

# Application of FENSAP-ICE-Unsteady to Helicopter Icing

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# Overview of this Presentation

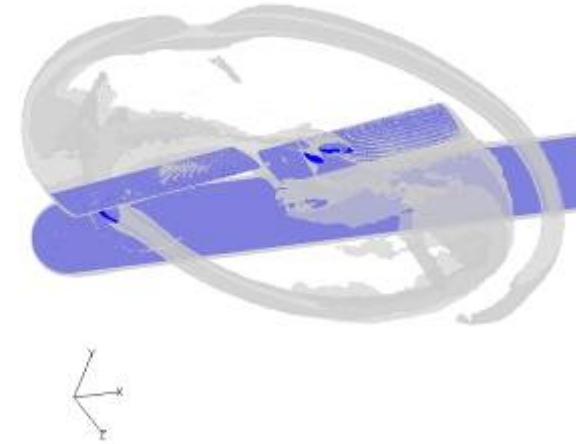
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- Introduction
  - Objectives of this work
- FENSAP-ICE-Unsteady
  - Coupling flow, droplets and ice accretion
  - Grid stitching
- Test case: Two-bladed rotor with airframe
  - Unsteady flow solution
  - Unsteady droplet solution
  - Unsteady ice accretion
- Conclusions

# Introduction

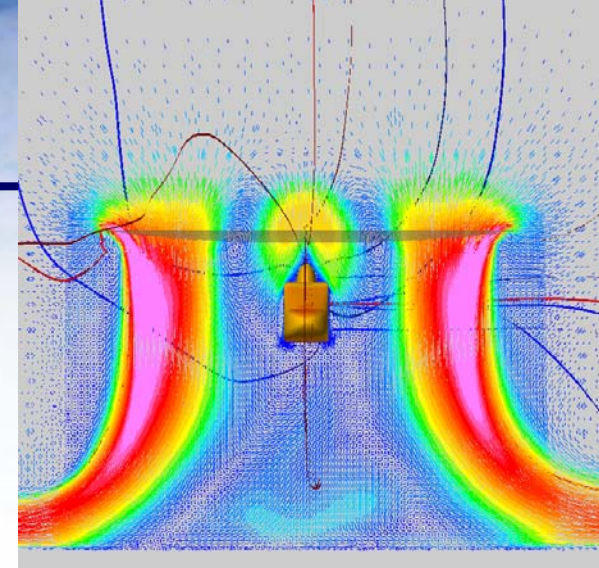
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- Complexity of low-speed forward flight makes simulation a **challenging task**
- The wake of the lifting rotor is composed of strong vortices that are shed away from the blade at a relatively low speed, interacting in time with the airframe
- This unsteady interaction, combined with rotor movement, affects the impingement pattern and ice accretion



# Introduction

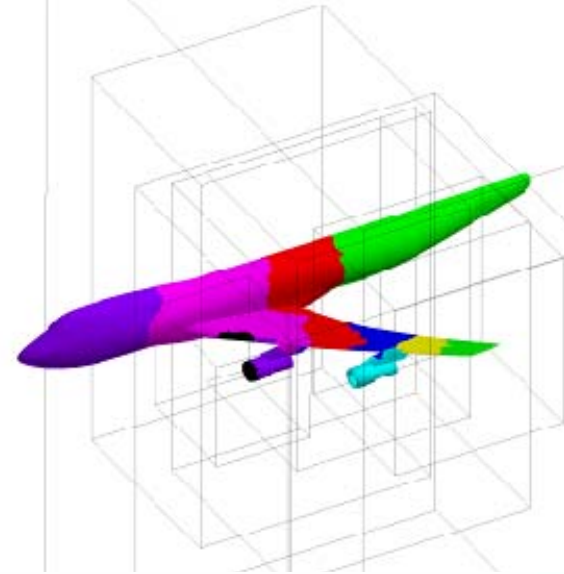
- 3D unsteady analysis are costly
- Steady-state or quasi-steady models:
  - Simpler models
  - Faster solution time
  - Can capture rotor impact on ice accretion over surrounding fixed structures
  - Cannot compute ice shapes on rotors



# Introduction

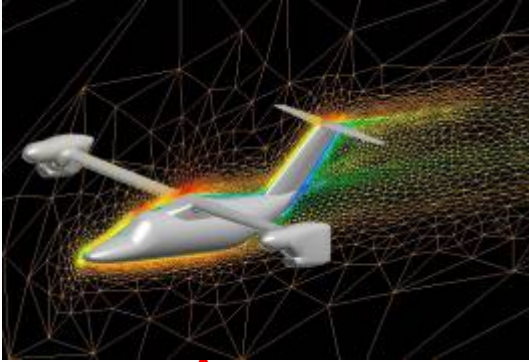
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- Computers allow solving unsteady Navier-Stokes
- For helicopter flows:
  - Assessing the unsteady interaction between fixed and rotating components
- For in-flight icing:
  - Better understanding and modeling of ice accretion

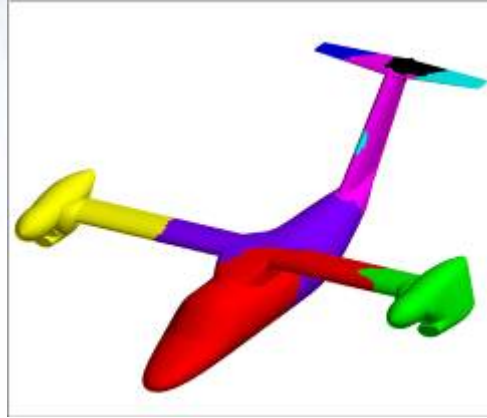


# The 4 Modules of FENSAP-ICE

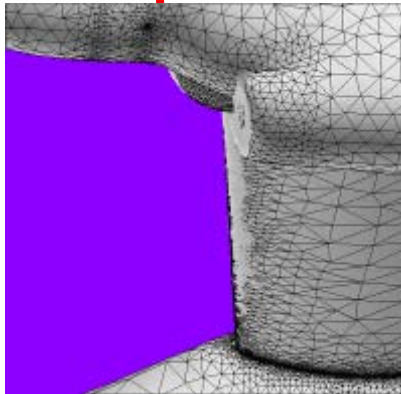
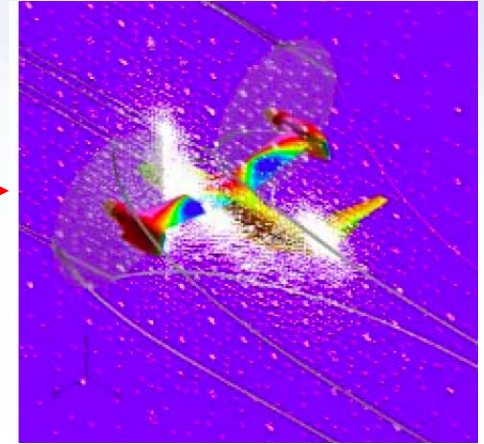
OptiGrid: Auto-adapting Meshes



