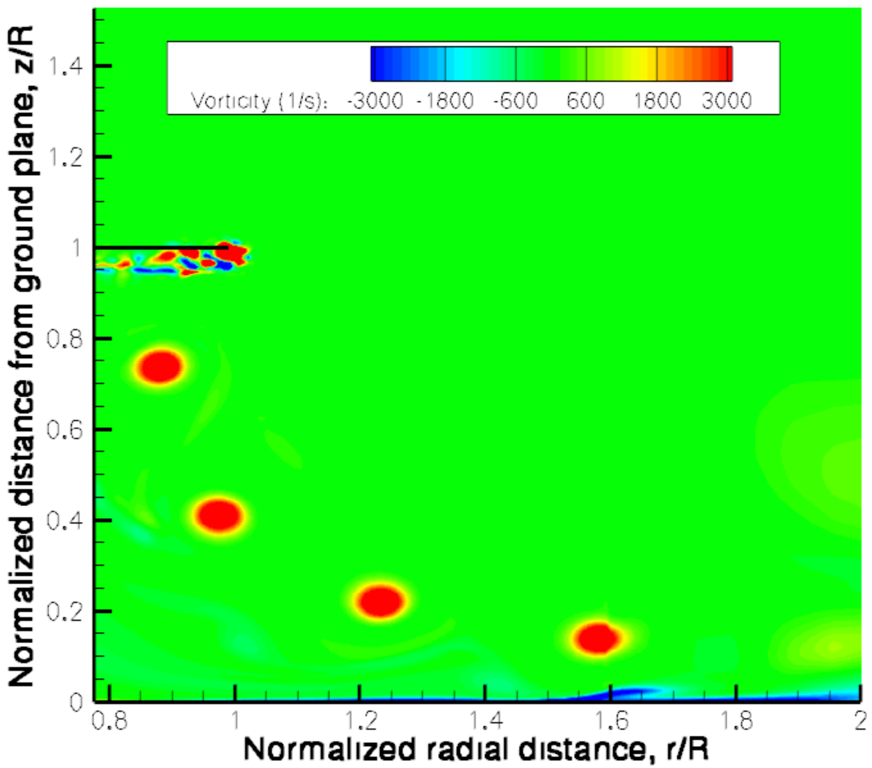
Computational

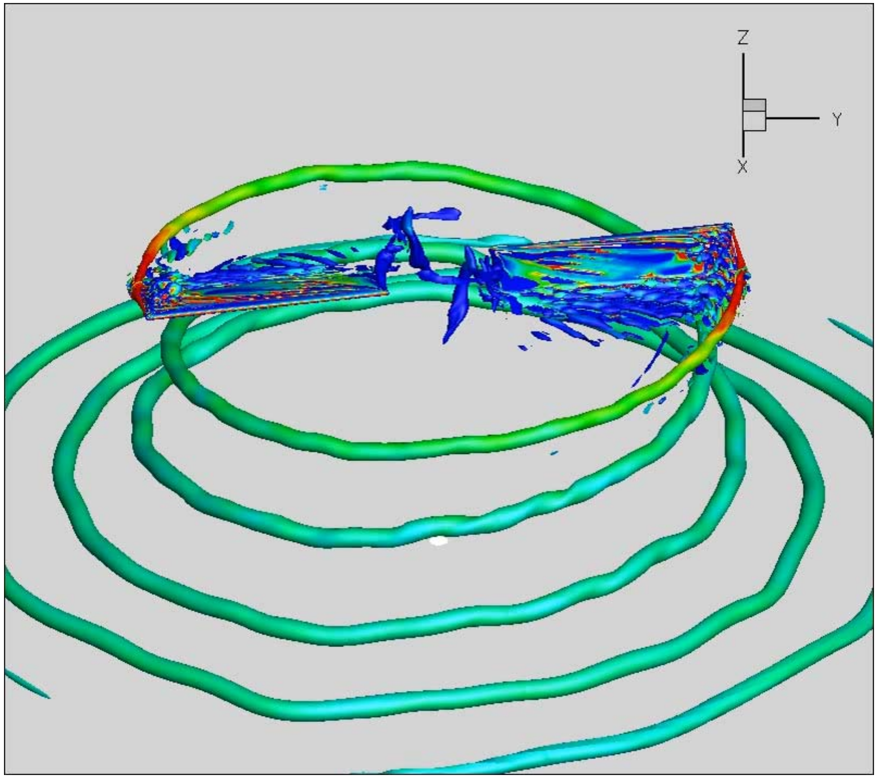
Experimental

Good comparison, especially at inboard locations

Flow Visualization, h/R = 1.0

Vorticity Contour





Iso-surface of q-criterion, q = 4.0

- Tip vortex resolved for over 2+ rotor revolutions
- Development of instabilities

Micro-Scale Coaxial Rotor

Experimental Setup (Micro-Scale Coaxial Rotor)

Two 2-bladed rotor setup of Bohorquez and Pines

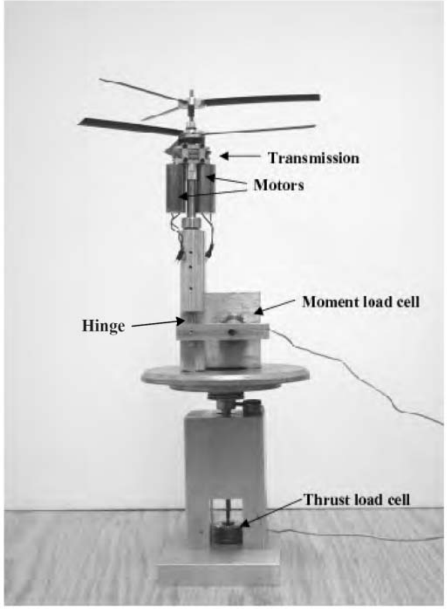
- ➔ Untwisted rectangular
- ➔ Aspect Ratio of 4.98
- ➔ Collective setting of 16°

Airfoil profile

- ➔ Circular Arc with sharp leading and trailing edge
- ➔ 2.2% Thickness
- ➔ 6% Camber

Flow conditions

- ➔ RPM → 1900 to 2700
- ➔ Re_{tip} → 19,000 to 27,000
- ➔ M_{tip} → 0.0665 to 0.0945



Experimental setup

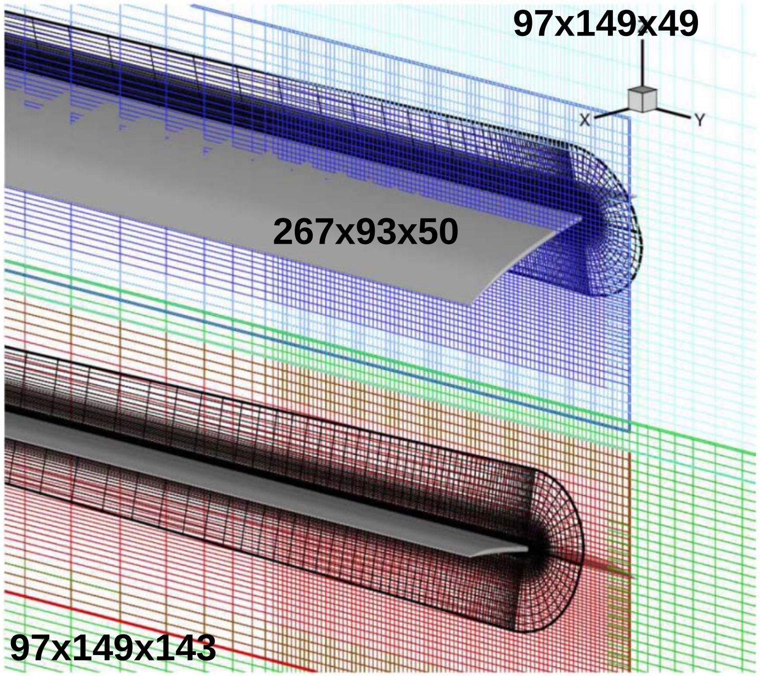
Bohorquez and Pines (Univ of Maryland)

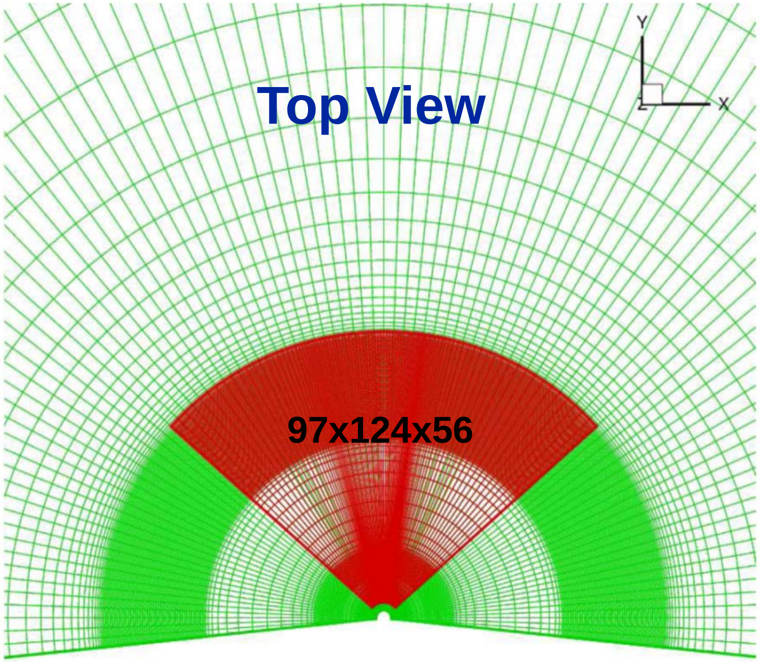
Torque balanced by adjusting bottom rotor RPM

- ➔ Percentile difference less than 2%

Computations performed assuming identical RPM

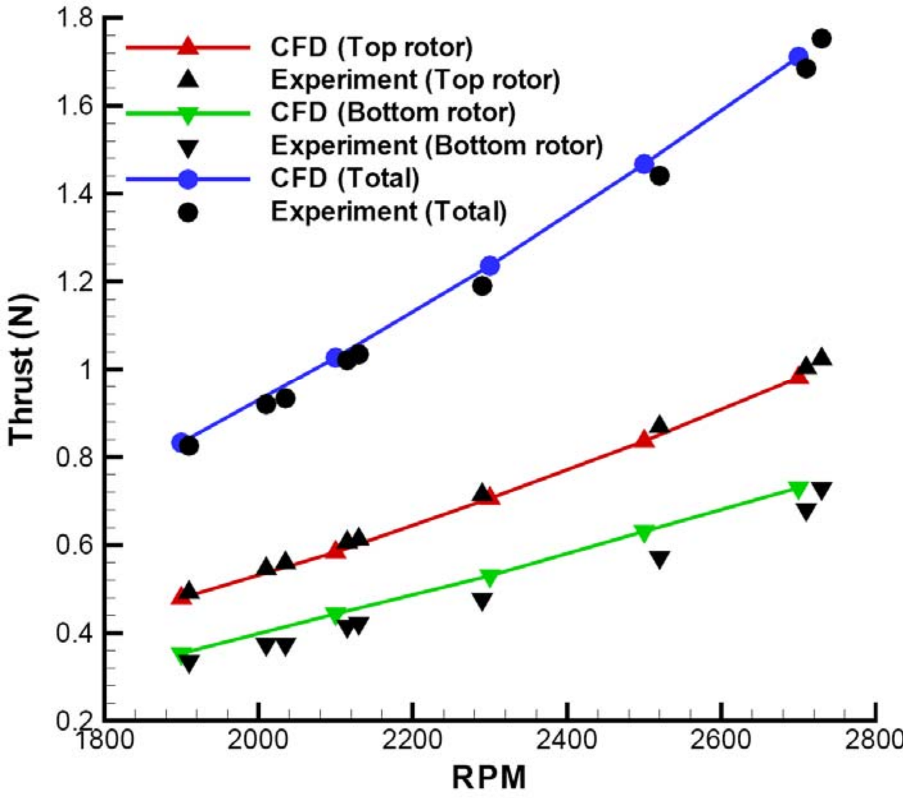
Mesh System

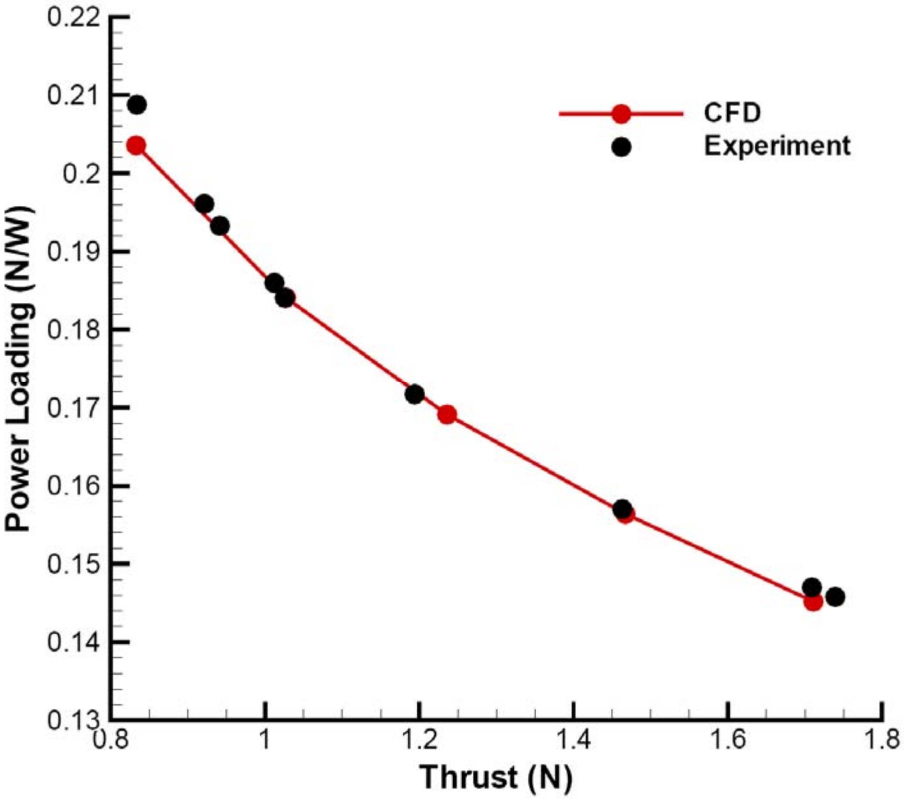




- **Total mesh points ~ 6.6 million**
- **In most refined regions**
  - ➔ Δr = 0.025 chords, Δz = 0.02 chords, $\Delta\psi = 0.3^o$,inner background
  - ➔ Δr = 0.025 chords, Δz = 0.04 chords, $\Delta\psi = 2^o$,outer background

Effect of RPM (h/R = 0.446)





Performance well predicted

Effect of Rotor Spacing (Mean Thrust)

h/R	C_T (top rotor)	C_T (bottom rotor)	C_T (total)	$C_{T_{top}}/C_{T_{total}}$	$C_{T_{total}}$ (Expt.)
0.268	0.0199	0.0163	0.0362	0.55	0.0349
0.357	0.0205	0.0158	0.0363	0.56	0.0349
0.446	0.0208	0.0157	0.0365	0.57	0.0350
0.536	0.0210	0.0155	0.0365	0.58	0.0350
0.625	0.0212	0.0153	0.0365	0.58	0.0350

- **As rotor spacing increases**
  - ➔ Induced inflow on top rotor decreases
  - ➔ Inflow on bottom rotor increases

