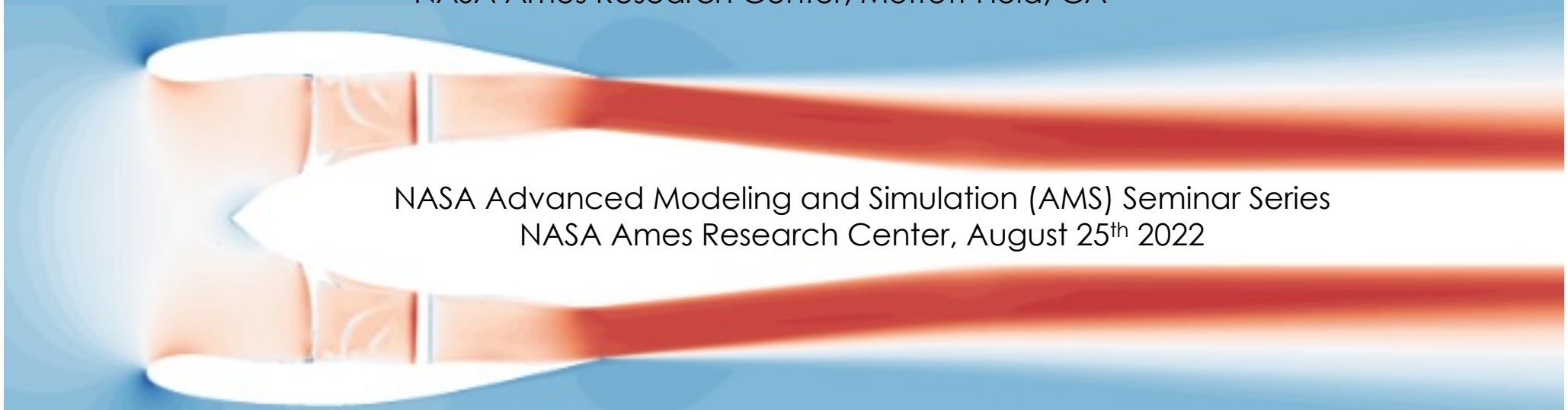
Validation of Actuator Disk, Actuator Line and Sliding Mesh Methods within the Structured Curvilinear Overset Solver

Gerrit-Daniel Stich*, Luis Fernandes*, Jared Duensing
Gaetan Kenway*, Jeffrey Housman and Cetin Kiris

Computational Aerosciences Branch
NASA Ames Research Center, Moffett Field, CA



NASA Advanced Modeling and Simulation (AMS) Seminar Series
NASA Ames Research Center, August 25th 2022

*Science and Technology Corporation (STC)

Outline

- **WHY** do we need propulsion models in CFD?
- **WHAT** are the different models that are implemented in LAVA?
- **HOW** do we solve these challenges – Numerical Method?

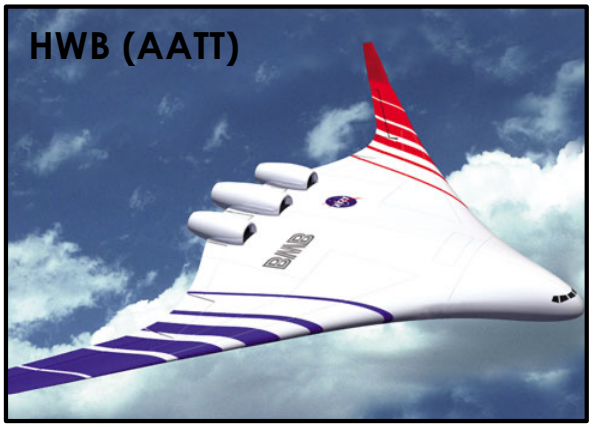
- **Part I: Validation and Verification of Actuator Disk Models**
- **Part II: Application of actuator methods to NASA projects**
  - NASA X-57 Maxwell Electrified Aircraft
  - NASA R4 Source Diagnostic Test (SDT)
- **Summary and Lessons Learned**

Why do we need propulsion models in CFD?

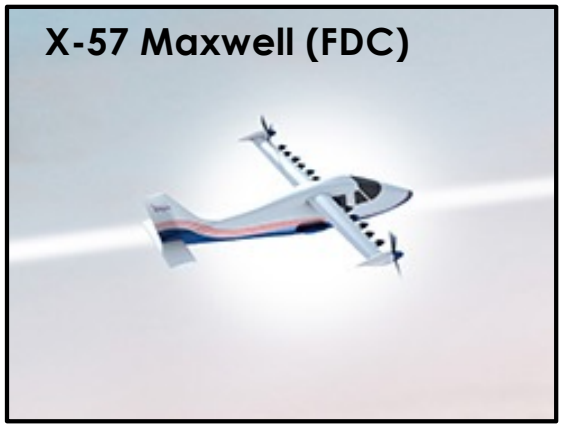
Concepts Supported by NASA Aeronautics Research Mission Directorate (ARMD)

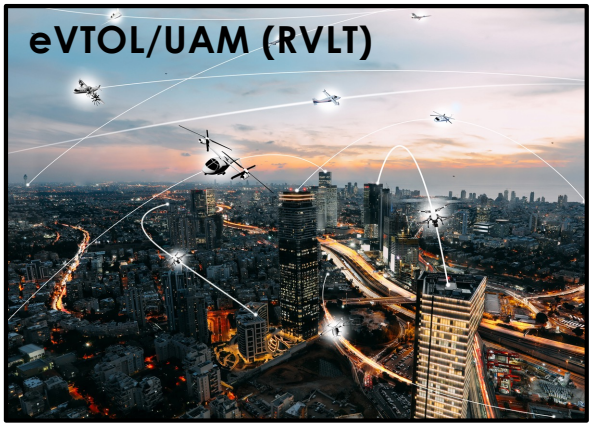




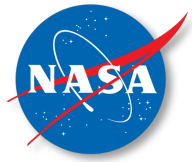








Launch, Ascent, and Vehicle Aerodynamics (LAVA) Framework[1]