FENSAP: Parallel CFD

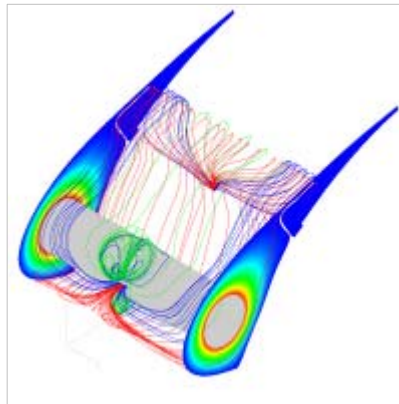


DROP3D: Impingement

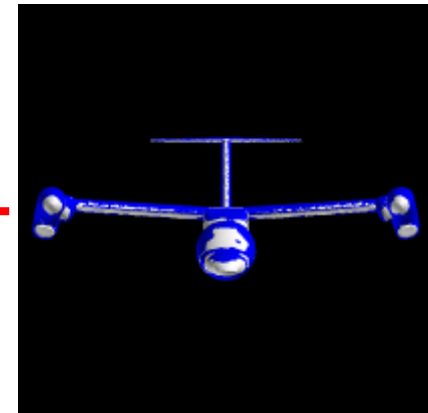


FENSAP: Auto-moving Meshes

CHT3D: Electro- or bleed-thermal anti-icing



ICE3D: Ice accretion and water runback



# Limitations of Modular Approach

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- The impact of ice on both air and droplets is only considered through snapshots in time, including:
  - Variation in time of heat fluxes
  - Impact of ice roughness on boundary layer
- Automatic mesh displacement may be difficult to achieve for large time steps (large accretion) on fine Navier-Stokes grids
- Not directly applicable to moving bodies (i.e. rotors, turbomachines, etc.)
- **Need fully-coupled ice accretion in time**

# Objectives of this Work

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- Model unsteady ice accretion by strongly coupling in time: flow + droplet + ice
- Develop a methodology for solving fixed and rotating components, while fully ensuring mass conservation
- Demonstrate the applicability of the new FENSAP-ICE-Unsteady to 3D rotor ice accretion

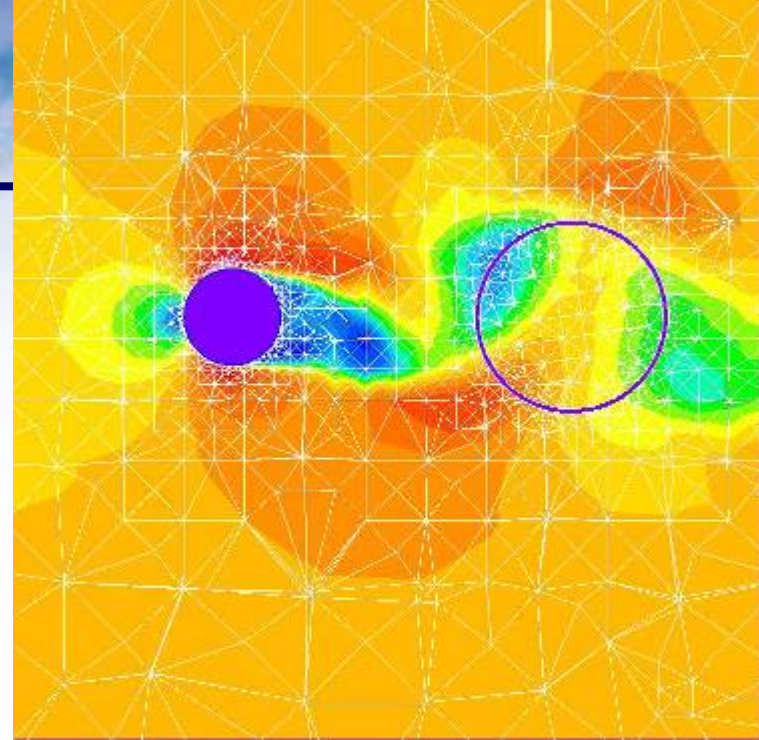
# FENSAP-ICE-Unsteady

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- Flow and droplet solvers:
  - Second-order accurate in both space and time
- Couples the equations for flow + droplet + ice
- Finite-Element based
- The equations are linearized by a Newton method
- Solves iteratively the linear matrix using GMRES
- Advances in time with an implicit Dual-Time Stepping scheme
- Stabilization via second-order upwinding
- Mesh movement using enhanced ALE

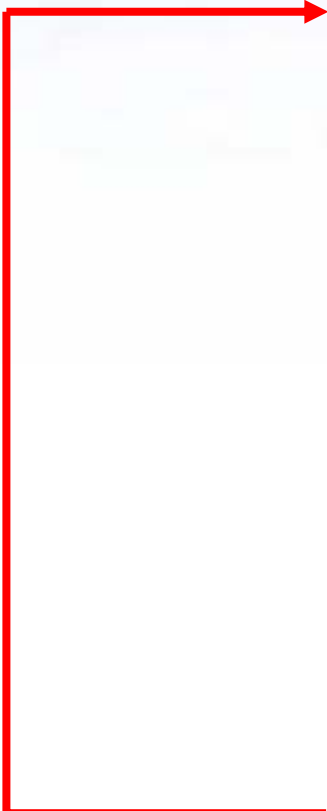
# Grid Stitching

- Based on an advancing front where the gap is filled by only adding tetras
- Start by joining surrounding surface triangles to nodes on the opposite surface
- The advancing front is constantly displaced as new elements are added to the grid
- This incremental procedure is repeated until the gap is completely filled with elements
- Has proven to be sufficiently robust to stitch surfaces of similar shape and element density