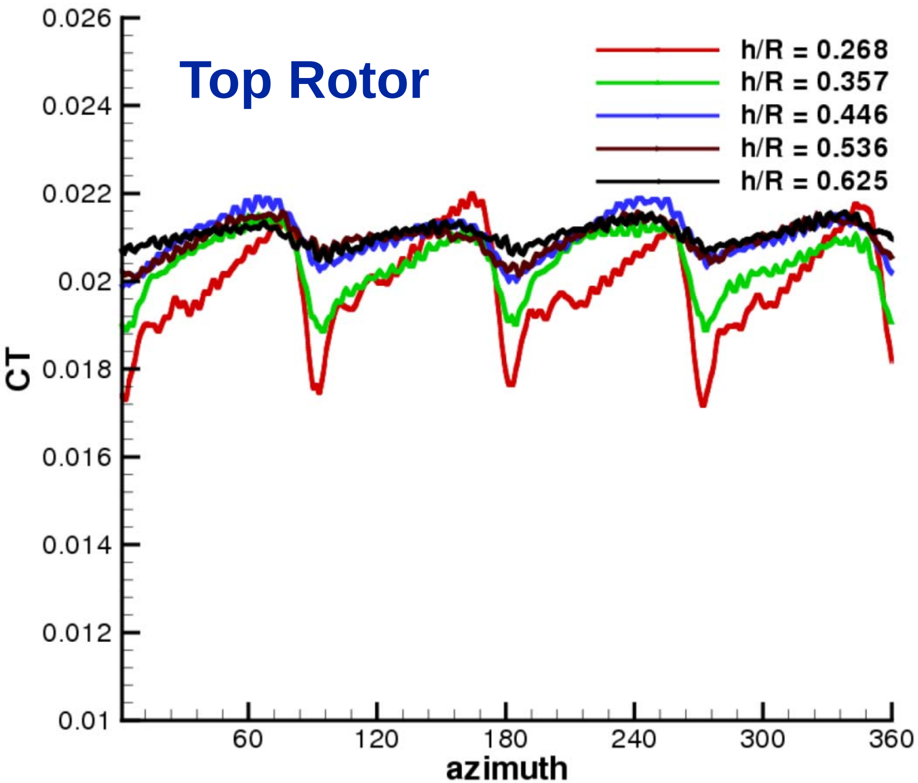
Effect of Rotor Spacing (Unsteady Thrust)

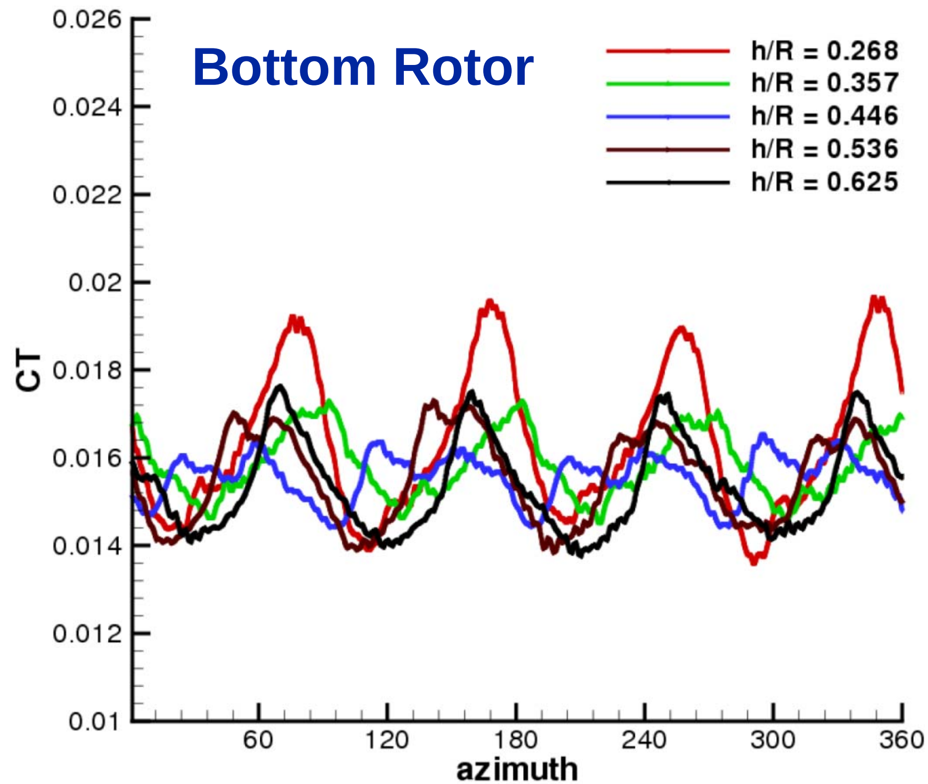
h/R	% fluctuation (top rotor)	% fluctuation (bottom rotor)	% fluctuation (total)
0.268	5.28%	10.06%	6.55%
0.357	3.17%	4.68%	2.04%
0.446	1.92%	3.63%	2.41%
0.536	1.71%	5.87%	3.29%
0.625	1.13%	6.86%	3.21%

- **As rotor spacing increases**
  - ➔ Unsteadiness in top rotor → decreases
  - ➔ Unsteadiness in bottom rotor → No trend (Different from full-scale)
- **3 – 8% fluctuation**
  - ➔ Significant for vibration and acoustic characteristics

Challenging to capture unsteadiness in experiments

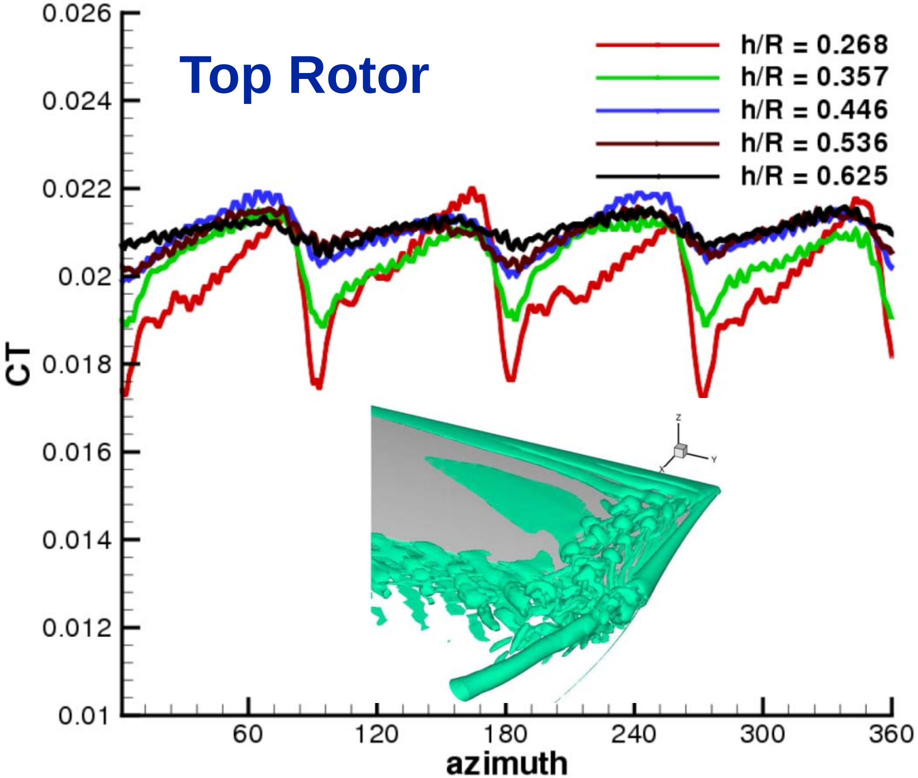
Temporal Variation of Thrust

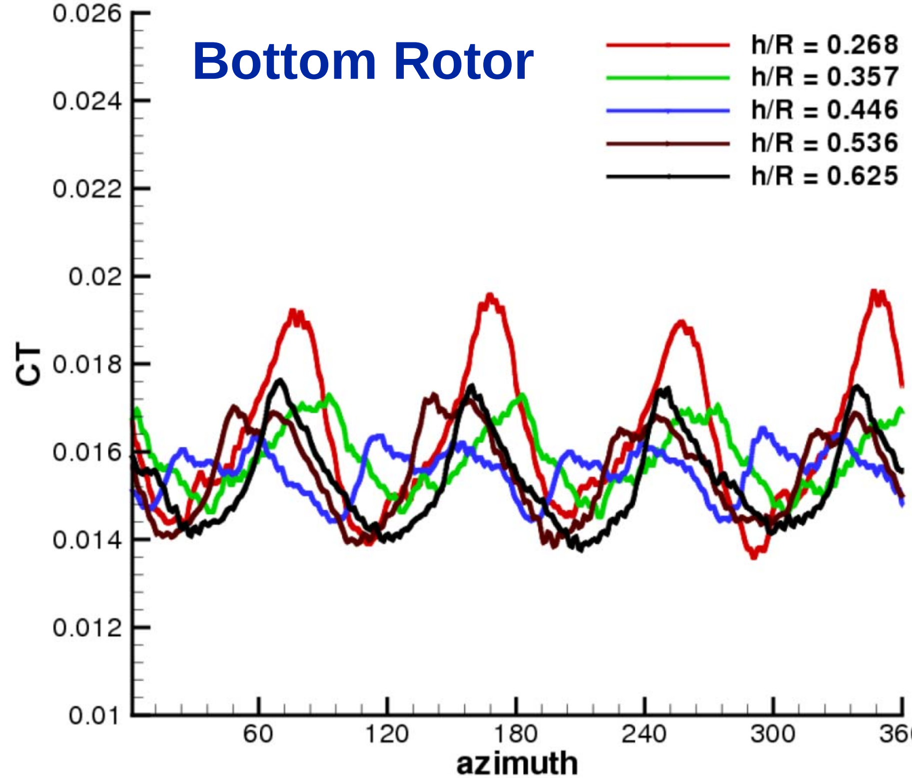




- **Dominant 4/rev frequency**
- **Unsteadiness caused by**
  - ➔ Loading effect
  - ➔ Wake effect
  - ➔ Shedding near trailing edge → High frequency unsteadiness

Temporal Variation of Thrust





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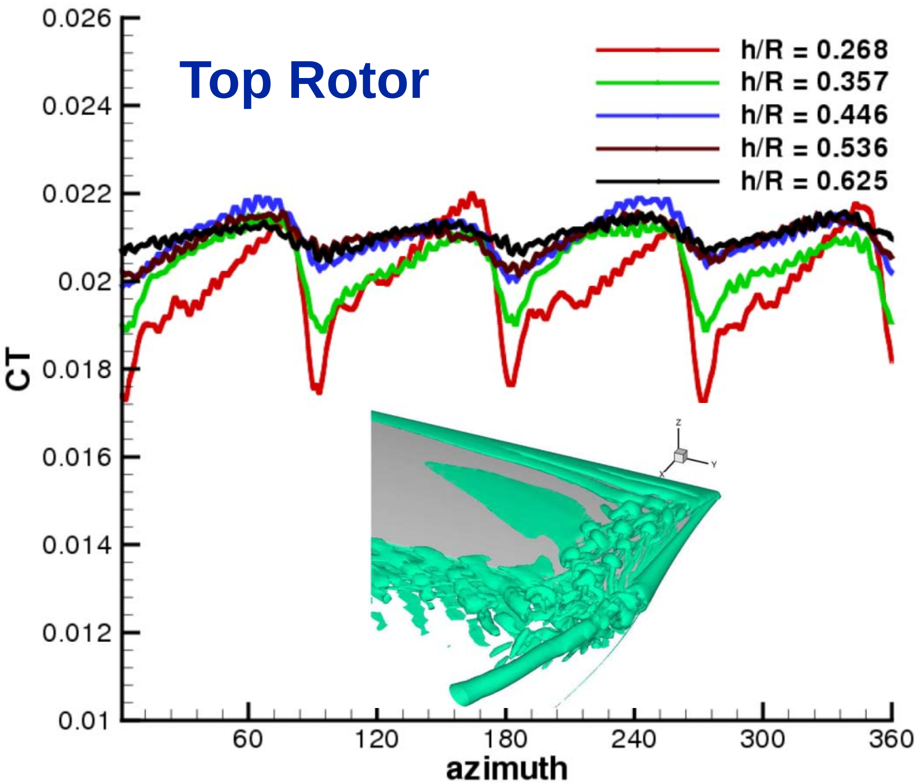