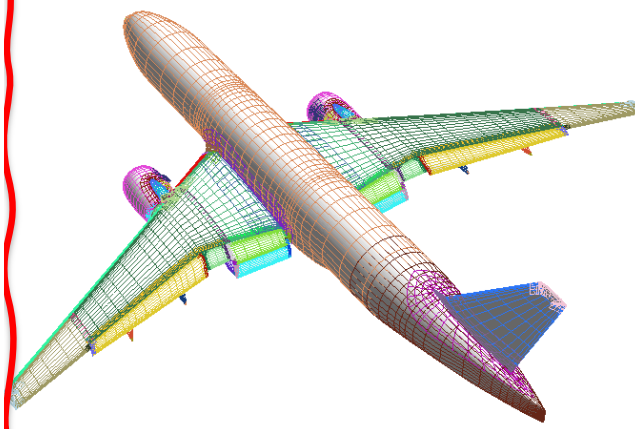
- Compressible Reynolds-averaged Navier-Stokes (RANS) equations
- 2nd order convective flux discretization, consisting of a modified Roe scheme with third order left/right state reconstruction and Koren limiter
- Spalart-Allmaras turbulence model with Rotation/Curvature Constitutive Relation (SA RC-QCR2000)
- Implicit BDF2 dual time-stepping used for unsteady RANS simulations
- **Propulsion models through actuator zone, actuator line and sliding mesh with prescribed body-force[2]**

[1]*Kiris et.al. "Computational Framework for Launch, Ascent, and Vehicle Aerodynamics (LAVA)", 2016*

[2]*Stich et.al. "Validation of Actuator Disk, Actuator Line and Sliding Mesh Methods within the LAVA Solver" ICCFD11-0903*

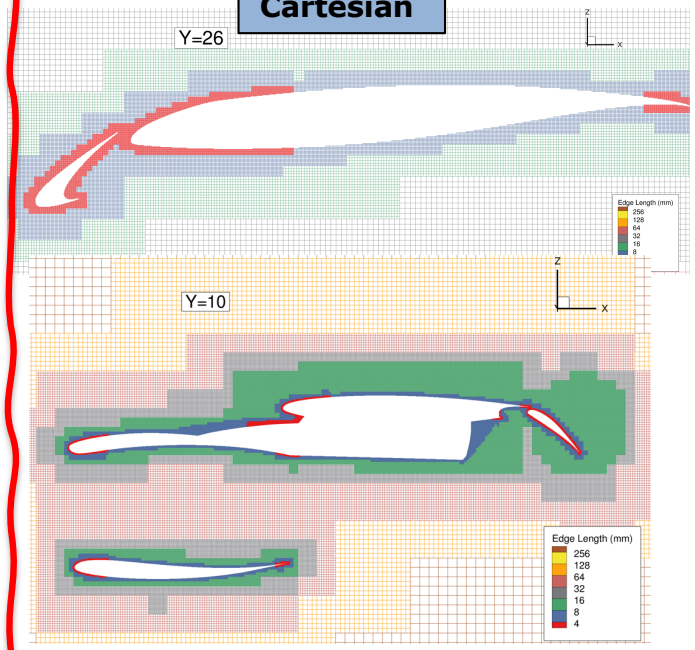
Launch, Ascent, and Vehicle Aerodynamics (LAVA) Grid Paradigms

Structured Curvilinear



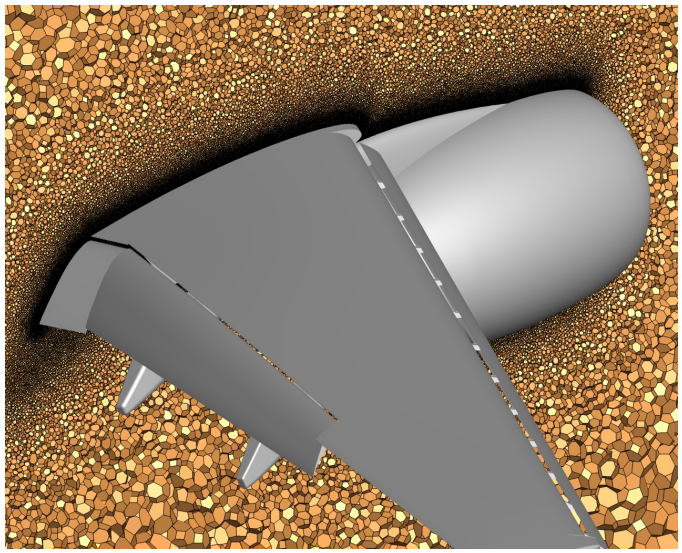
- High quality body fitted grids
- Low computational cost
- Reliable higher order methods
- Grid generation largely manual and time consuming

Cartesian



- Automatic volume grid generation
- High-order methods are efficient and mature
- Isotropic grid cells nonideal for boundary layer resolution
- Wall Modeling is a key

Unstructured



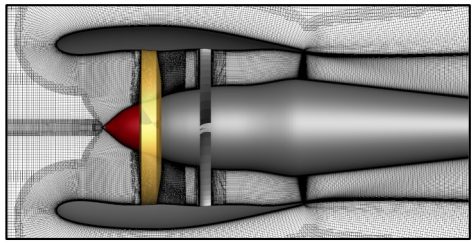
- Partially automated grid generation
- Body fitted grids
- Grid quality can be challenging
- High computational cost
- Higher order methods yet to fully mature

What are the different propulsion models implemented in the LAVA solver?



blade modeled as disk → blade as line load (no BL/Wake mesh) → blade meshed →

simulation costs



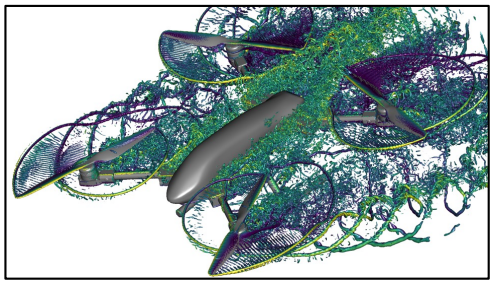
RANS simulation actuator disk method

increased grid points and meshing complexity

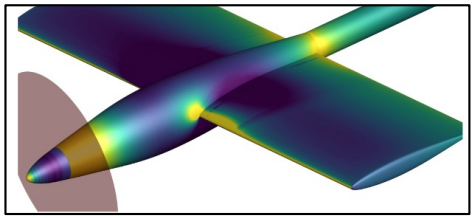
LES / HRLES

sliding mesh (uRANS)

actuator disk/line (uRANS)



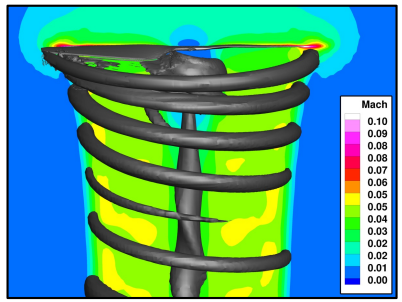
LAVA-LES simulation performed by Cadieux et.al. for SUI Quadcopter
https://www.nas.nasa.gov/publications/ams/2019/12-18-19.html