# Coupling Air, Droplets and Ice Accretion

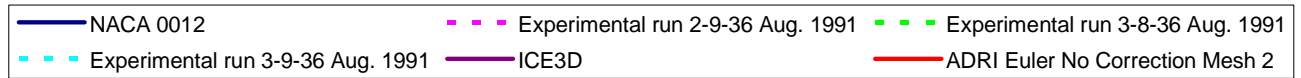
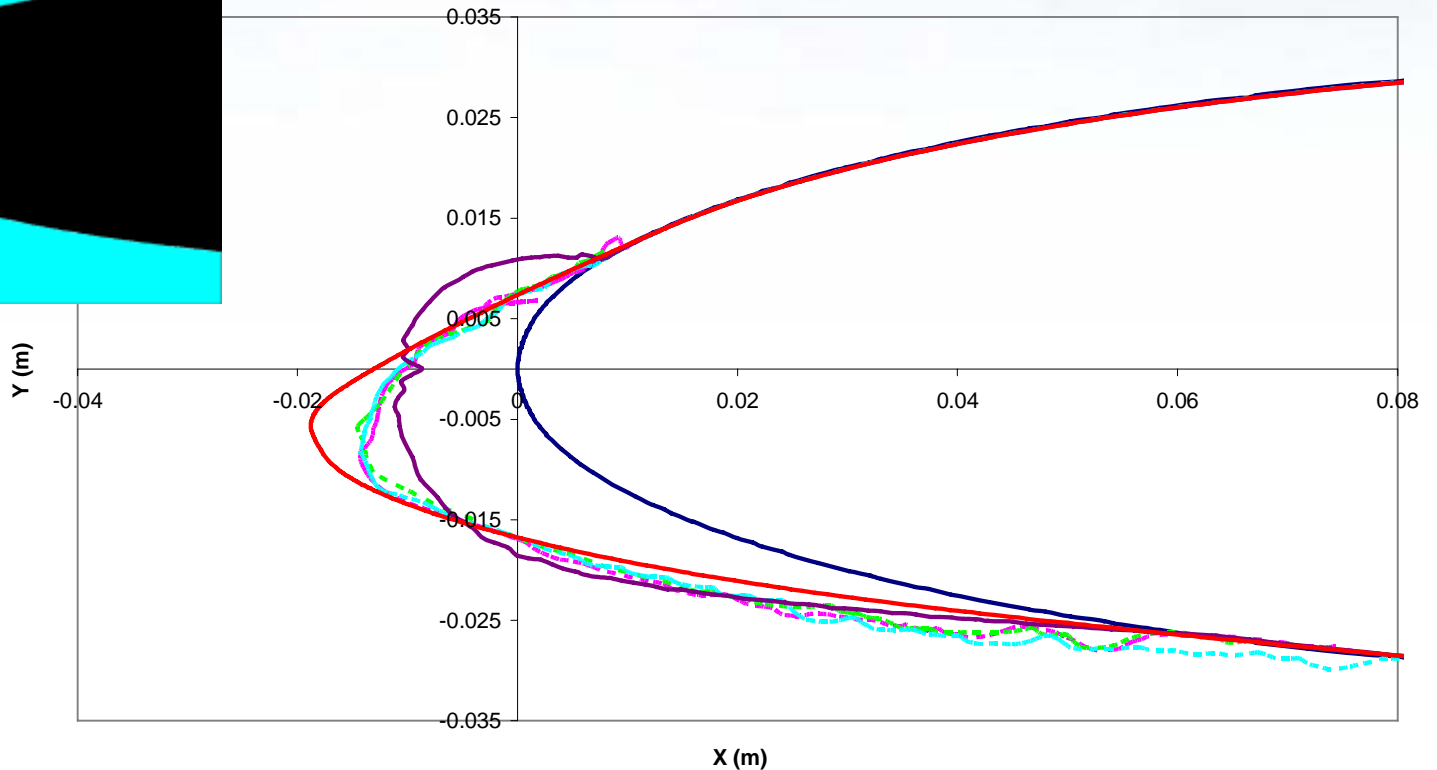
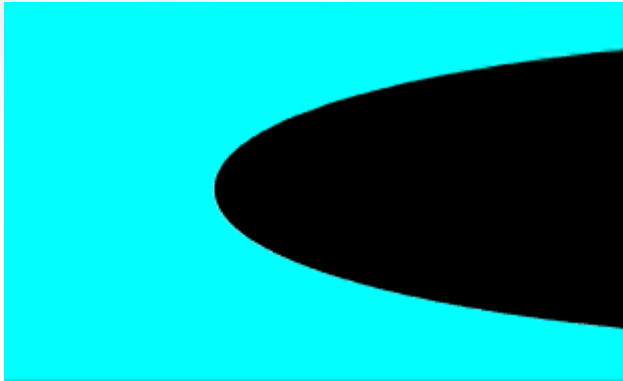
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- Update time step
  - Displace rotor
  - Stitch gap with elements
  - Grid partitioning for MPI
  - Solve for flow
  - Solve for droplet
  - Solve for ice (rime or glaze)
  - Grid speed = rotor speed + accretion speed
  - Save solutions

# Validation for Rime Ice Accretion

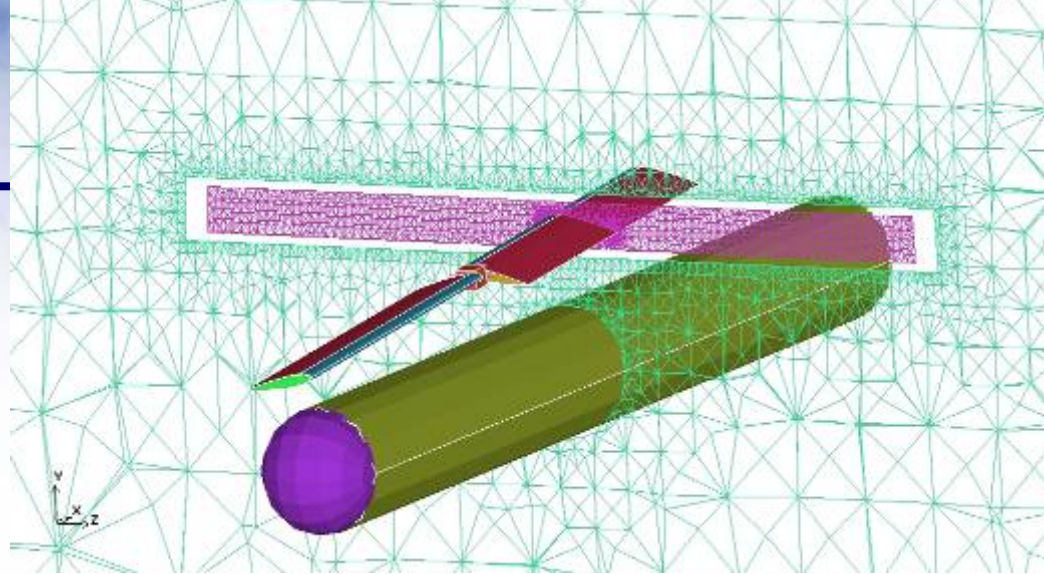
Rime Ice Accretion after 7 min with Constant Ice Density

$T_{inf} = 241.49$  K, A.o.A = 3.5 deg,  $V_{inf} = 102.8$  m/s,  $P_{inf} = 100$  kPa,  $LWC = 0.55$ g/m<sup>3</sup>, time = 7 min, MVD = 20 microns,  $\tau_t = 0.50$  sec,  $R_{hoice} = 917$  kg/m<sup>3</sup>, Mesh 2



# Test Case

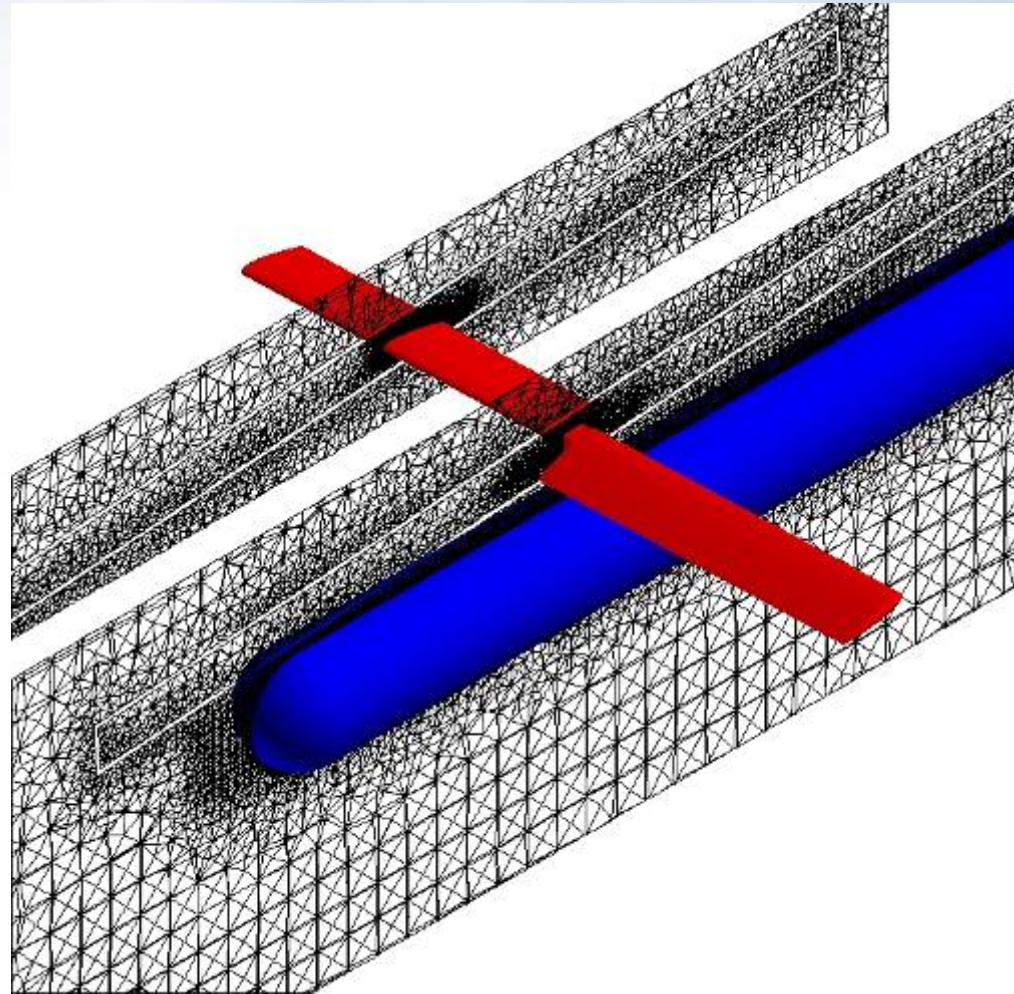
- From Georgia Tech
- Two-bladed rotor
- Cylindrical airframe
- NACA 0015 airfoil constant section
- The pitch angle is constant at 10 degrees
- The 0.457 m radius rotor has tip path plane longitudinal and lateral flapping angles of, respectively, 4.06 and 2.03 degrees
- Shaft speed 2,100 rpm, leading to an advance ratio of 0.1