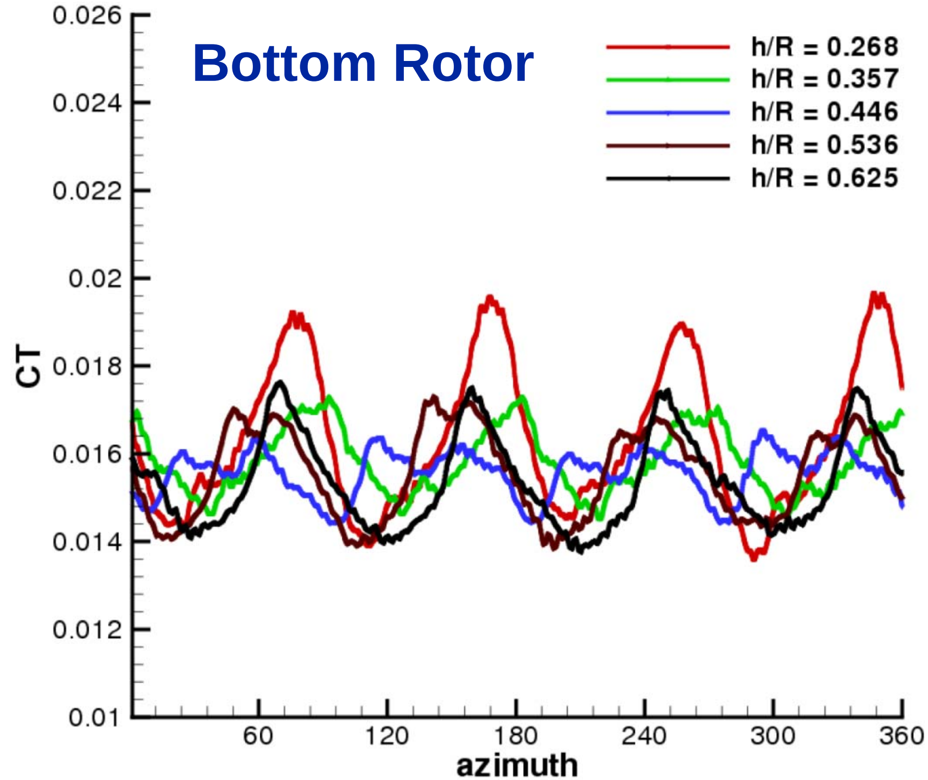

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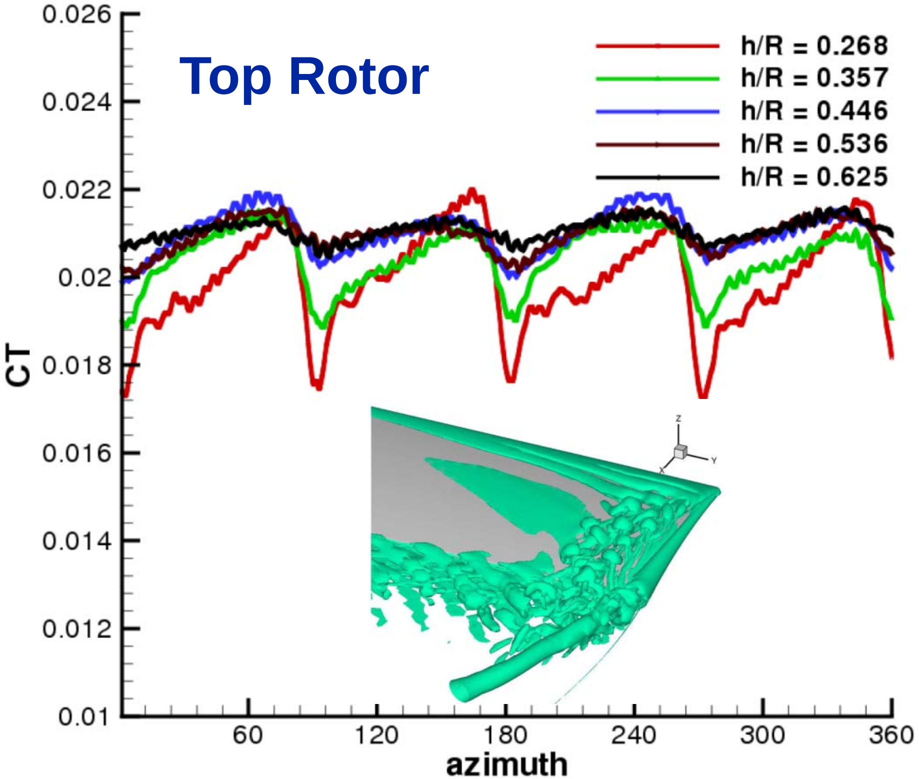
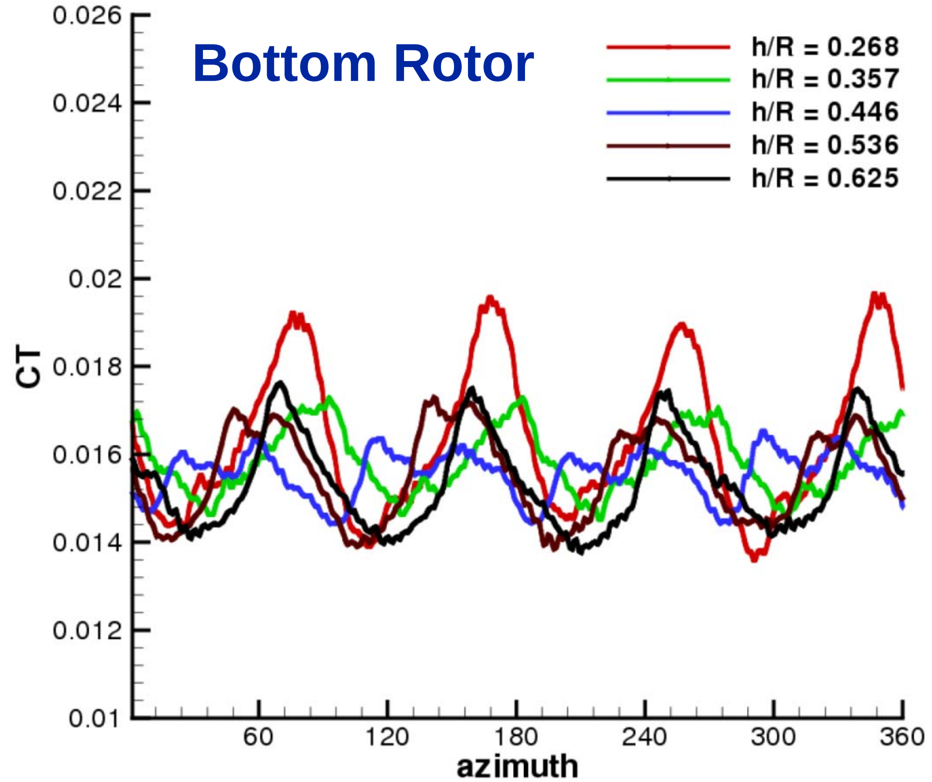
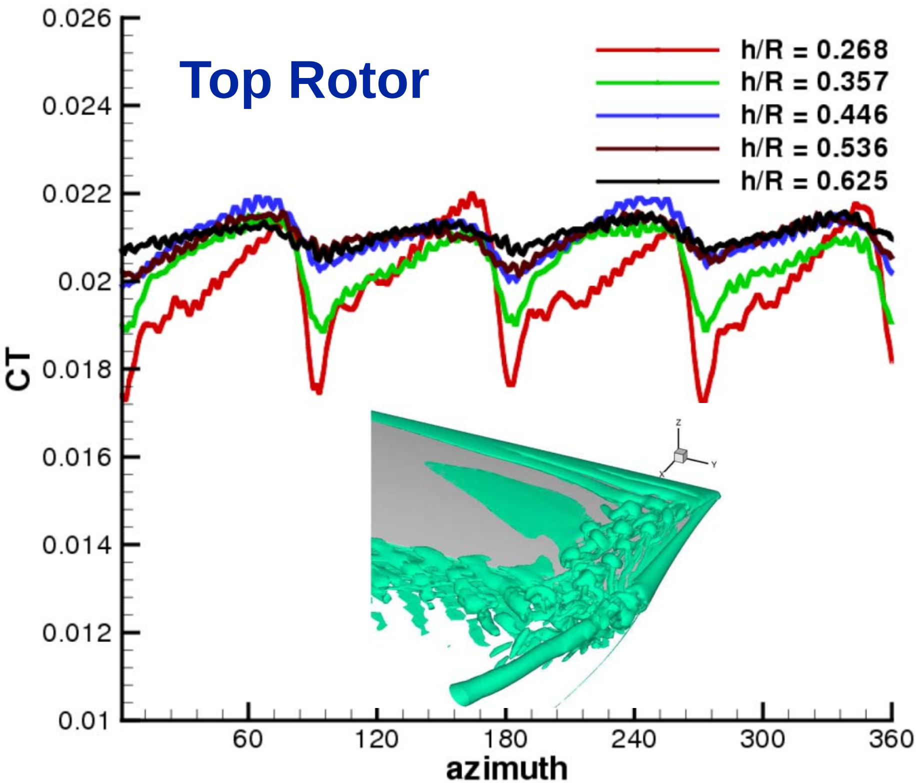
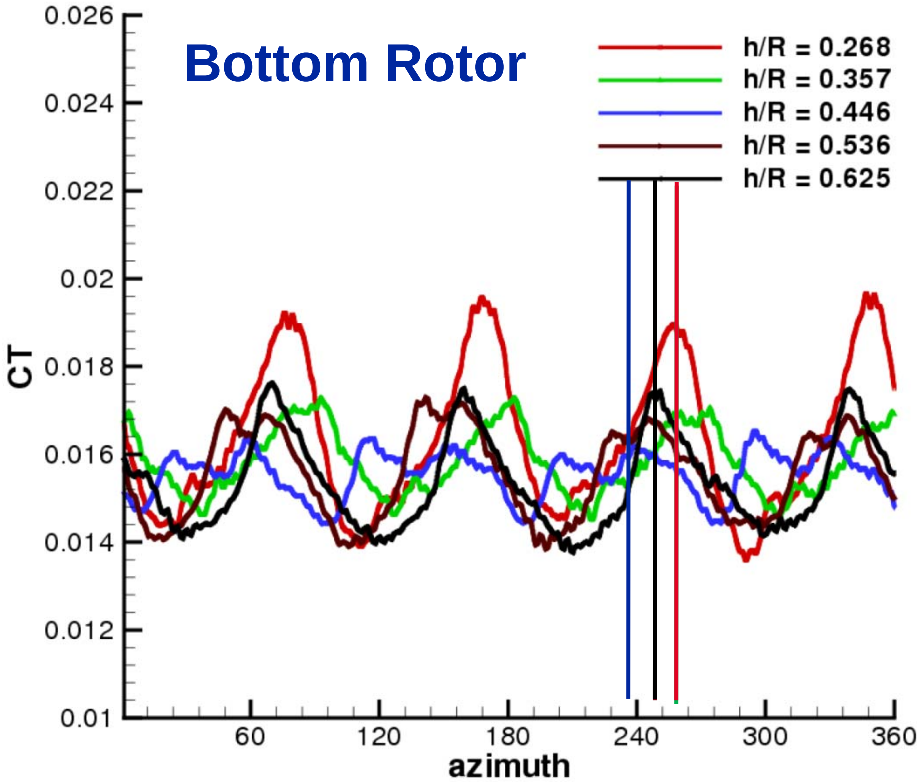




- **Two Peaks**
  - ➔ Loading effect
  - ➔ Vortex impingement

Temporal Variation of Thrust





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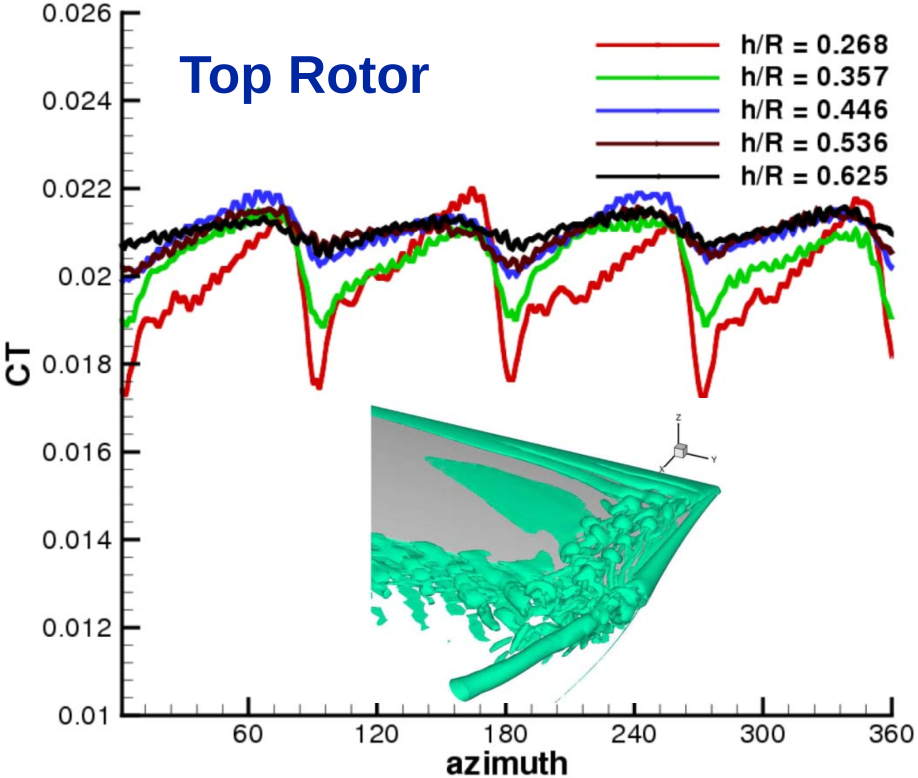