Increase in simulation cost due to unsteady flow solve

actuator disk (RANS)

actuator disk (Euler)



LAVA uRANS simulation actuator line method

potential flow methods

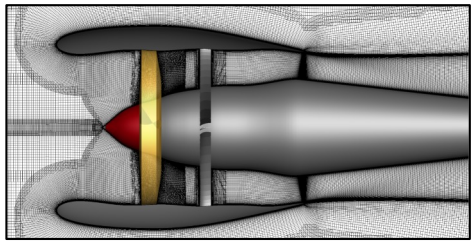
simulation fidelity

empirical models | steady-state CFD | unsteady CFD (RANS) | scale-resolving

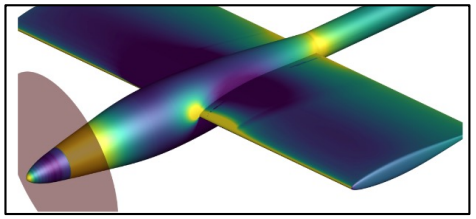
What are the different propulsion models implemented in the LAVA solver?

blade modeled as disk → blade as line load (no BL/Wake mesh) → blade meshed →

simulation costs



RANS simulation actuator disk method



potential flow methods

actuator disk (Euler)

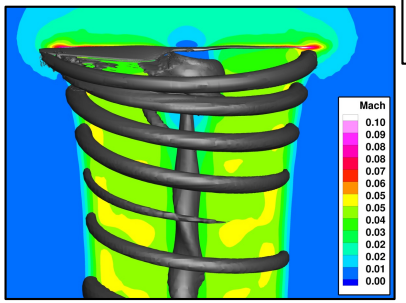
actuator disk (RANS)

Fidelity I

Increase in simulation cost due to unsteady flow solve

actuator disk/line (uRANS)

Fidelity II



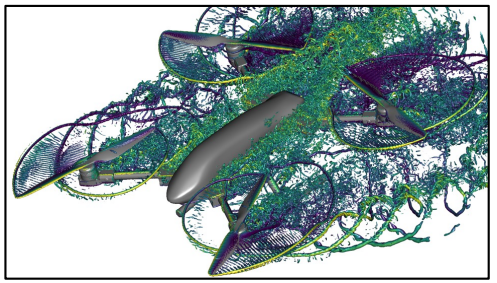
LAVA uRANS simulation actuator line method

increased grid points and meshing complexity

Fidelity III

sliding mesh (uRANS)

LES / HRLES

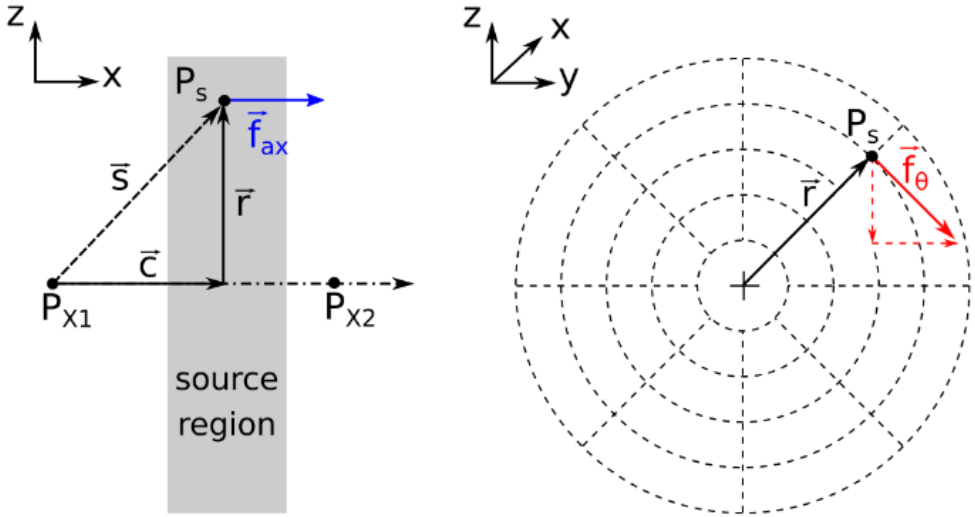


LAVA-LES simulation performed by Cadieux et.al. for SUI Quadcopter
https://www.nas.nasa.gov/publications/ams/2019/12-18-19.html

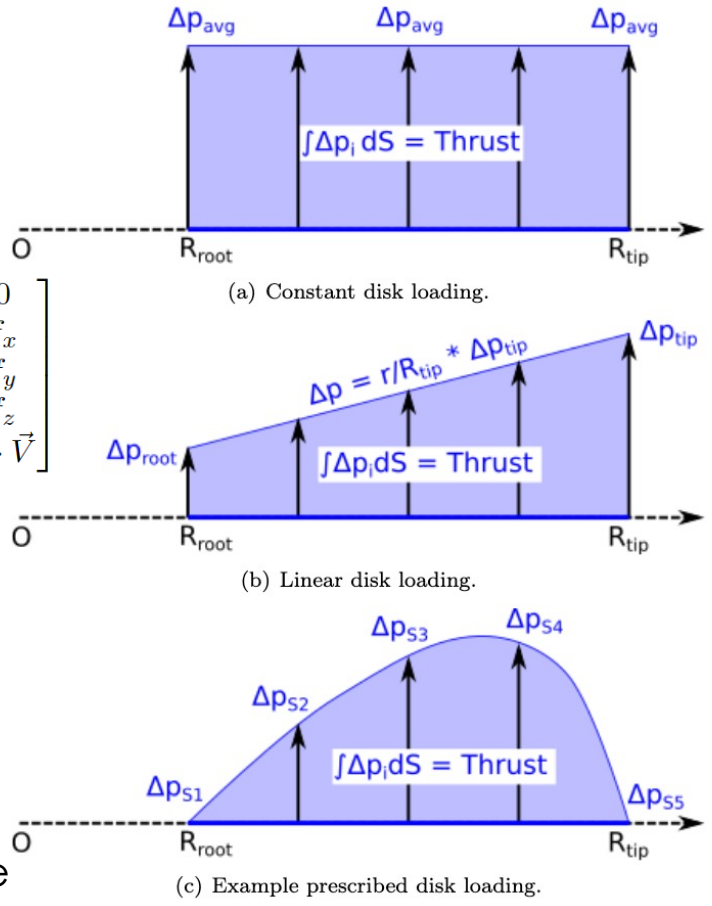
simulation fidelity

empirical models | steady-state CFD | unsteady CFD (RANS) | scale-resolving

Fidelity I: Actuator Disk Propulsion Model (steady-simulation)



$$\mathrm{RHS} = \mathrm{RHS} + \begin{bmatrix} 0 \\ f_x \\ f_y \\ f_z \\ \vec{f} \cdot \vec{V} \end{bmatrix}$$