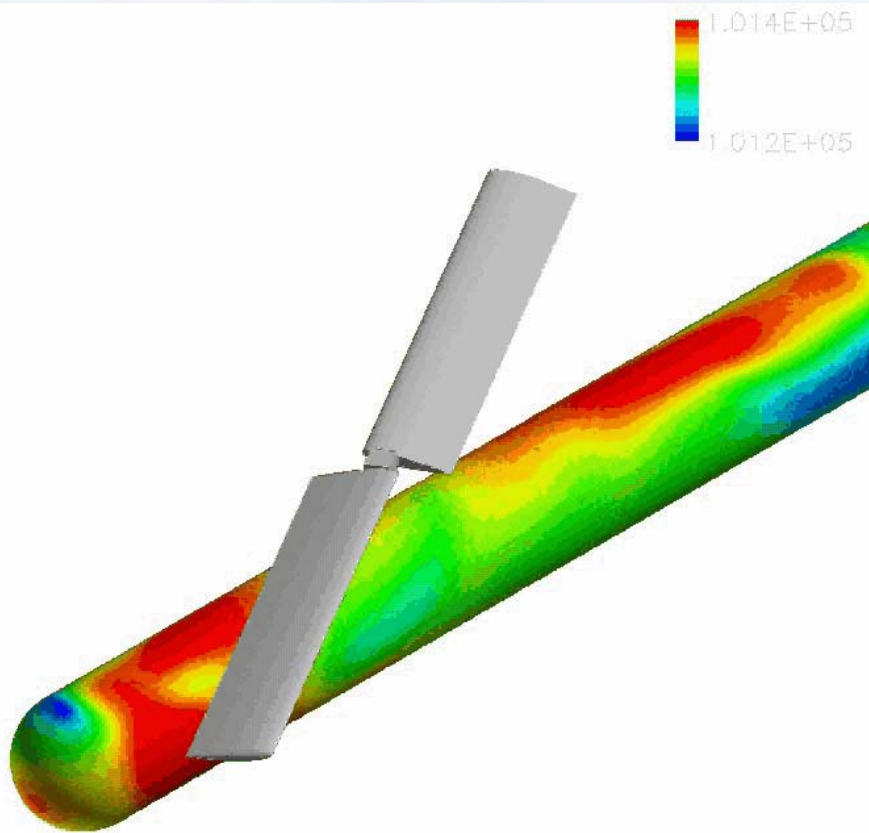
# Computational Domain

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- Unstructured grid (tetra + prism)
- Two volumes: airframe (blue) and rotor (red)
- Both separated by a small gap in space
- Grid points (2.2 M) and elements (7.4 M) are kept small to minimize solution time