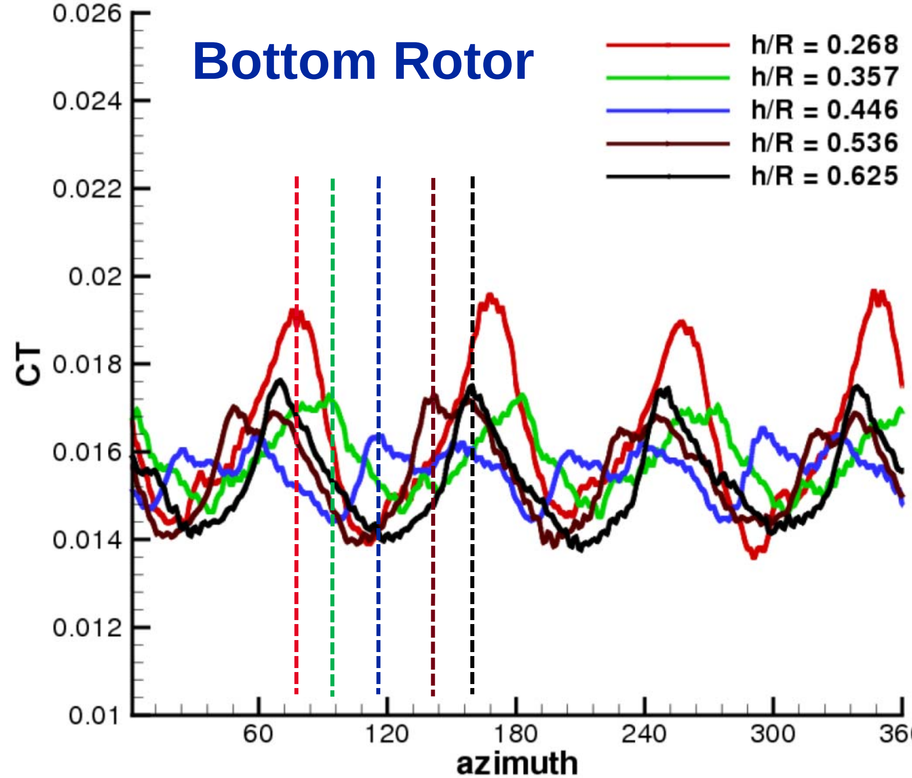

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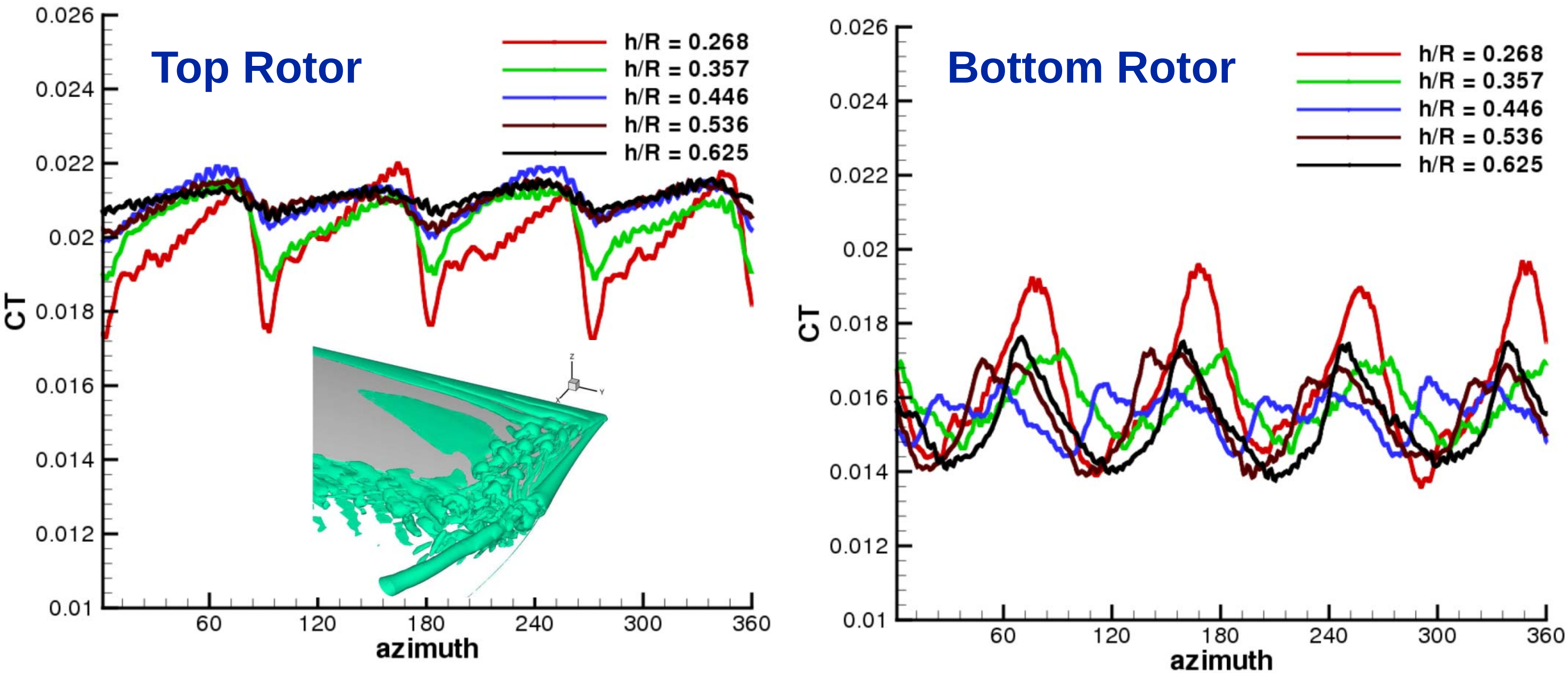
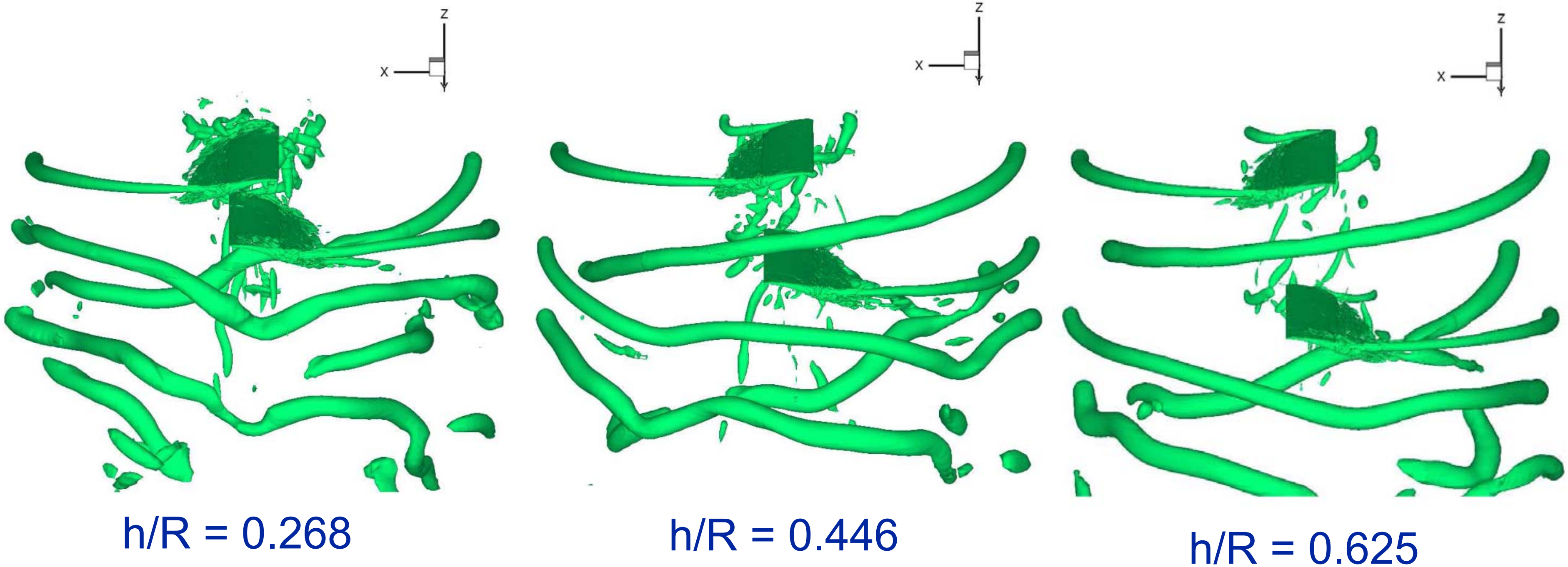


- **Phasing of vortex impingement is significant**
  - ➔ When peaks coincide, large unsteadiness
  - ➔ When peaks are farthest apart, smaller unsteadiness

Wake Trajectory



Iso-surface of q-criterion, q = 0.2

- **Tip vortex resolved for 2-blade passage**
- **Significant interaction between top and bottom rotor wake**
- **Straining in the top rotor vortices as it passes bottom rotor**

Micro-Scale Shrouded Rotor

Micro-Scale Shrouded Rotor

Setup of **Hrishikeshavan and Chopra**

Rotor Configuration

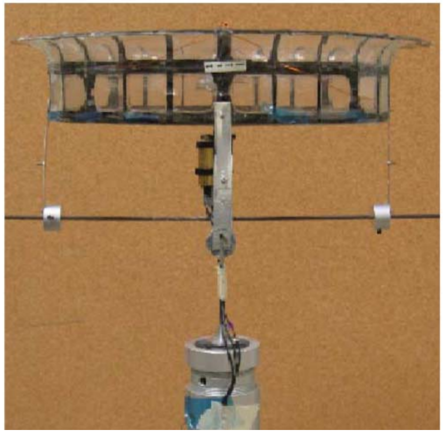
- 2 bladed with 2:1 taper from 60%R
- Aspect Ratio of 4.84
  - 121mm radius and 25mm chord

Airfoil profile

- Circular arc w/ LE sharpened from 8% chord
- 2% Thickness & 10% Camber

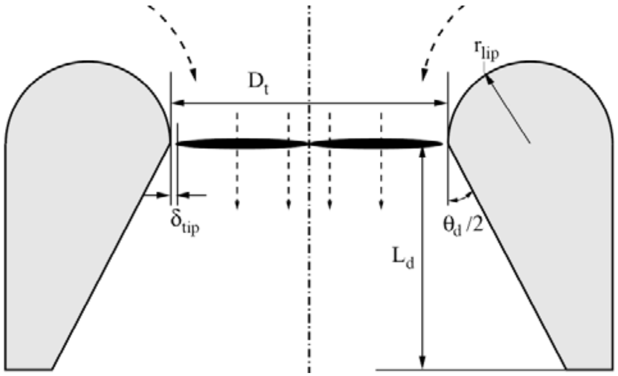
Shroud Configuration

- Throat diameter (D_t)
- Tip clearance (δ_{tip})
- Lip radius (r_{lip})
- Diffuser length (L_d)
- Diffuser angle (θ_d)
- Shape of outer portion of shroud not significant



Experimental setup

- **Hrishikeshavan and Chopra**



Schematic of shroud

Micro-Scale Shrouded Rotor

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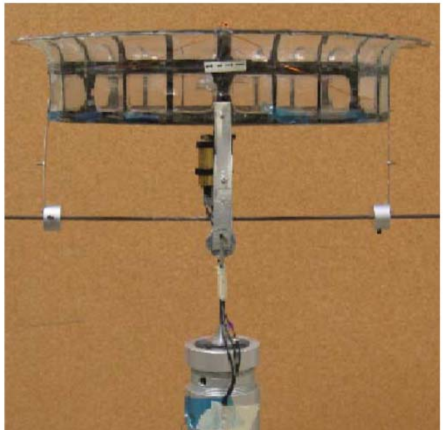
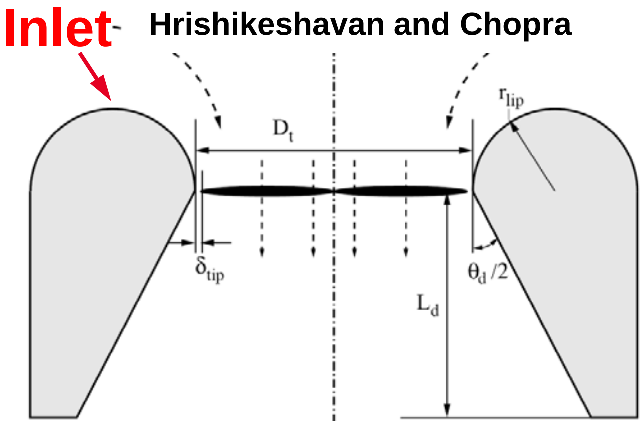


Experimental setup

Hrishikeshavan and Chopra



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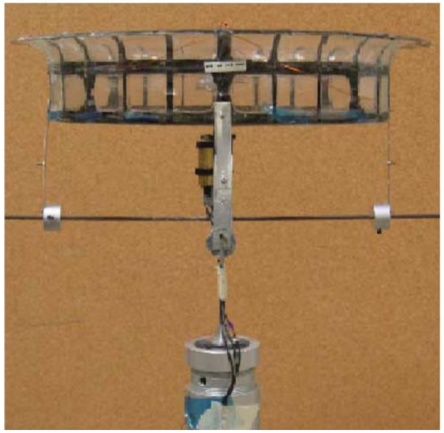
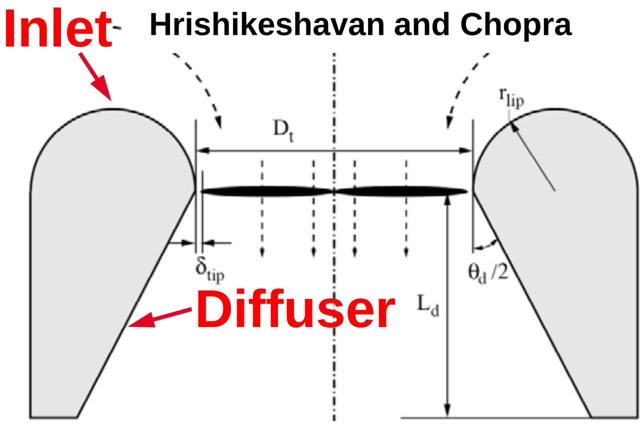


Experimental setup

Hrishikeshavan and Chopra



Schematic of shroud

Micro-Scale Shrouded Rotor

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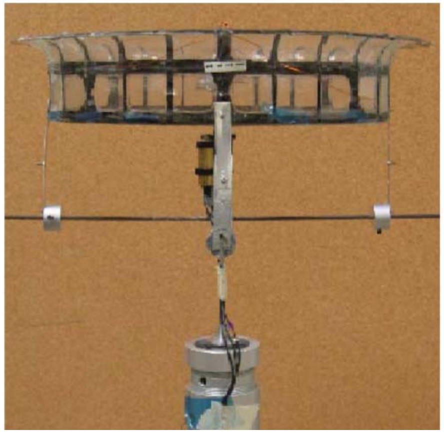
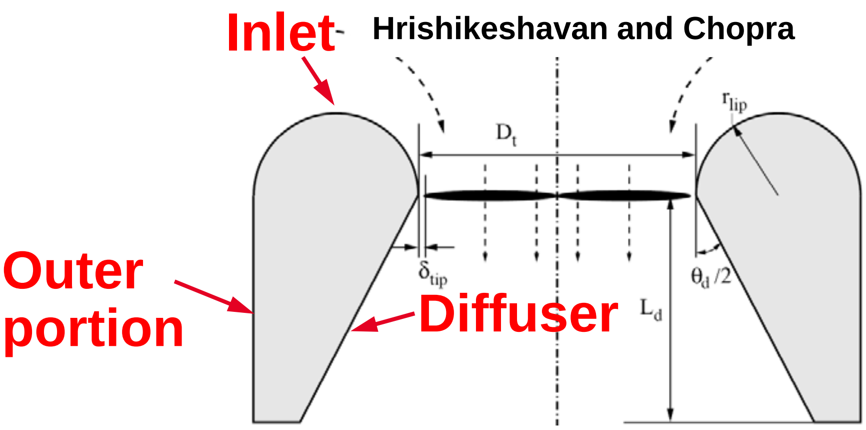


Experimental setup

Hrishikeshavan and Chopra



Schematic of shroud

Micro-Scale Shrouded Rotor

Setup of **Hrishikeshavan and Chopra**

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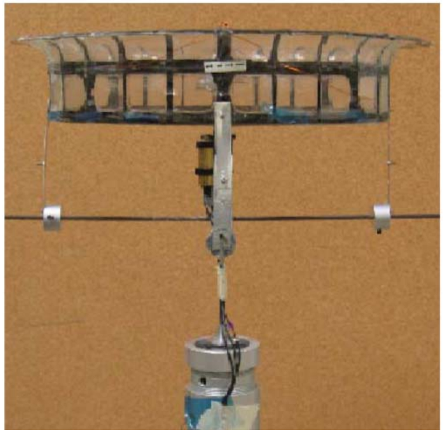
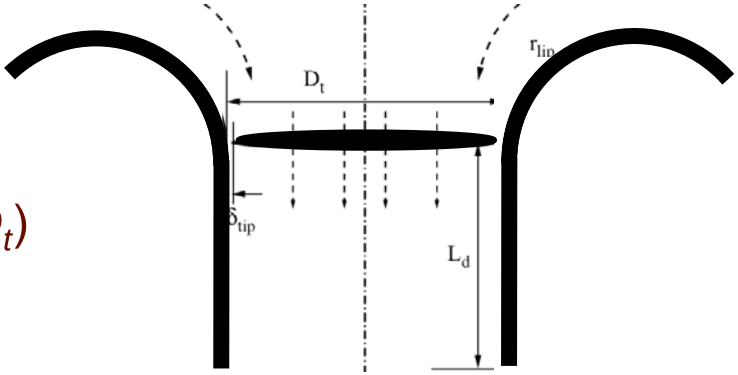


Experimental setup

\- **Hrishikeshavan and Chopra**

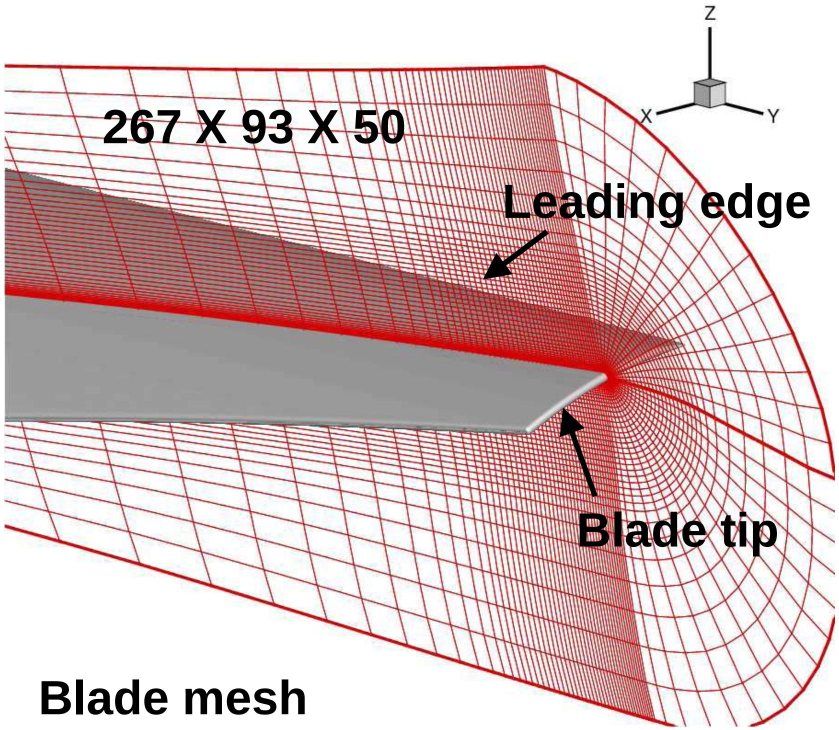
Shroud Configuration

- ➔ Throat diameter (D_t) → 247mm
- ➔ Tip clearance (δ_{tip}) → 2.5mm (~1% D_t)
- ➔ Lip radius (r_{lip}) → 9% D_t
- ➔ Diffuser length (L_d) → 15% D_t
- ➔ Diffuser angle (θ_d) → 0^o
- ➔ Shape of outer portion of shroud not significant