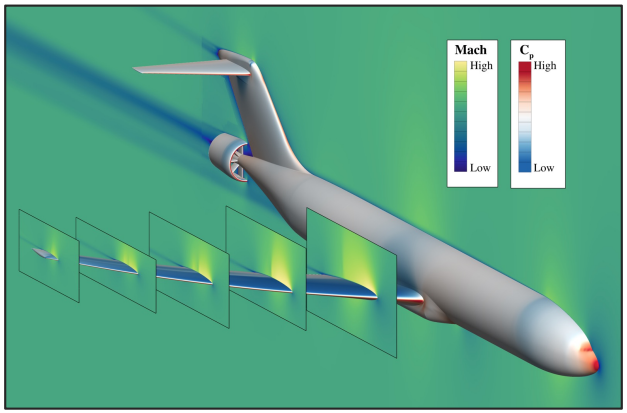


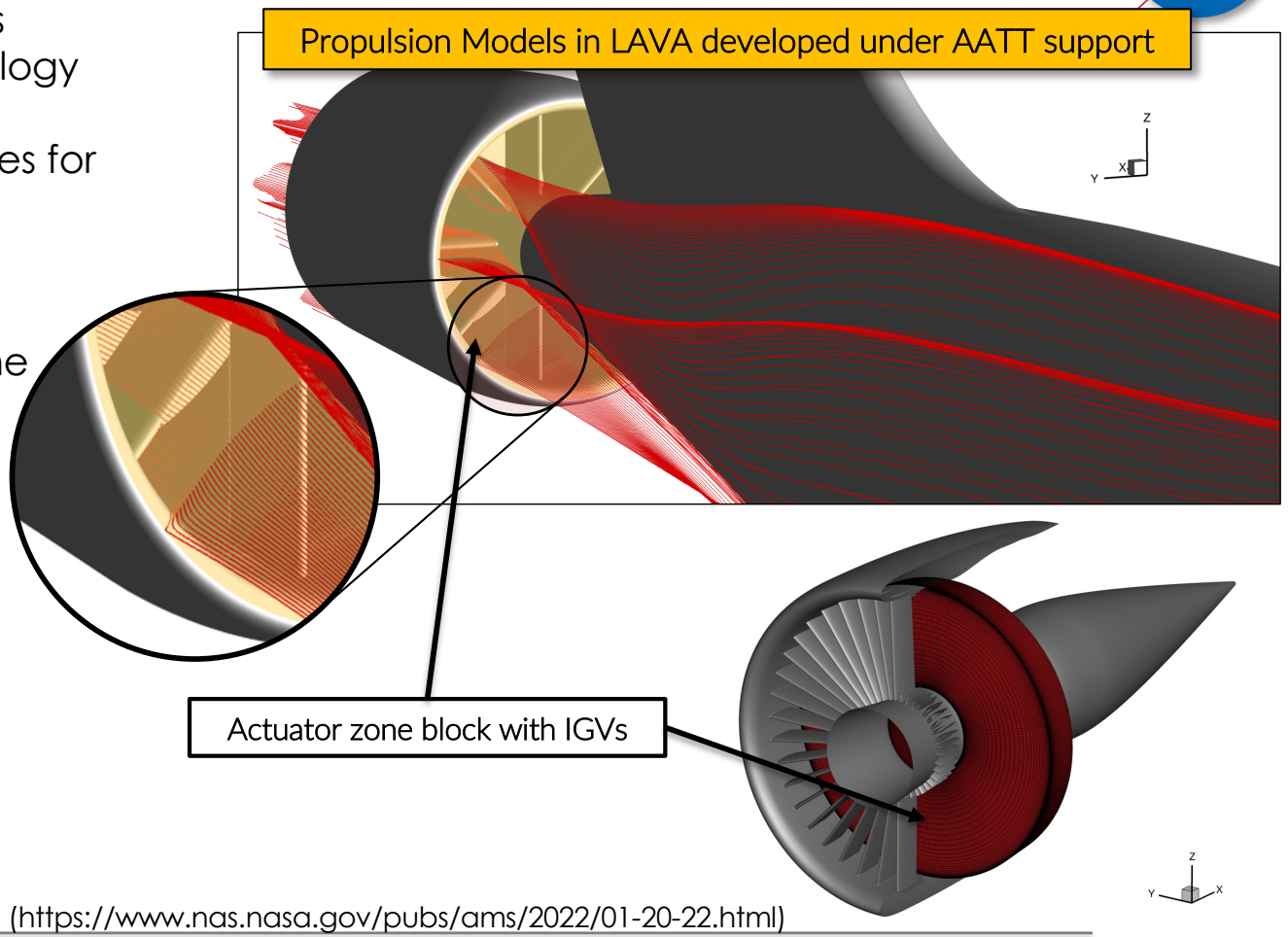
- Time averaged solution of rotor with finite number of blades
- Body force computed a-priori in a preprocessing step and applied as a source term to the RHS and LHS momentum and energy equation
- Extremely efficient and computationally cheap
- Different load distributions can be supplied for thrust and torque (radially and azimuthally varying)

Stich et.al. "Validation of Actuator Disk, Actuator Line and Sliding Mesh Methods within the LAVA Solver" ICCFD11-0903

Computational Analysis Support for the CRM Tail Cone Thruster

- One of the objectives of NASA's Advanced Air Transport Technology (AATT) project is to explore and design key enabling technologies for subsonic fixed wing aircraft with dramatically reduced fuel burn
- Boundary layer ingesting (BLI) propulsion systems are one of the technologies currently being considered