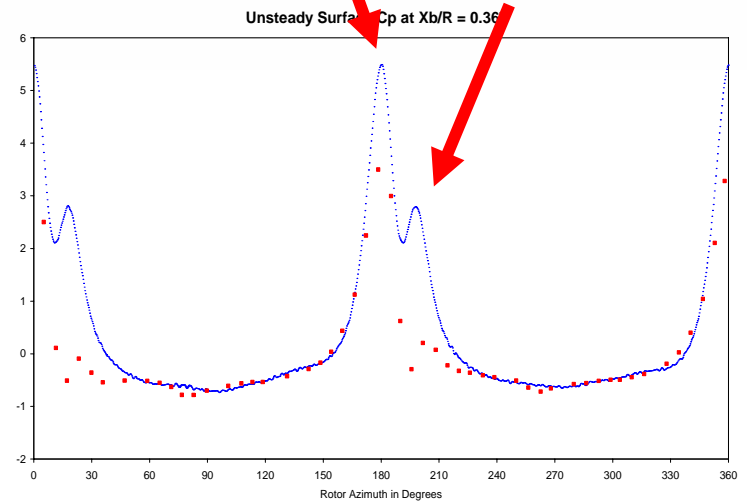


# Periodic $C_p$ at Station 2

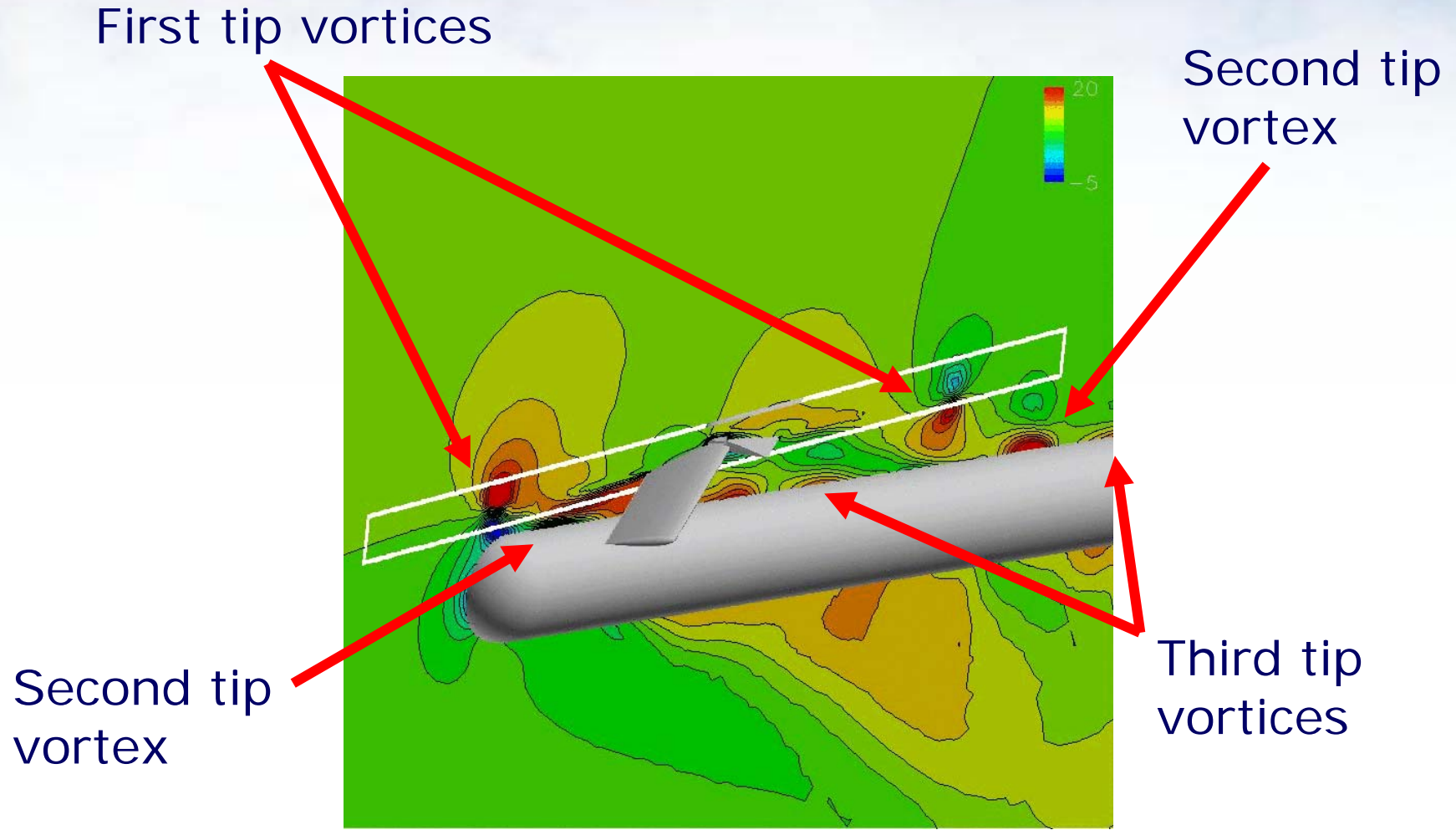


Passage of blades  
over station 2

Passage of  
blade tip  
vortex

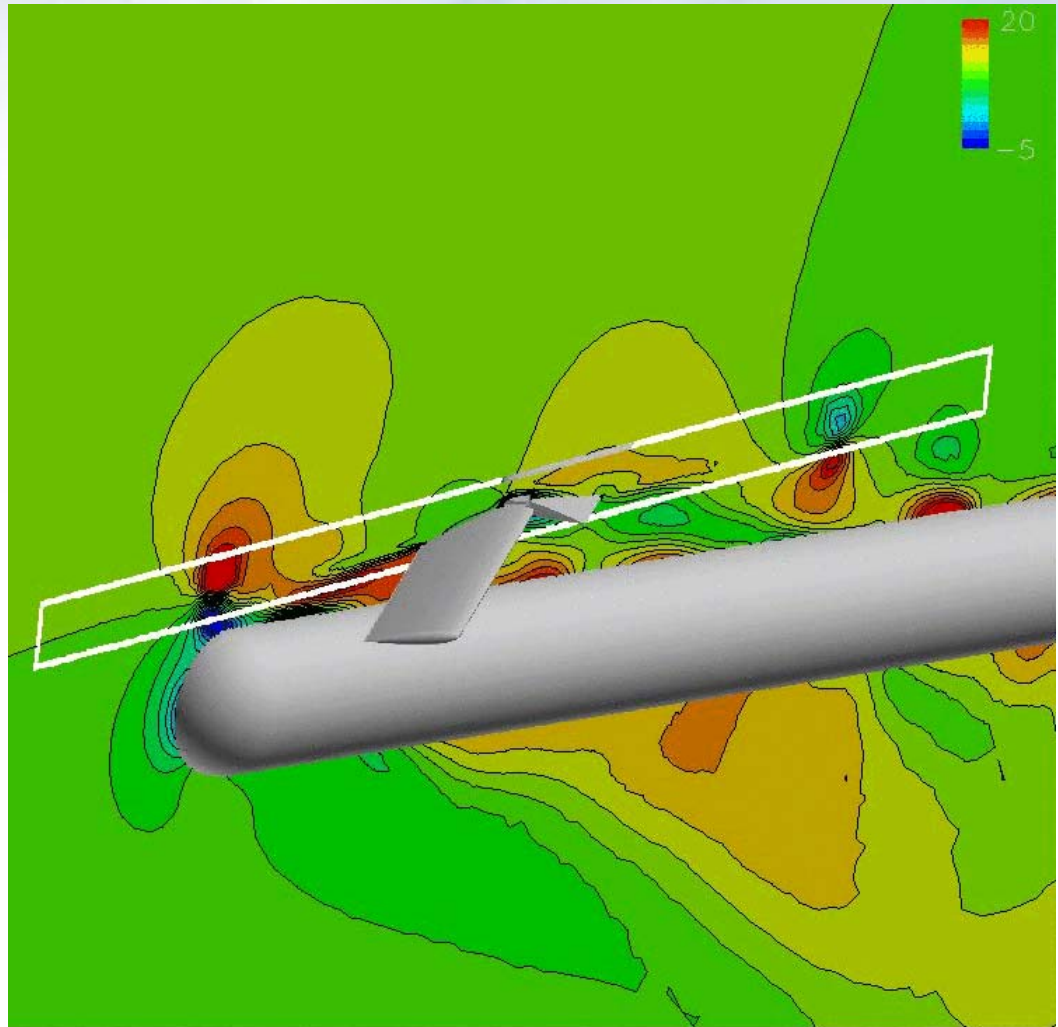


# Vortex Structures (Axial Velocity)

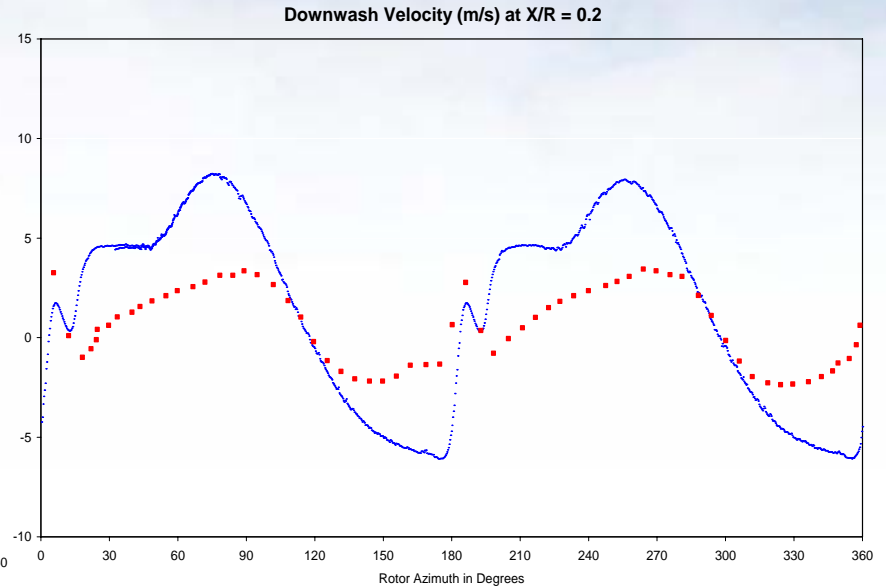
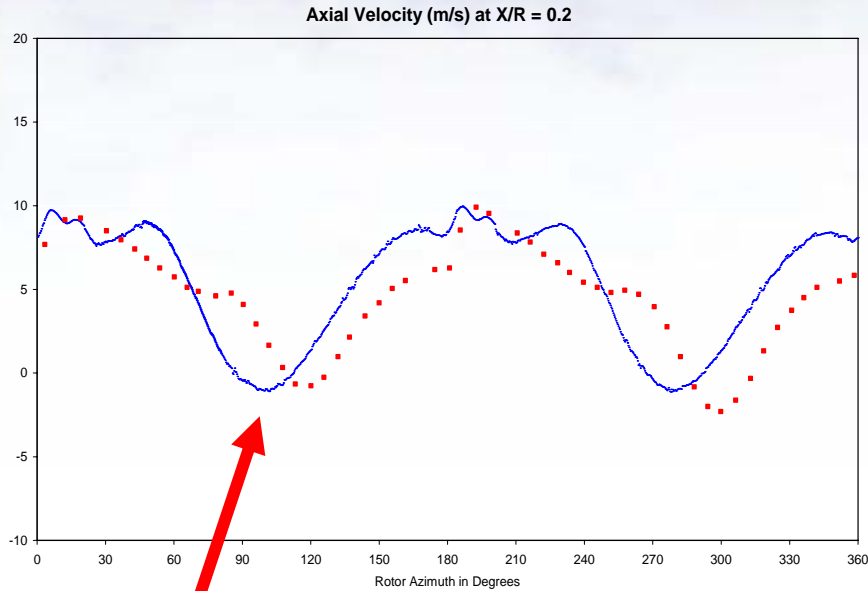