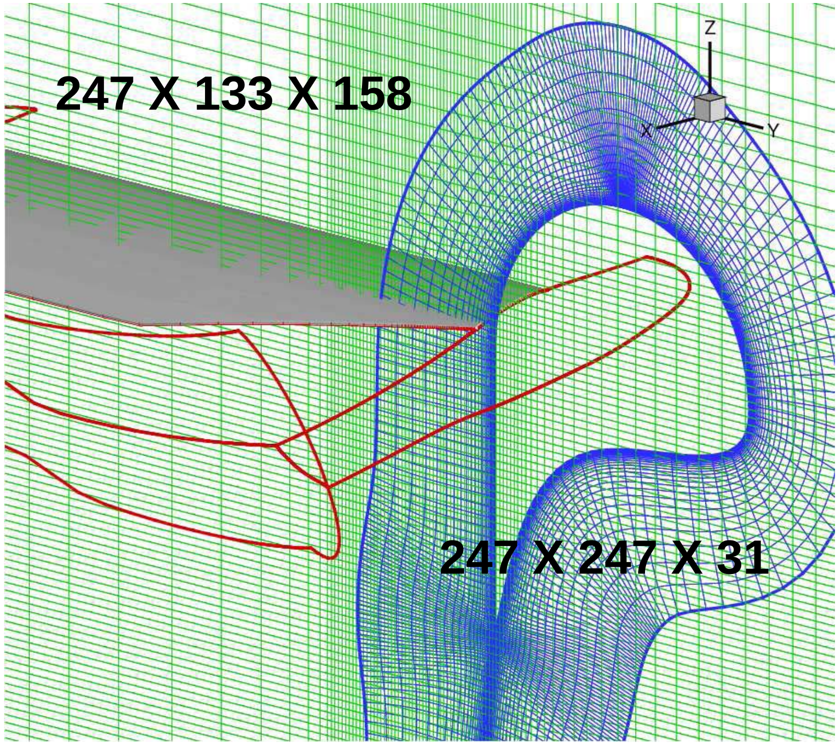


Schematic of shroud

Mesh System



Blade mesh

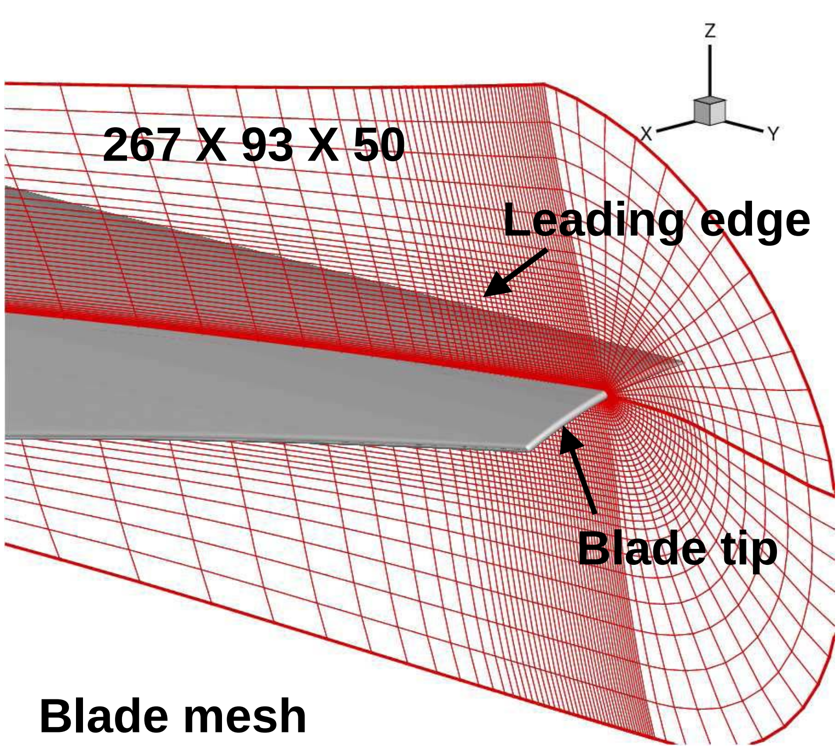


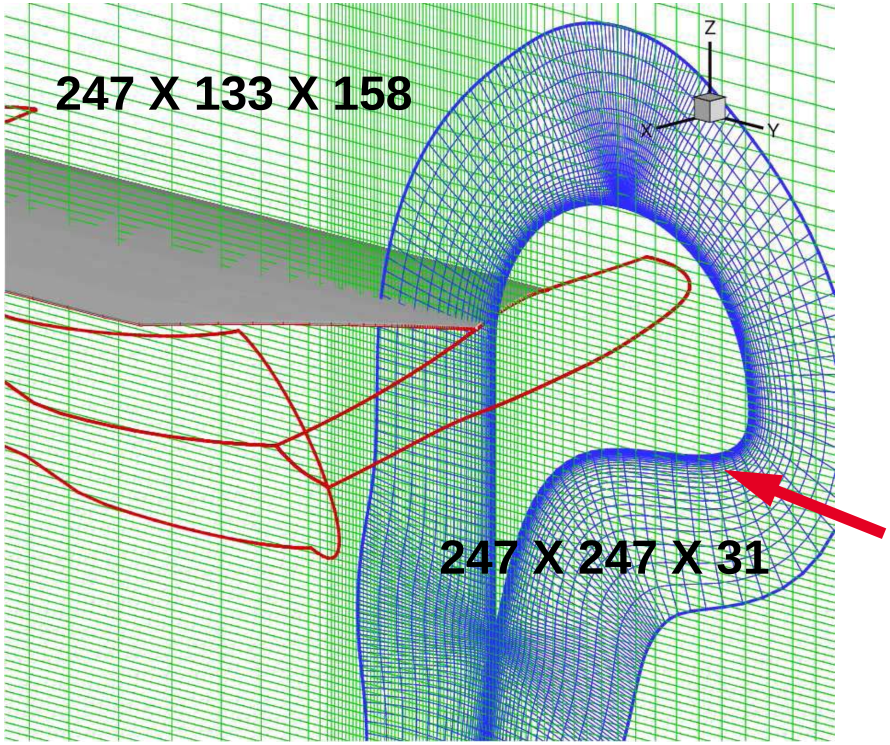
Background and shroud meshes

- **Total mesh points ~ 10 million**
- **In most refined regions**

➔ $\Delta r = 0.025$ chords, $\Delta z = 0.04$ chords, $\Delta\psi = 1.5^o$, background

Mesh System





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- **Total mesh points ~ 10 million**
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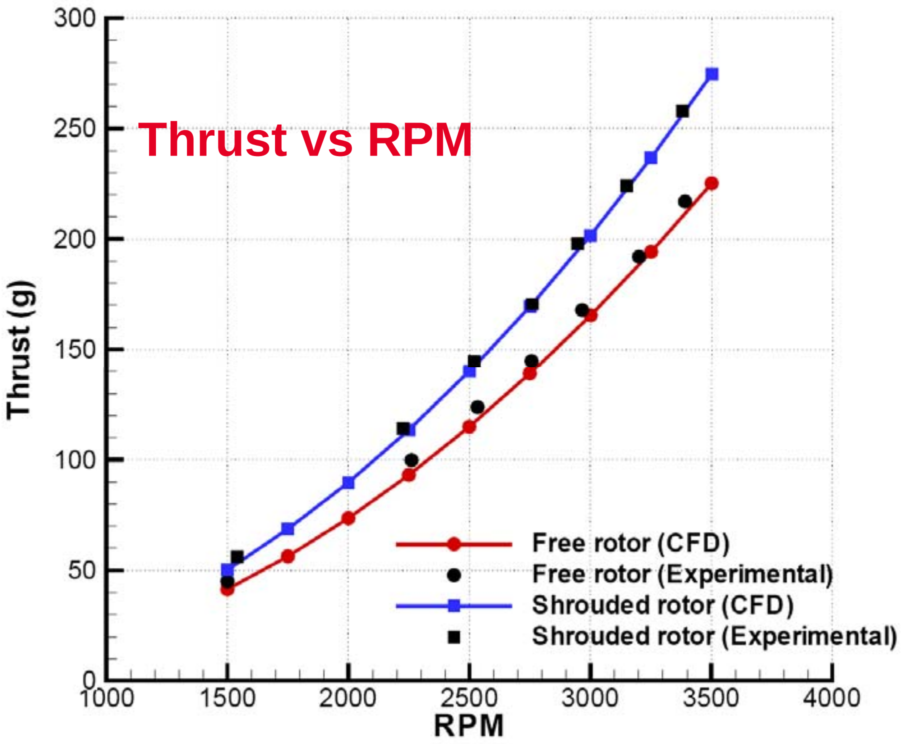
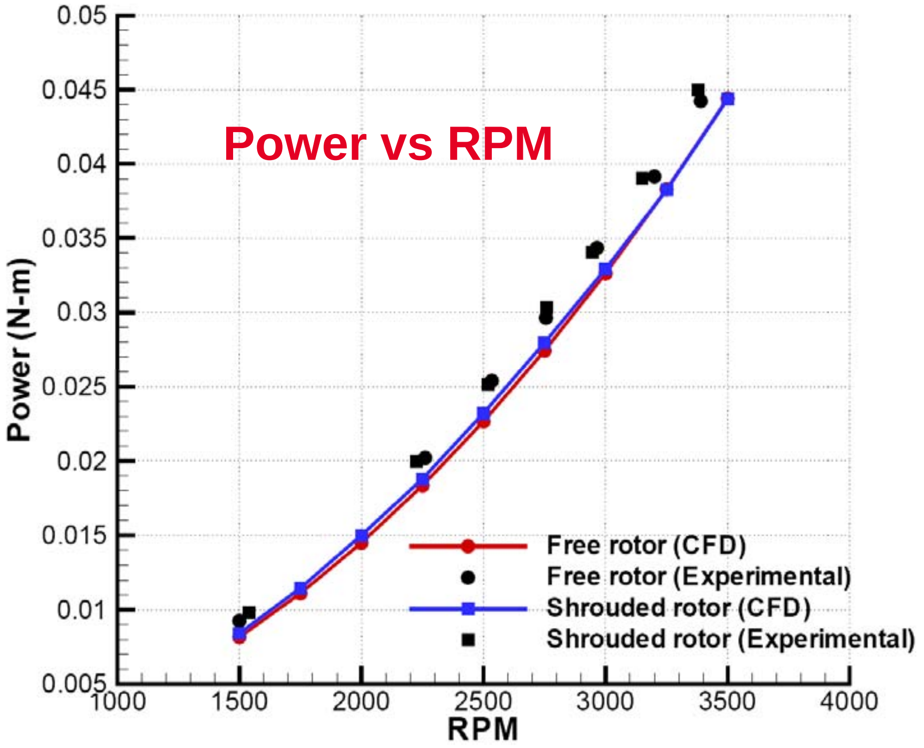
Outer portion of shroud closed to allow C-type mesh

Performance Comparison with Experiments

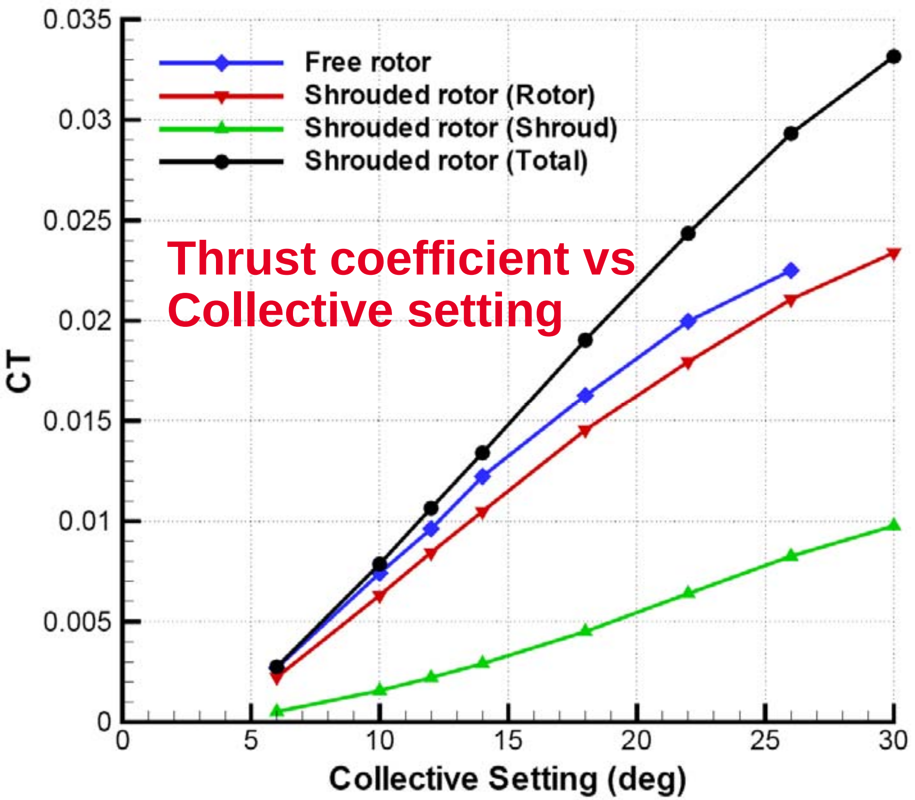
- Collective angle → 22°
- Tip Reynolds number → 30,000 to 70,000
- Tip Mach number → 0.056 to 0.131