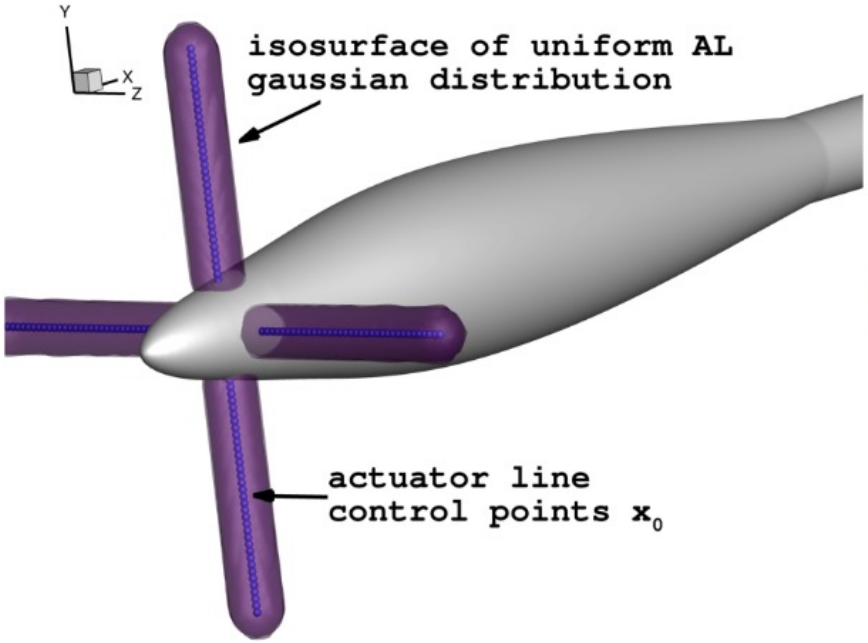




See NASA AMS Seminar by Luis Fernandes et.al. (https://www.nas.nasa.gov/pubs/ams/2022/01-20-22.html)

Fidelity II: Actuator Line Propulsion Method (time-dependent simulation)

$$\Theta(x_c, x_t, x_r) = \frac{1}{\epsilon_c \epsilon_t \epsilon_r \pi^{3/2}} \exp\left(\frac{(x_c - x_{c,0})^2}{\epsilon_c^2} - \frac{(x_t - x_{t,0})^2}{\epsilon_t^2} - \frac{(x_r - x_{r,0})^2}{\epsilon_r^2} \right)$$

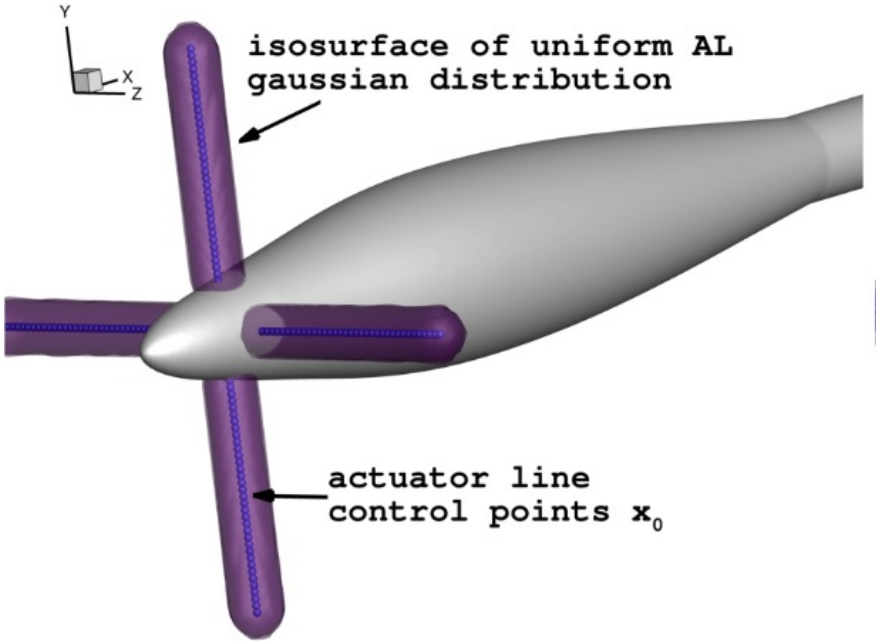


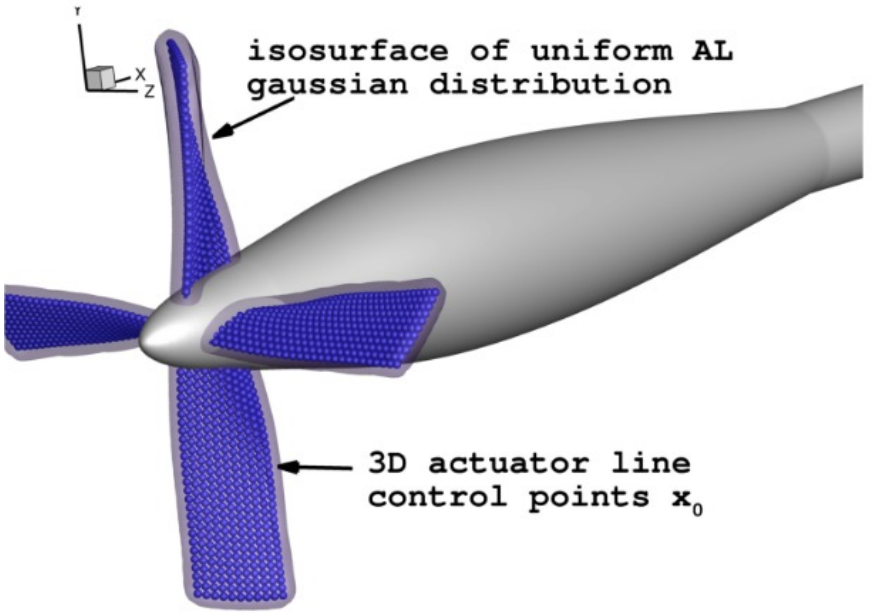
- Source term is applied to RHS and LHS momentum and energy equation
- Gaussian Distribution function applied around user specified actuator line control points x_0
- Method is sensitive to choice of gaussian filter width ϵ *

*see: Sorensen et.al. 2005, Martinez-Tossas et.al. 2015

Fidelity II: Actuator Line Propulsion Method (time-dependent simulation)