# Vortex Structures (Axial Velocity)

They propagate in both downwash ( $-Z$ ) and axial ( $+X$ ) directions, interacting in time with the airframe



# Axial and Downwash Velocities



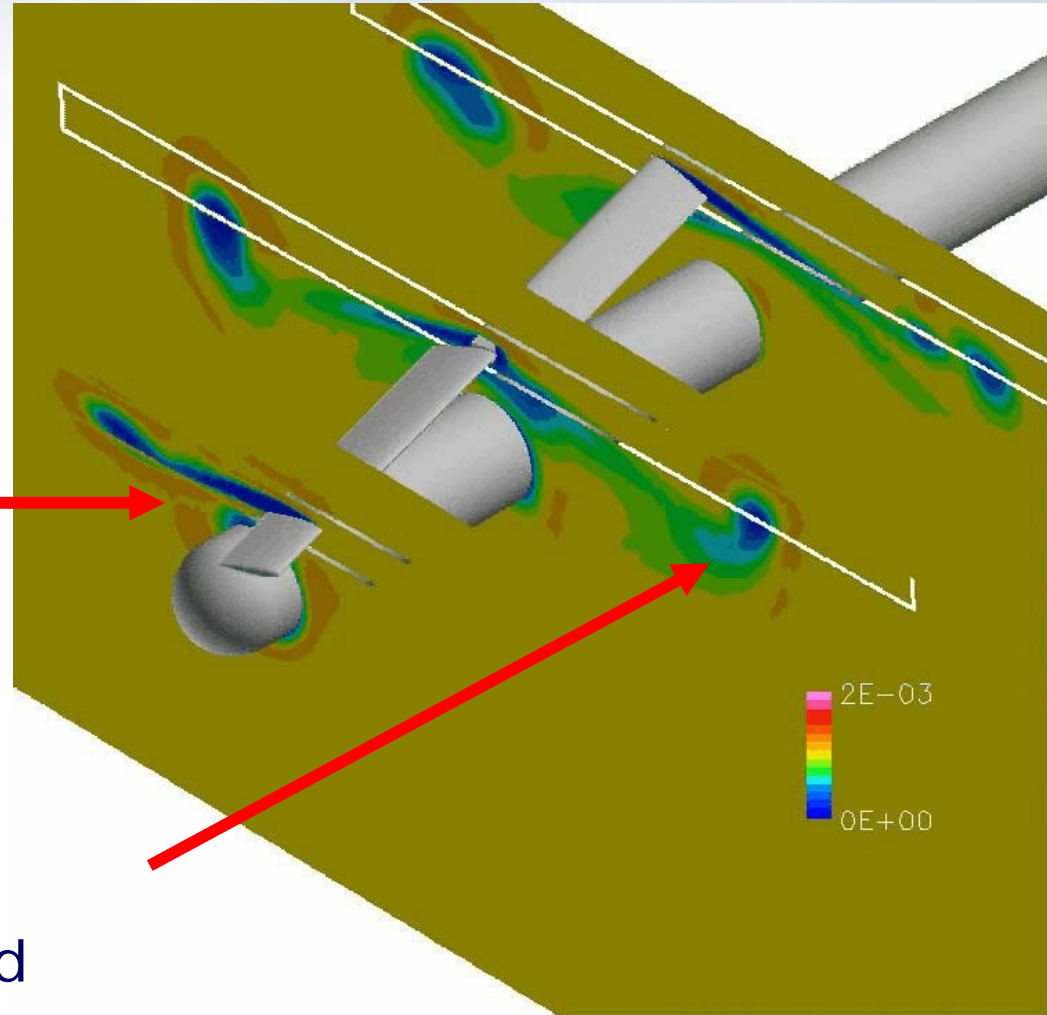
Sharp dip corresponds to passage of the tip vortex

Small error in the position of the min axial velocity, and a large downwash, both due to the inviscid assumption