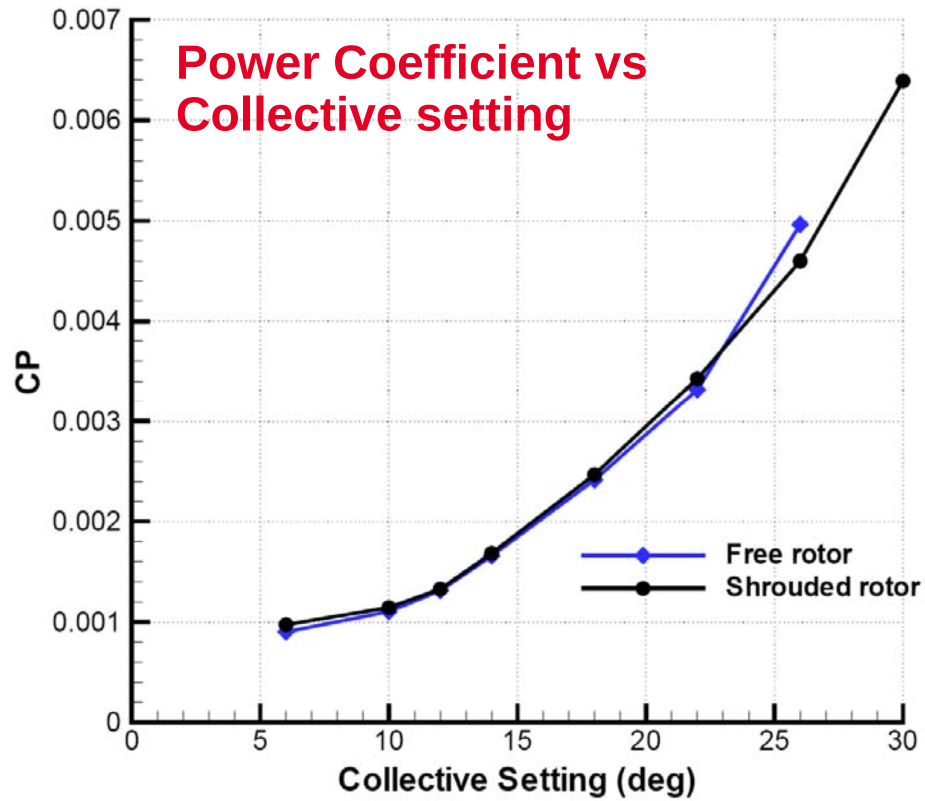




Good comparison between CFD and experiment

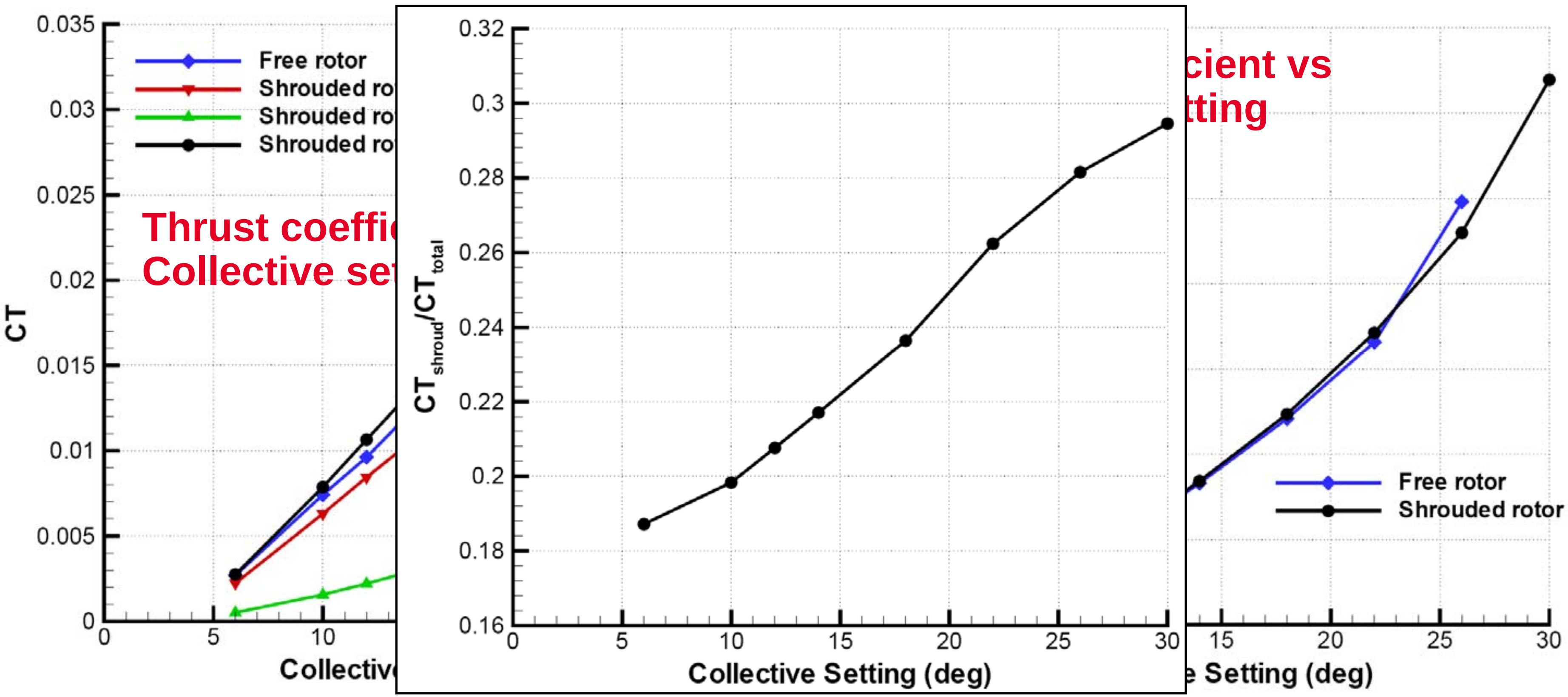
Collective Angle Sweep (2500 RPM)





- **Shrouded rotor performance as compared to free rotor**
  - ➔ Increased total thrust; decreased rotor thrust
  - ➔ Almost Identical power

Collective Angle Sweep (2500 RPM)



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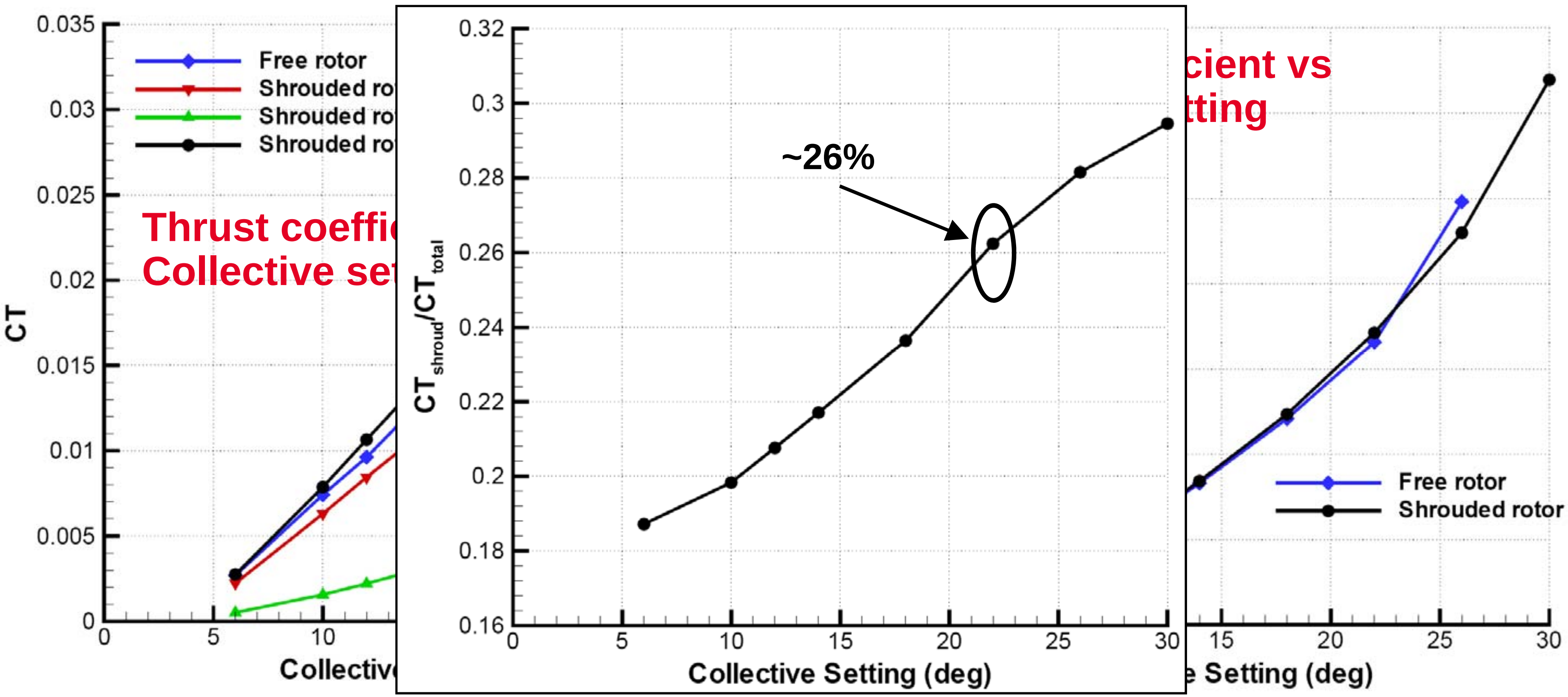

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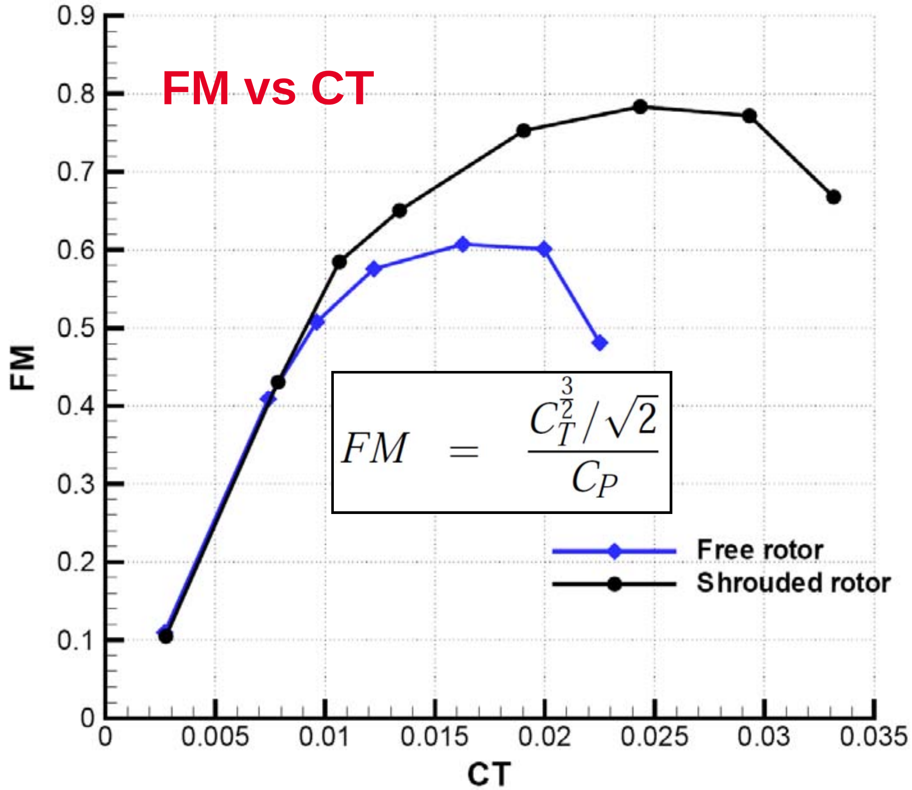
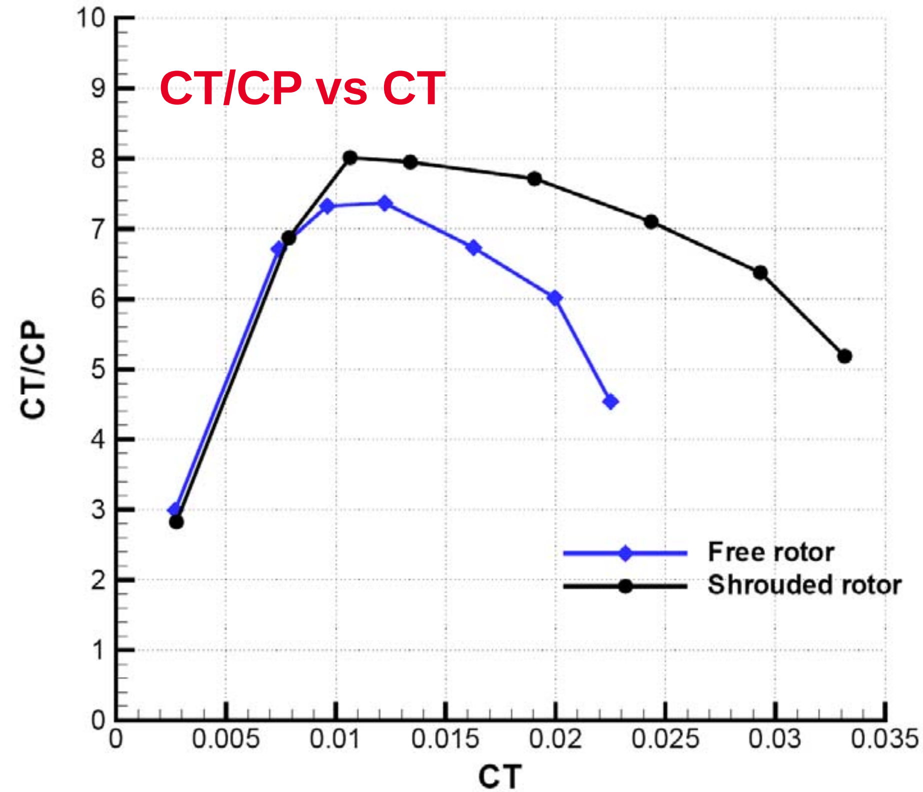
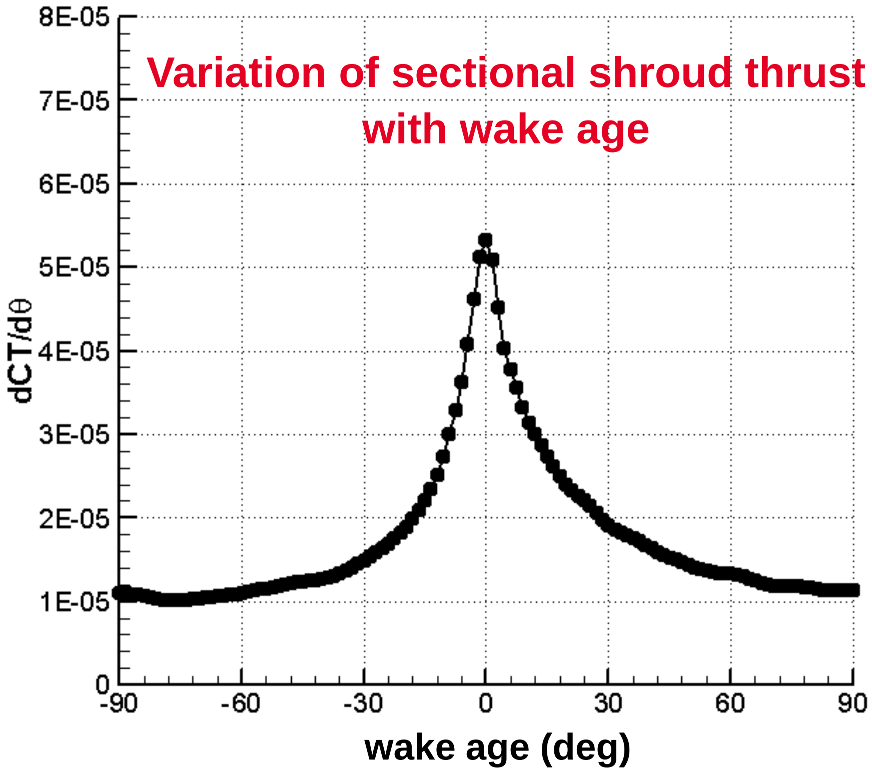
Collective Angle Sweep (2500 RPM) cont…

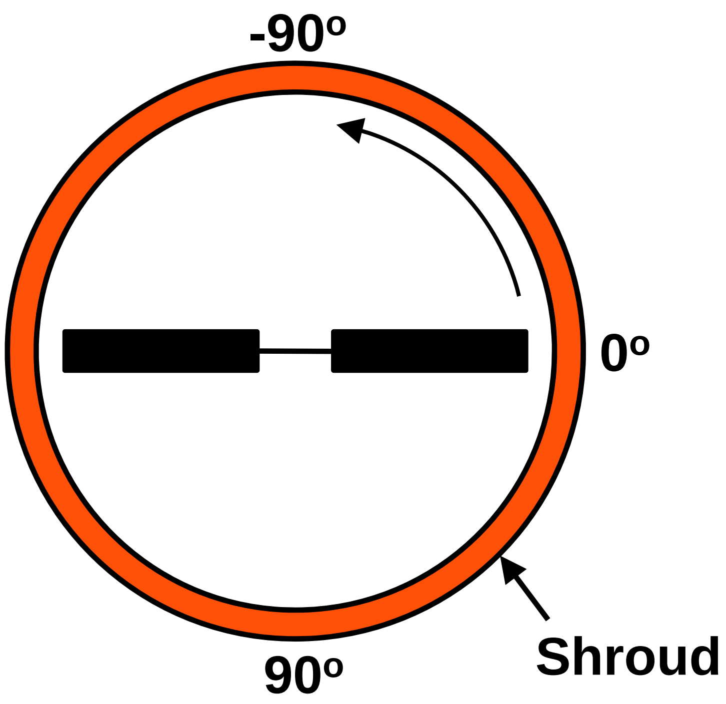




- **Improved performance for shrouded rotor (~25%⬆ in max FM)**
  - ➔ Peak FM achieved at higher thrust coefficient
  - ➔ High FM and CT/CP for larger range of thrust coefficient