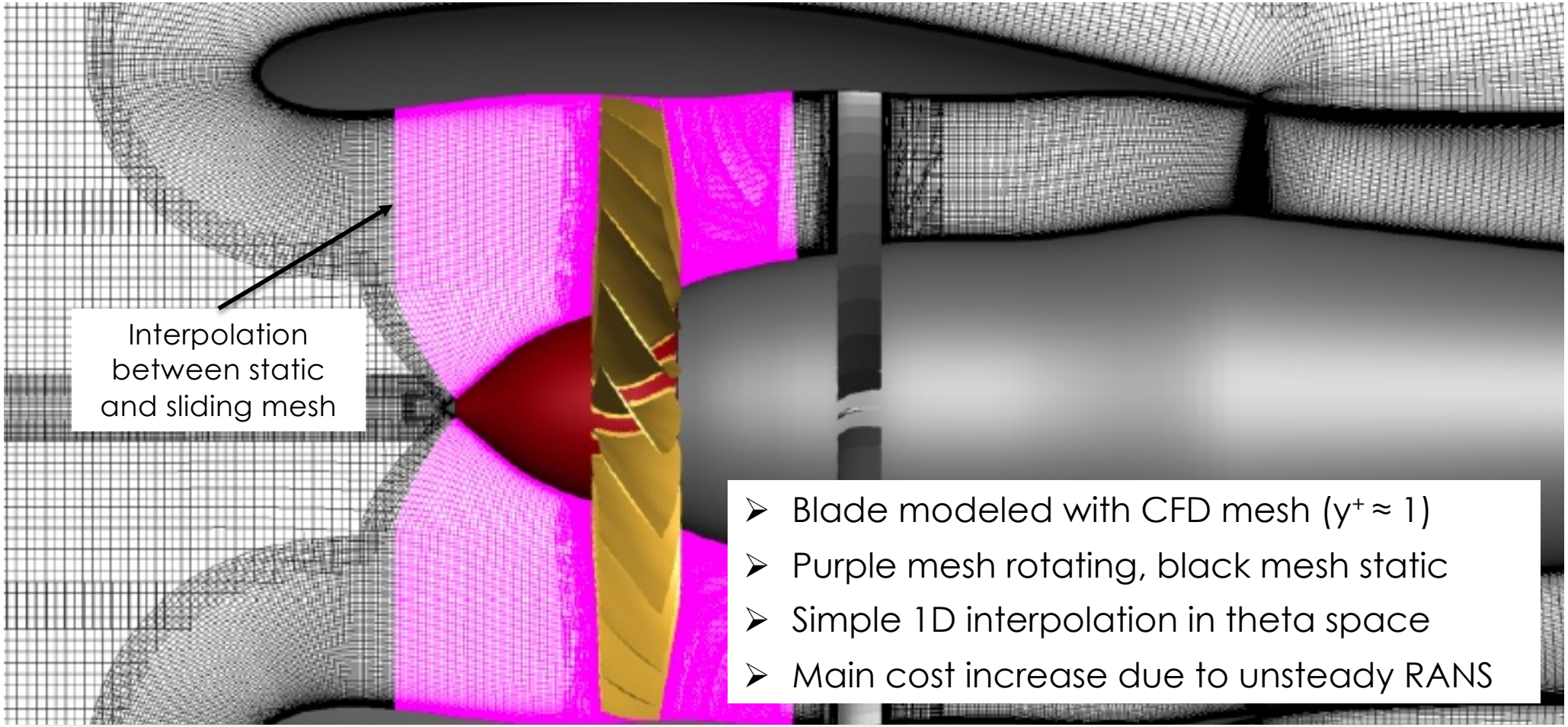
$$\Theta(x_c, x_t, x_r) = \frac{1}{\epsilon_c \epsilon_t \epsilon_r \pi^{3/2}} \exp\left(\frac{(x_c - x_{c,0})^2}{\epsilon_c^2} - \frac{(x_t - x_{t,0})^2}{\epsilon_t^2} - \frac{(x_r - x_{r,0})^2}{\epsilon_r^2} \right)$$





- Improved representation of blade shape, including twist by using 3D control points instead of 1D line

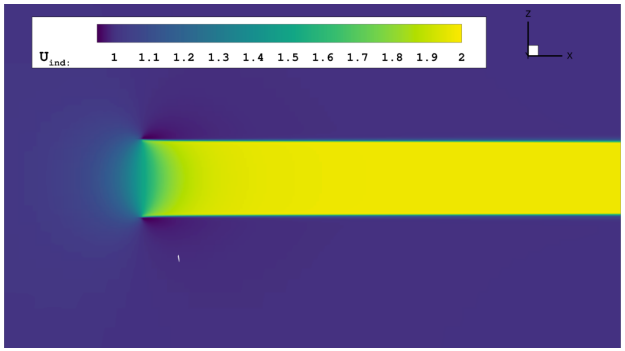
Fidelity III: Sliding Mesh (time-dependent simulation)



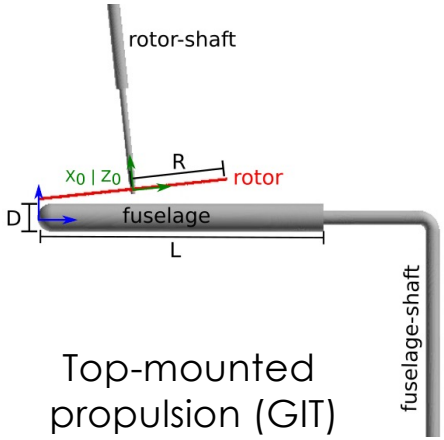
- Blade modeled with CFD mesh ($y^+ \approx 1$)
- Purple mesh rotating, black mesh static
- Simple 1D interpolation in theta space
- Main cost increase due to unsteady RANS

Part I
Validation and Verification of Actuator Disk

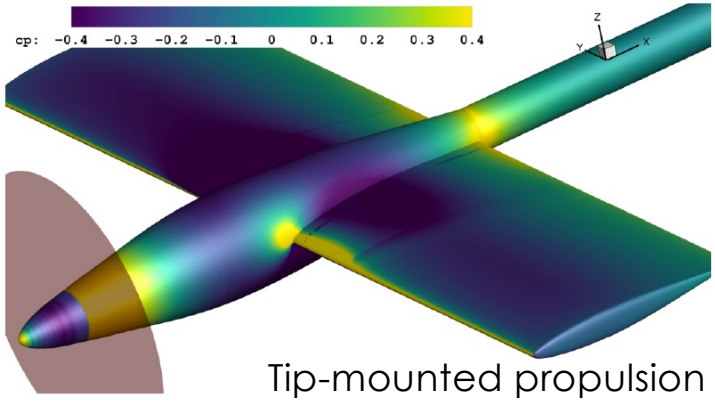
- 3 Problems have been simulated and are presented in paper
  - Isolated rotor – validation with momentum theory
  - Top-mounted propulsion – Georgia Institute of Technology (GIT) rotor
  - Tip-mounted propulsion – rotor mounted on simplified fuselage & wing