# Unsteady LWC Analysis

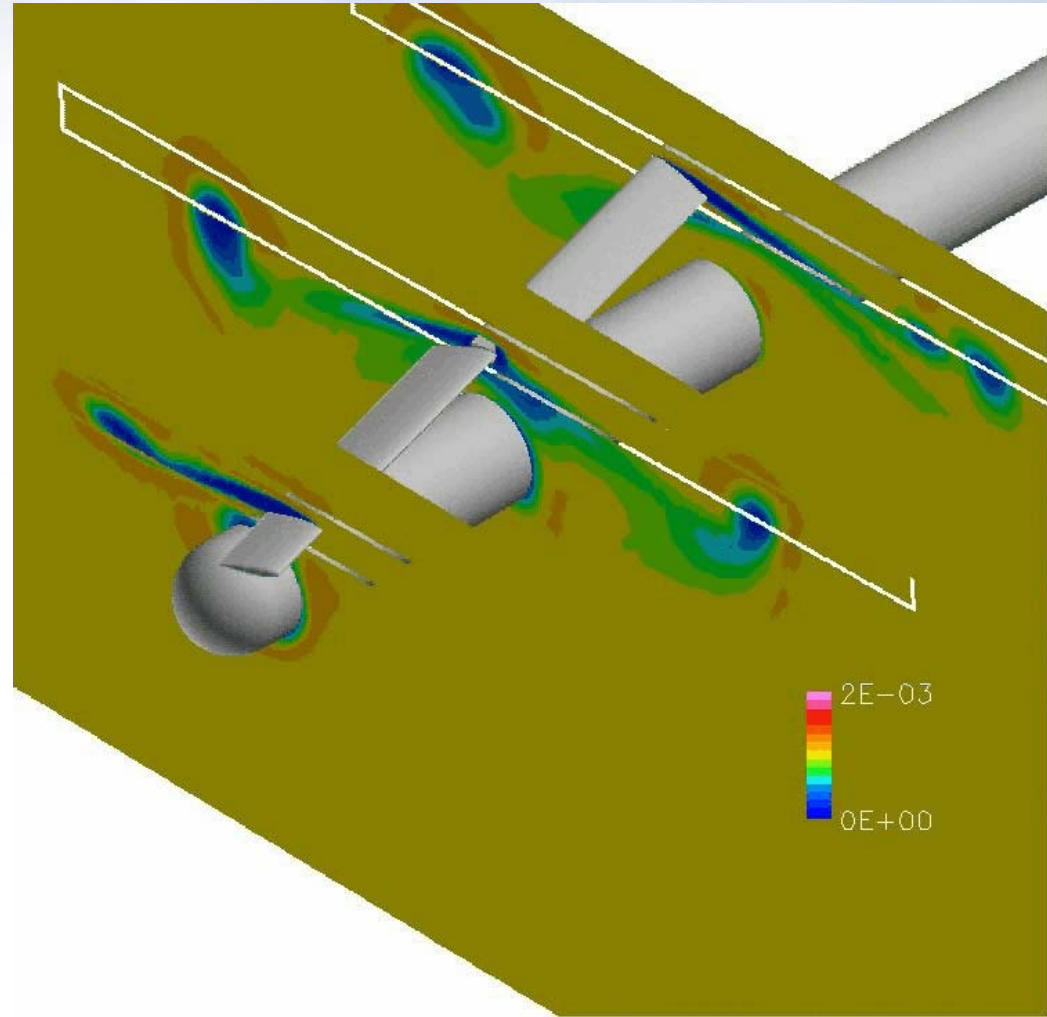
Shadow zone on the upper surface of the blade and aft

Tip vortices induce recirculation in the droplet velocity field



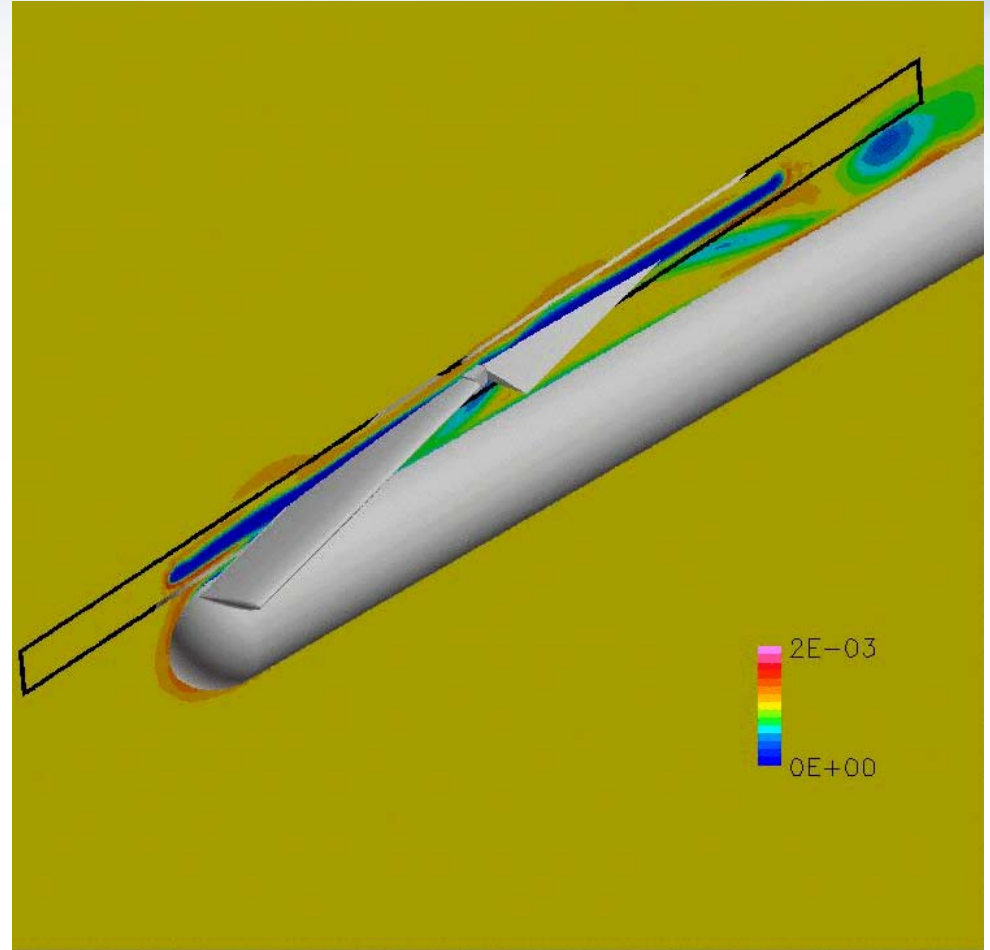
# Unsteady LWC Analysis

The vortex structure is also affected by passage of the next rotor blade that cuts it in two and pushes it further downward