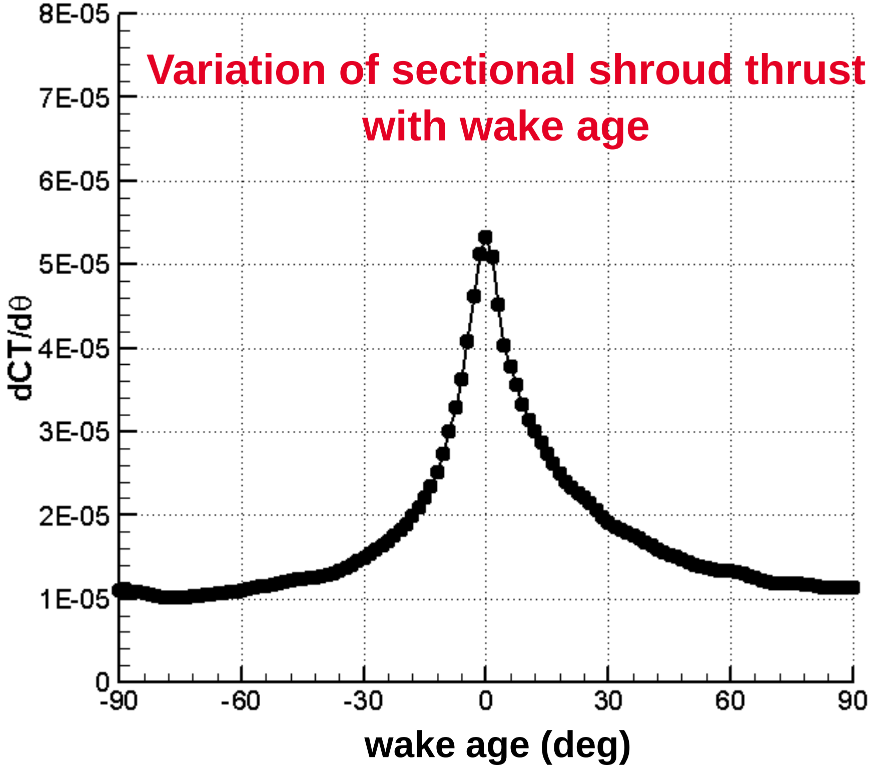
Shroud Performance (22° Collective Setting, 2500 RPM)

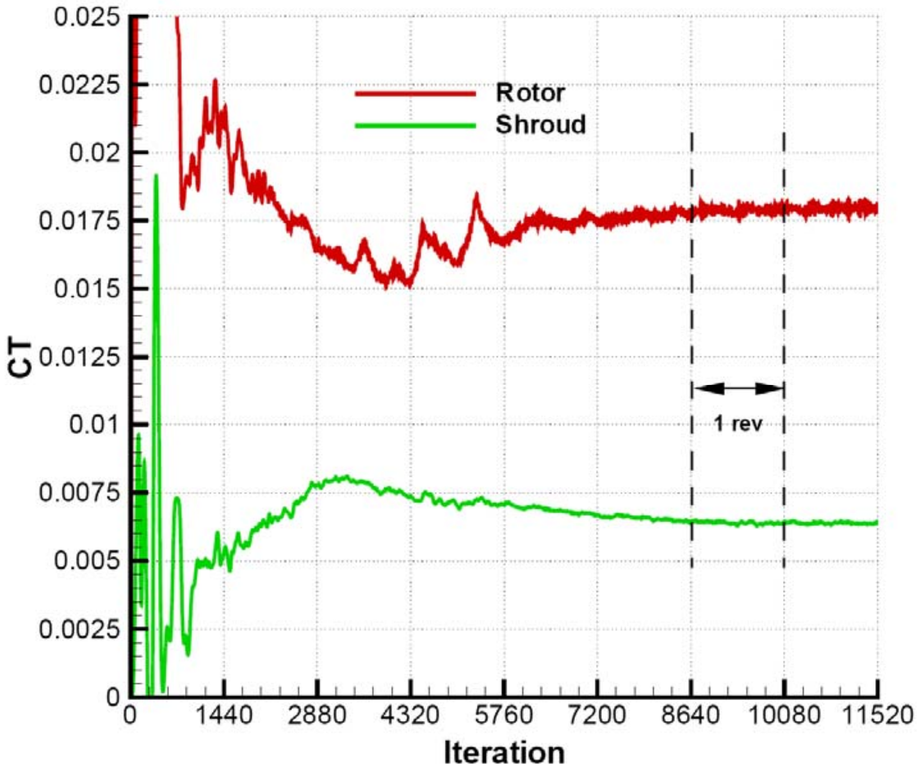




- **Shroud thrust**
  - ➔ Peaks near the blade position

Shroud Performance (22^o Collective Setting, 2500 RPM)

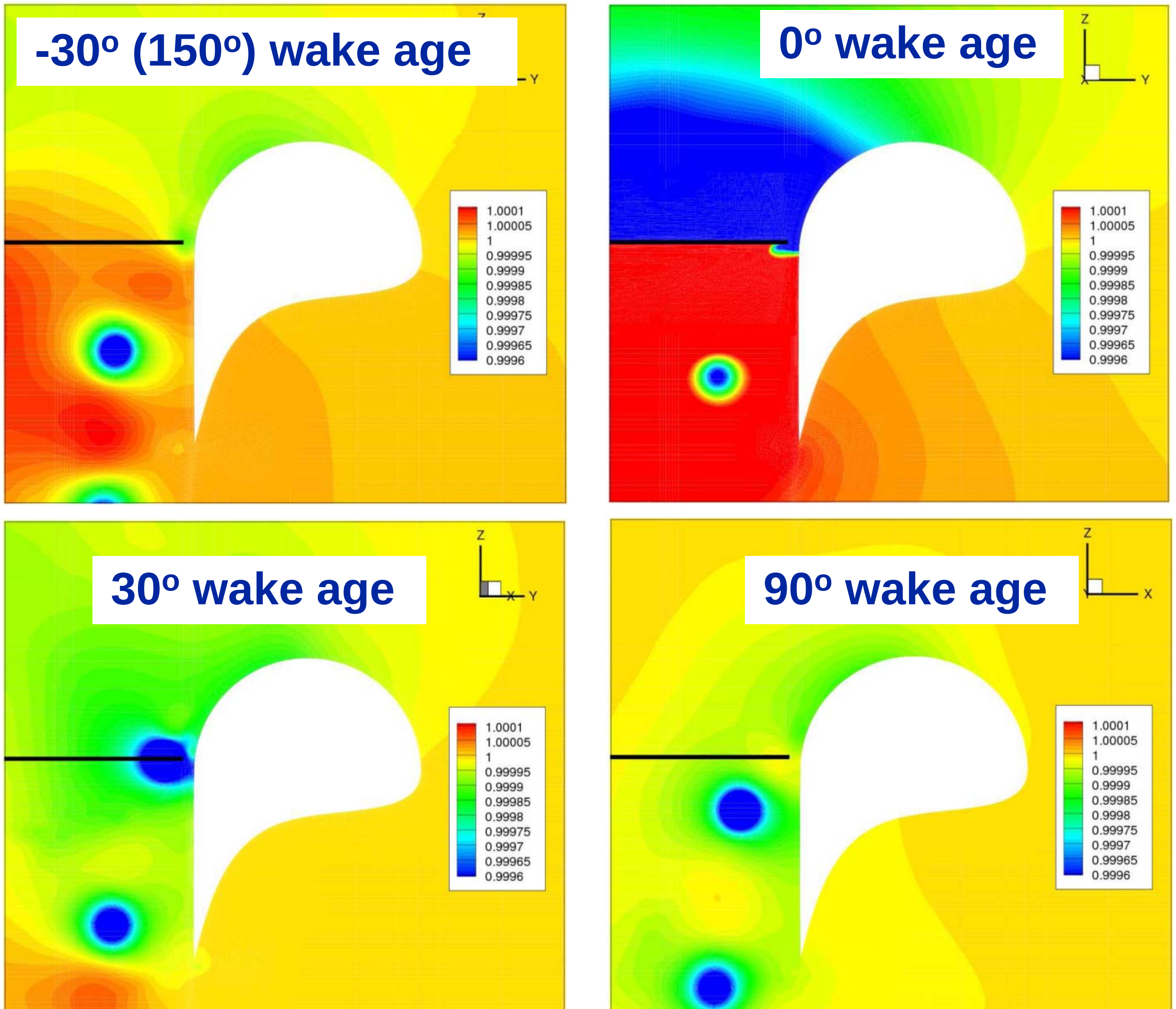




Convergence of rotor and shroud thrusts

Both rotor and shroud thrust remain fairly constant with time

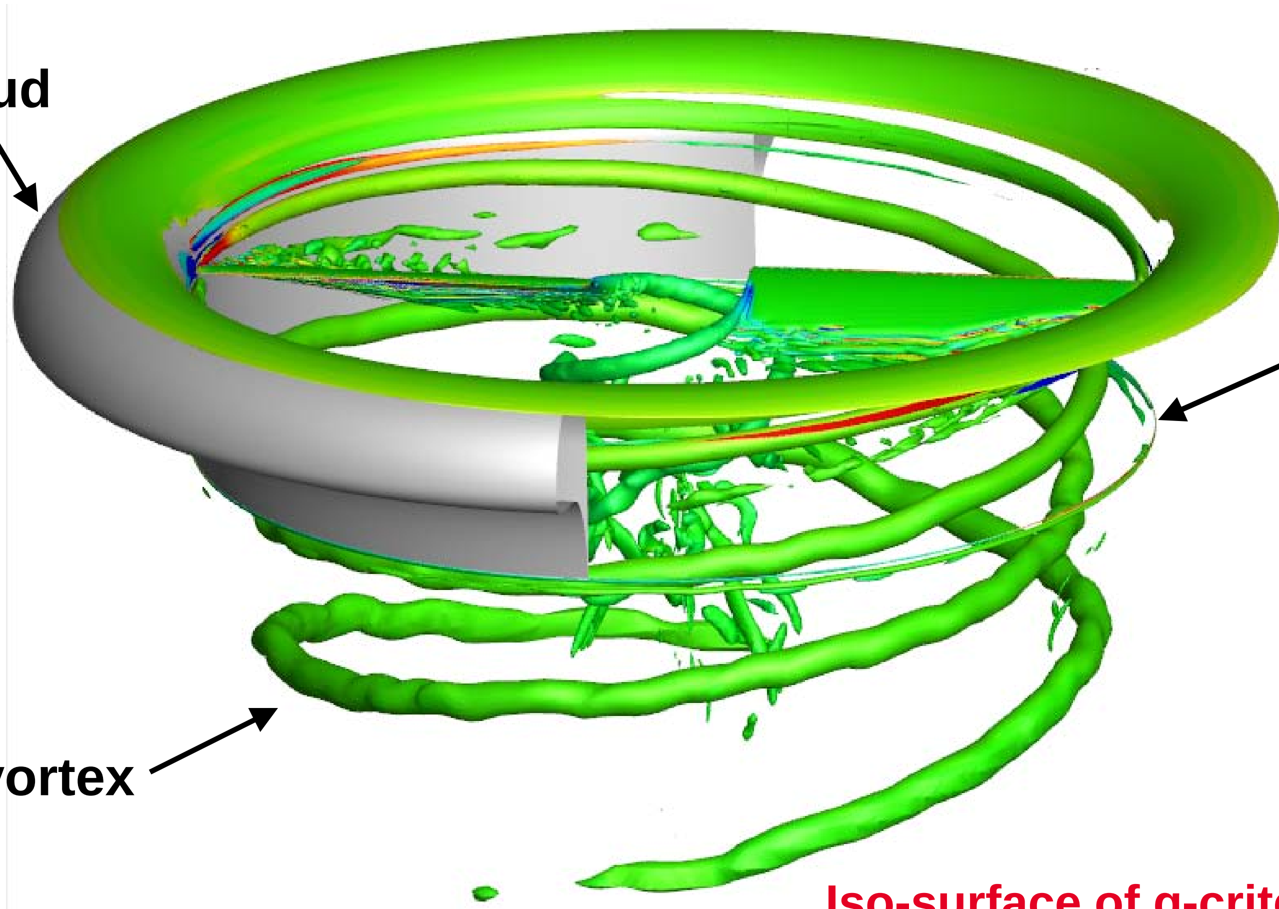
Sectional Pressure Contour (22º Collective Setting, 2500 RPM)



Two thrust producing mechanisms

- ➔ Low pressure created by blade acting on shroud
- ➔ Flow acceleration around shroud inlet producing low pressure
  - → Accelerated by tip vortex

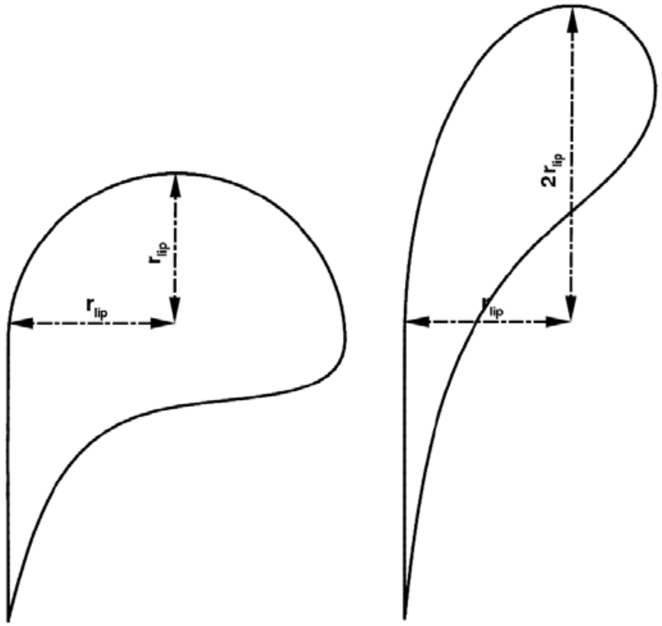
Flow Visualization
(22º Collective Setting, 2500 RPM)



Iso-surface of q-criterion, q = 0.25

Proposed New Shroud Design

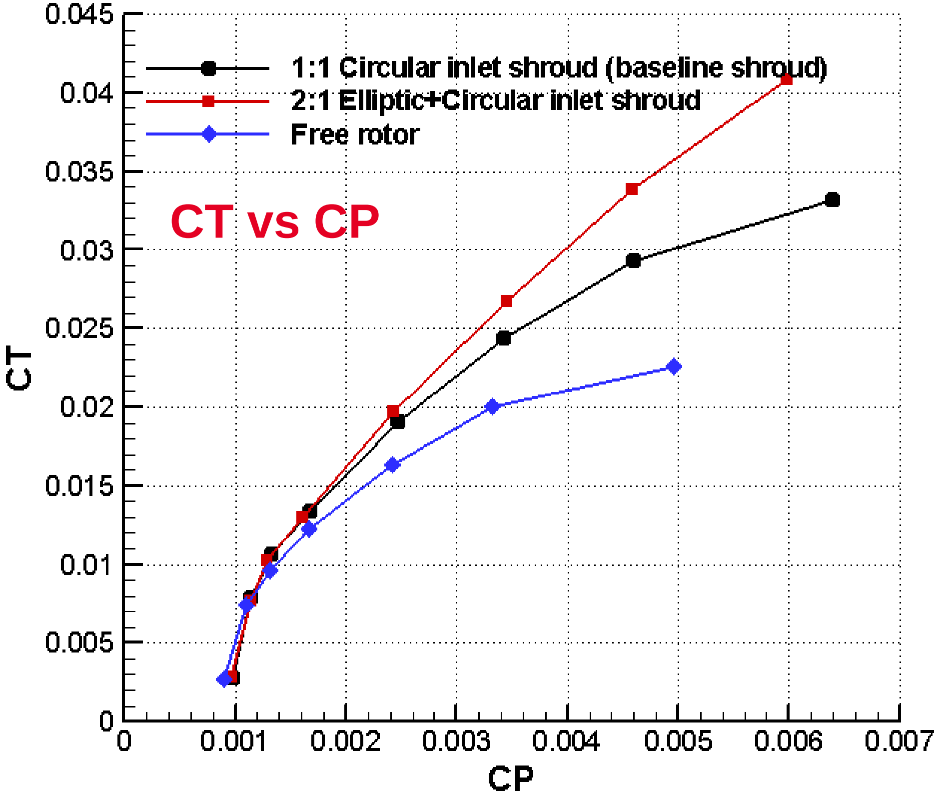
- **Proposed modified shroud which is more aerodynamic from a detailed shroud parametric study**
  - ➔ Inner portion of inlet modified to 2:1 ellipse
  - ➔ At leading edge, ellipse transformed to circle with identical radius
  - ➔ Spline fit to close the trailing edge