Isolated Rotor in Hover

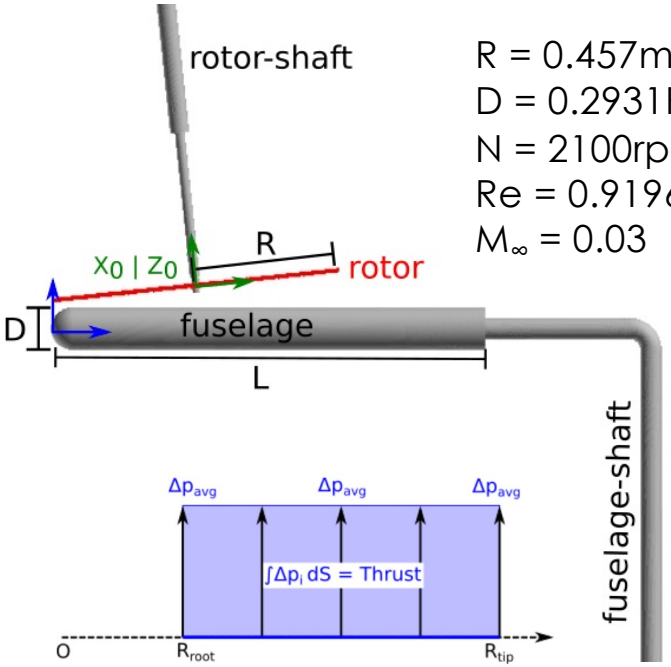


Top-mounted propulsion (GIT)



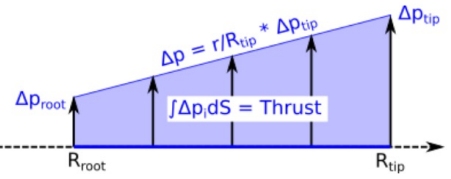
Tip-mounted propulsion

Georgia Institute of Technology (GIT) Rotorcraft Model

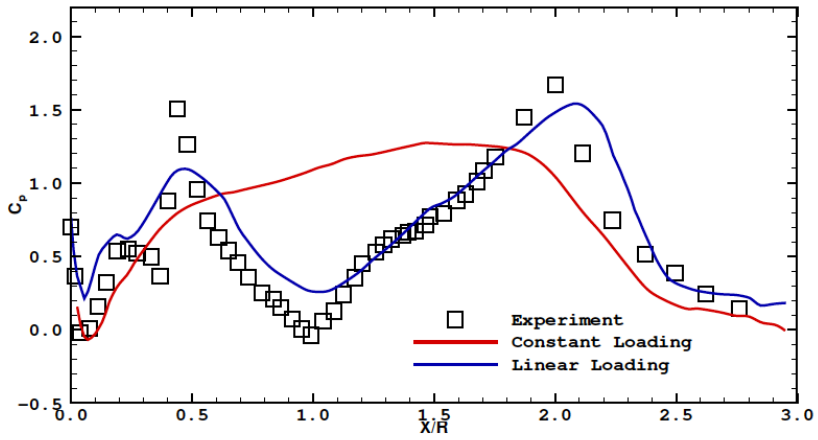


R = 0.457m
D = 0.2931R
N = 2100rpm
Re = 0.9196M
M_∞ = 0.03

(a) Constant disk loading.



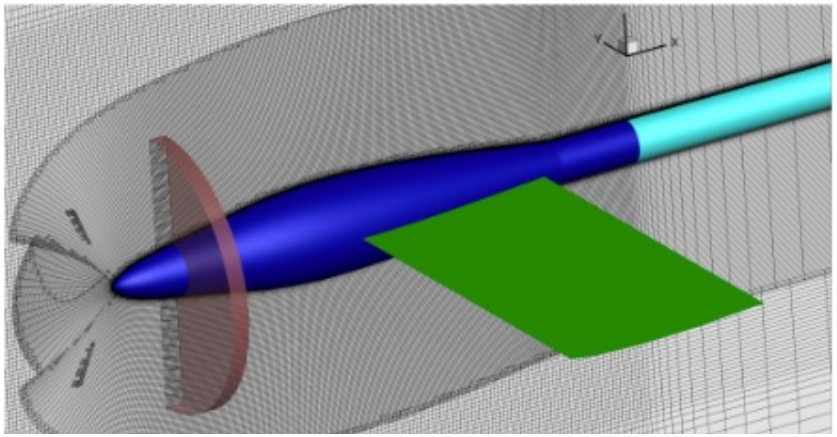
(b) Linear disk loading.

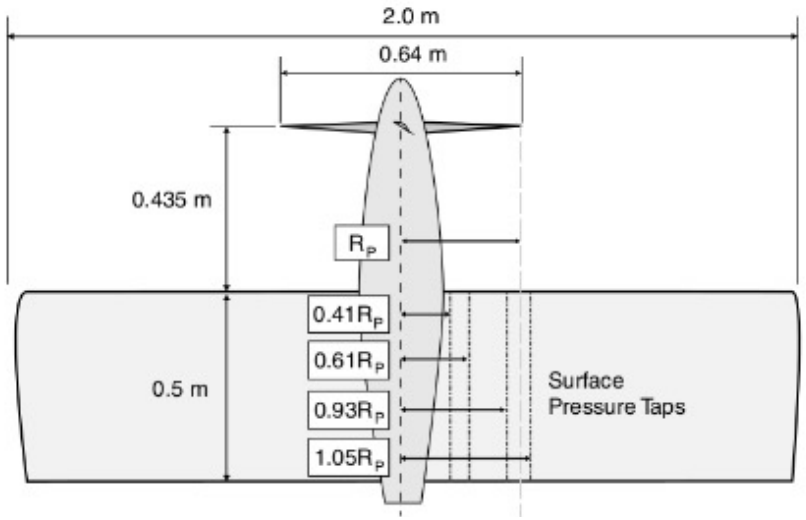


- Choice of load distribution has strong impact on pressure distribution and velocity profiles
- Good agreement with experiment and literature
- Actuator disk method can capture effects of rotorcraft systems while being computationally very inexpensive
- Differences in simplified rotor-shaft have impact on solution accuracy (see paper)