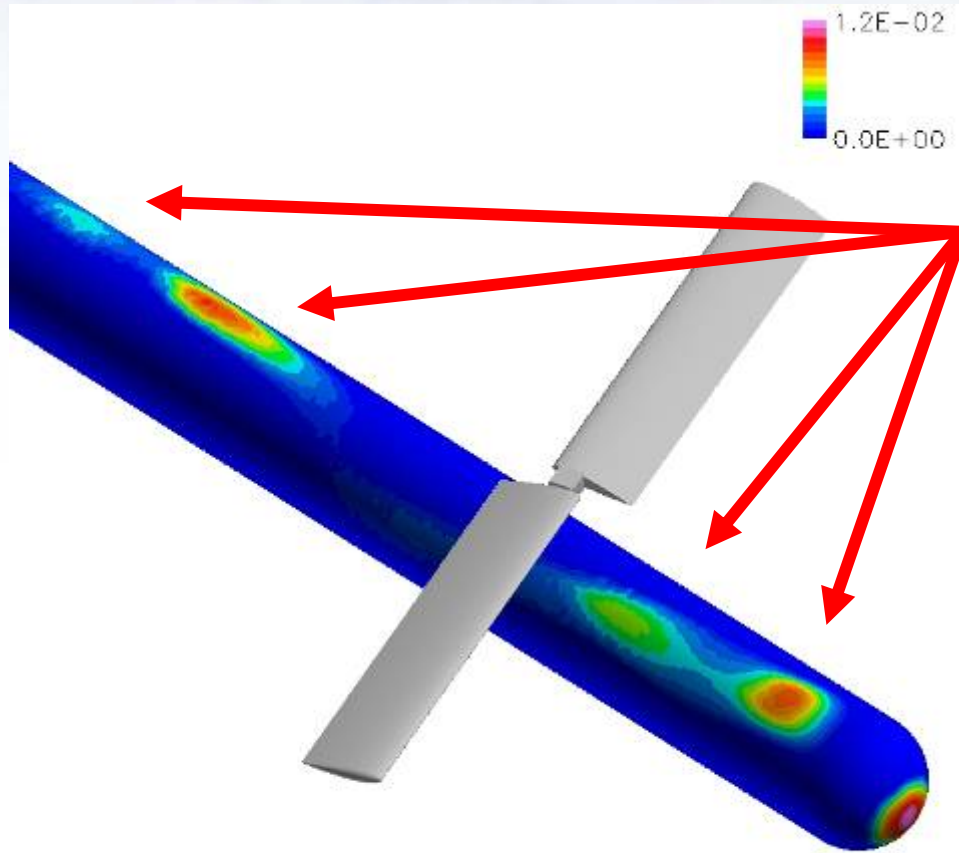


# Unsteady LWC Analysis

Droplet vortices are slowly shed downward, due to the small advance ratio



# Collection Efficiency on Airframe



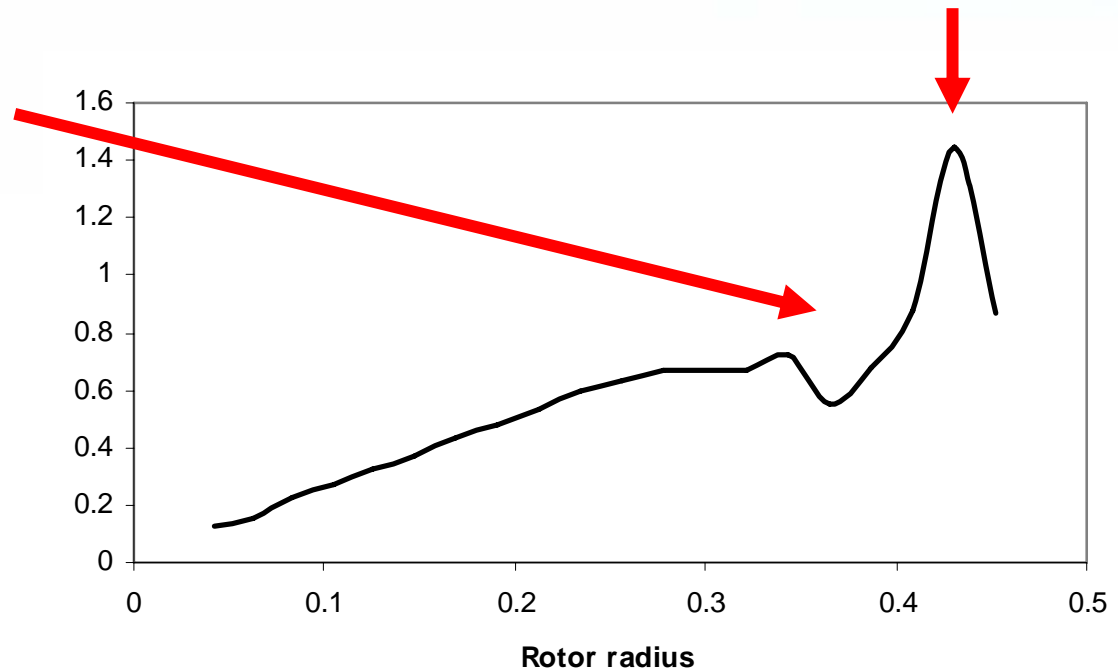
The downward direction of droplet vortices generate impingement on the airframe below and downstream of the rotor

The spot on the nose is due to forward motion and would be captured in a steady-state analysis

# Collection Efficiency on Rotor

At this instant in time, the rotor leading edge interacts with the droplet tip vortex generated by passage of the other blade

Most of the impingement occurs on blade tip rather than root



# Strategy for Ice Accretion

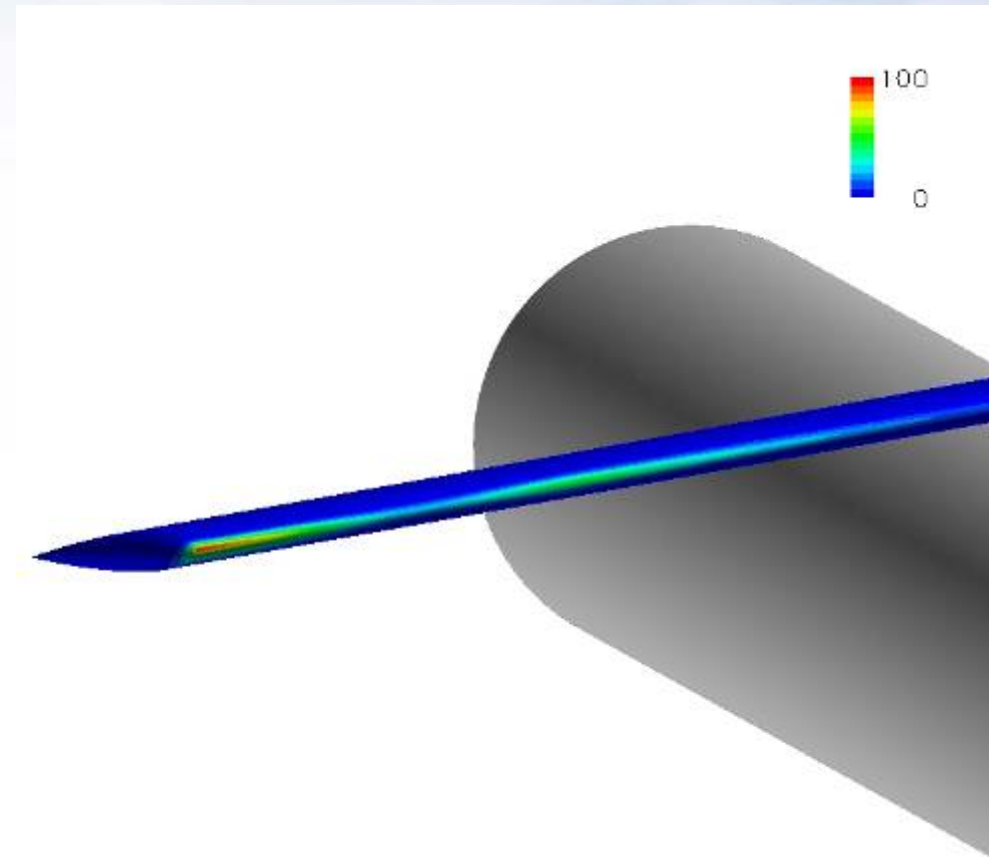
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- Solving for one minute of ice accretion at this rotor speed requires 2,100 full rotations
- The proposed strategy consists of computing ice rate and location (accumulated ice in time) over only one full rotation, and to assume that ice growth in time is then a multiple of the initial ice thickness
- This corresponds to a quasi-steady ice accretion approach where the impact of ice growth on the flow and drop fields is neglected

# Ice Accretion

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- Ice location  $\cong$  unsteady LWC and drop velocity
- Ice accretes mainly on the rotor tip due to the higher relative  $\beta$
- Only traces of ice are observed on the airframe, in regions of droplet vortices impingement and on nose



# Conclusions

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- Validation of the unsteady inviscid flow solution:
  - The unsteady interaction has been captured, as well as the structure of tip vortices
  - Some small differences were noted in the predicted downwash velocity and in the phase of the axial velocity, but these are not considered to invalidate the conclusions of this study
- Coupling in time air and droplet:
  - Droplet vortices interacted in time with the rotor and airframe
  - Impingement on the airframe below and downstream of the rotor
  - Unsteady variation of  $\beta$  on rotor

# Conclusions

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- Rime ice accretion:
  - The calculation was performed over one full rotation (quasi-steady approach)
  - It showed that rime ice accreted mainly on the rotor tip
  - Traces of ice were observed on the airframe due to the interactions of drop vortices with the generic cylinder

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**Thank you!**