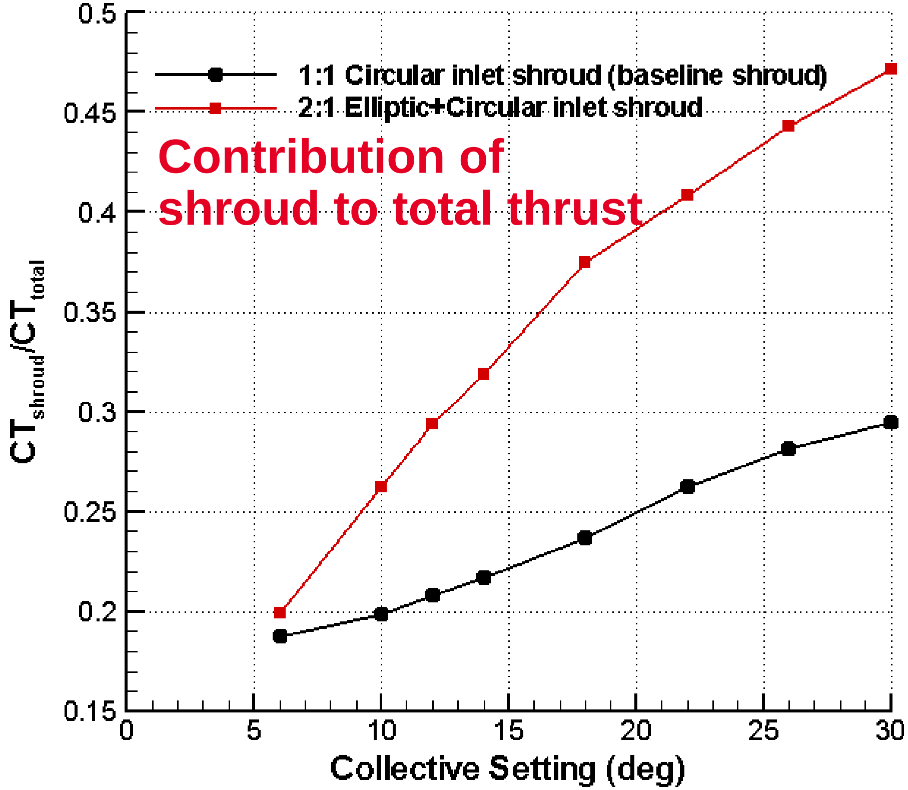


Original Shroud

2:1 Elliptic+Circular Inlet Shroud

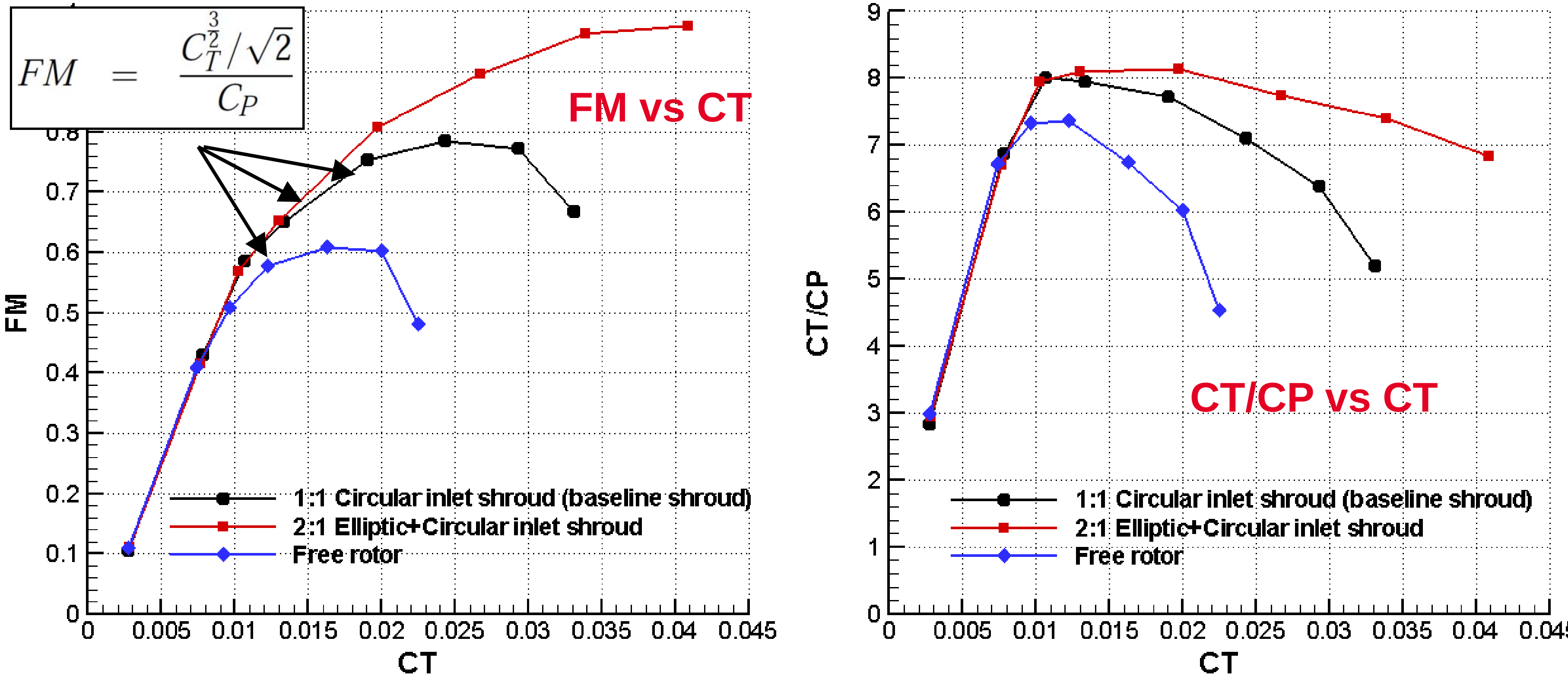
Modified Elliptic Inlet Shroud (Collective Angle Sweep, 2500 RPM)





- **Improved performance for elliptic inlet shrouded rotor**
  - ➔ Increase in thrust; Similar power
  - ➔ Shroud contribution significantly higher (48% at highest collective angle)

Modified Elliptic Inlet Shroud (Collective Angle Sweep, 2500 RPM) cont…



- **Improved performance for elliptic inlet shroud configuration compared to baseline shrouded rotor (~25%⬆ in max FM)**

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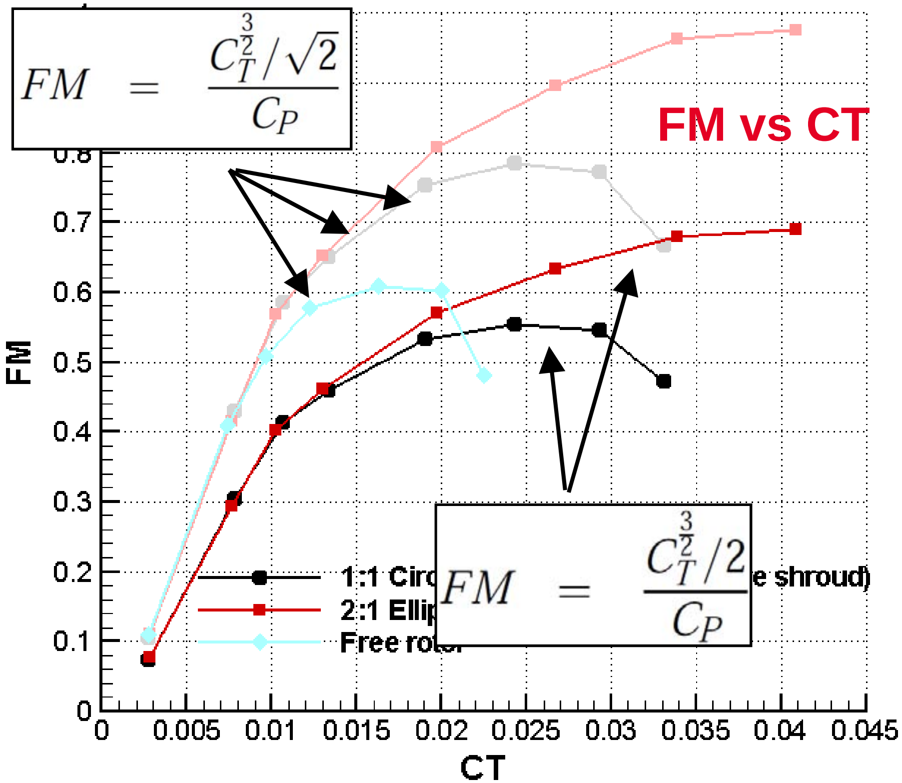
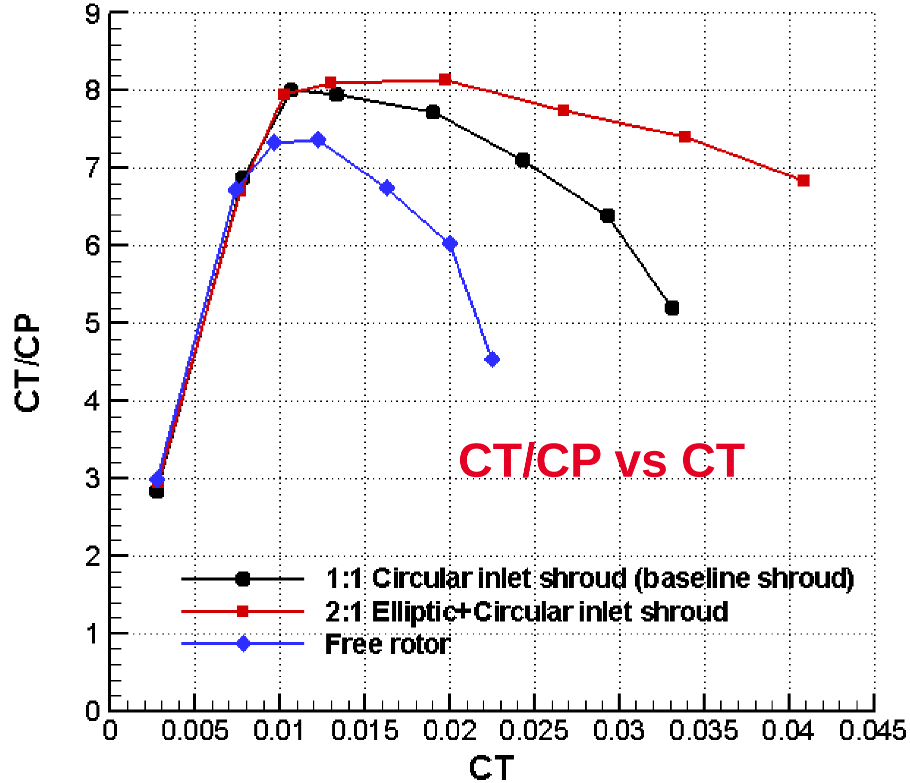
Modified Elliptic Inlet Shroud (Collective Angle Sweep, 2500 RPM) cont…





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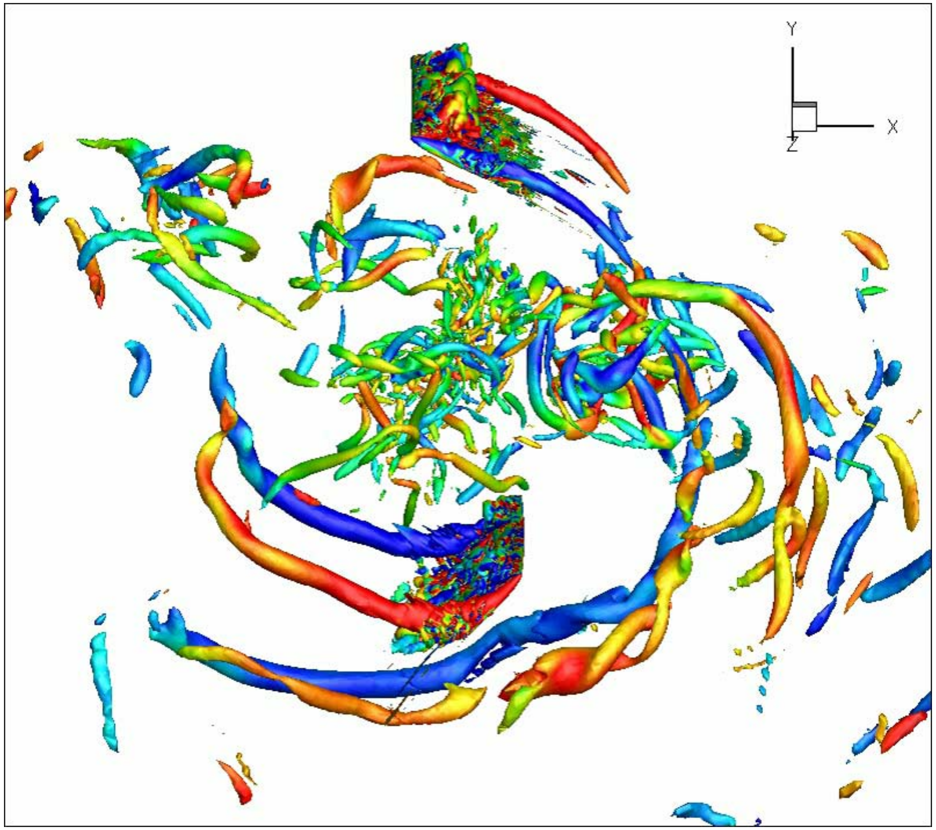
Summary

- Improved Implicit Hole-Cutting (IHC) method by introducing new blanking technique
  - ➔ New blanking technique applicable even to traditional hole-cutting method

- Performed complex micro-hovering rotor calculations using overset grids and validated the results with available experimental data
  - ➔ Micro-scale single rotor: Setup of Ramasamy et al.
  - ➔ Micro-scale single rotor in IGE: Setup of Lee et al.
  - ➔ Micro-scale coaxial rotor: Setup of Bohorquez and Pines
  - ➔ Micro-scale shrouded rotor: Setup of Hrishikeshavan and Chopra
  - ➔ Micro-scale cycloidal rotor: Setup of Benedict et al. (not shown)

- Provided insight into the flow physics of various configurations

Questions?



Flow visualization from Cycloidal Rotor simulation