Tip Mounted Propulsion Validation

Samuelson 1988



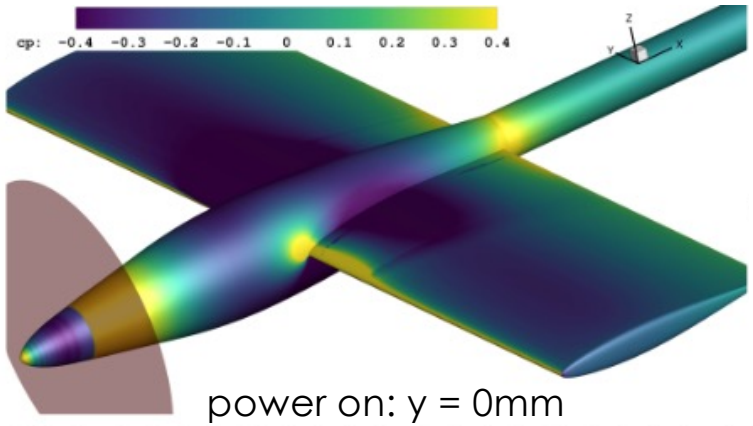


- Simulations performed for four configurations:
  - Fuselage only | power off
  - Fuselage only | power on
  - Fuselage + wing | power off
  - Fuselage + wing | power on
- Wing consist of NACA 63_{010}A012 airfoil
- Comparisons are made with RANS by Guzel et.al. 2014

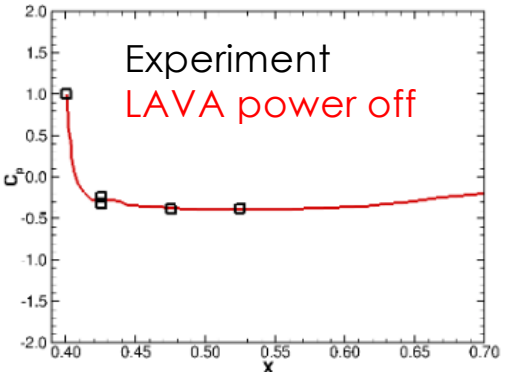
Parameter	Value
Advance ratio J	0.705
Reference length L	1.672 m
Reynolds number Re_L	1.7×10^6
Mach number M_∞	0.15
Reference Velocity	$50\,\mathrm{m\,s^{-1}}$
Thrust Coefficient C_T	0.23
Power Coefficient C_P	0.23

[1] Samuelson 1988, "Low Speed wind tunnel investigations of propeller slipstream aerodynamic effects on different nacelle / wing combinations"

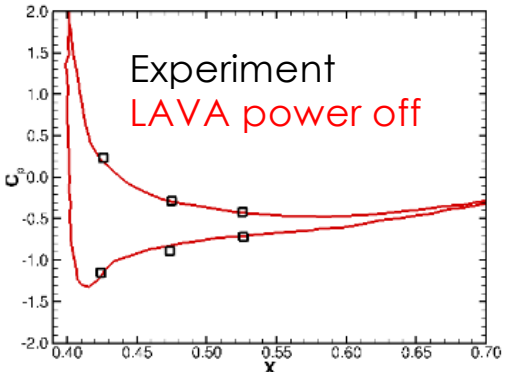
Tip Mounted Propulsion Validation Case (Samuelson 1988)



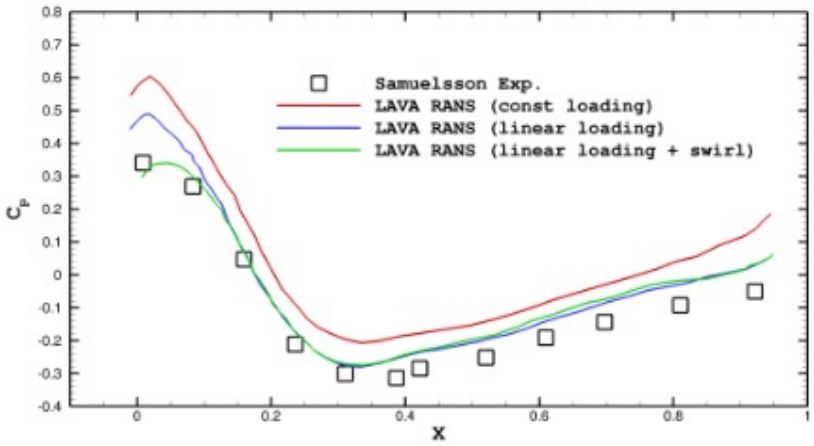
power on: y = 0mm

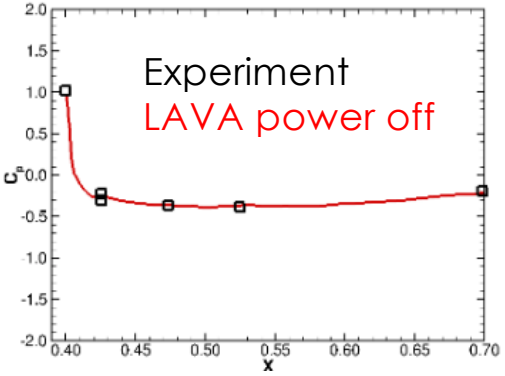


power off: y = 260mm

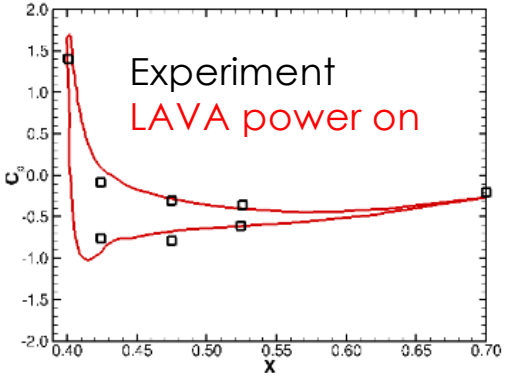


power on: y = 260mm



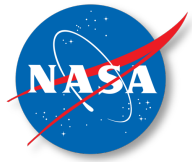


power off: y = 300mm



power on: y = 300mm

[1] Guzel et.al. "Implementation and validation of an actuator disk model for aerodynamic analysis of propelled UAV's", 2014



Part II
Application of Propulsion Methods to NASA AATT & FDC Projects

X-57 Design Overview

Work supported by NASA's Flight Demonstrations and Capabilities (FDC) project

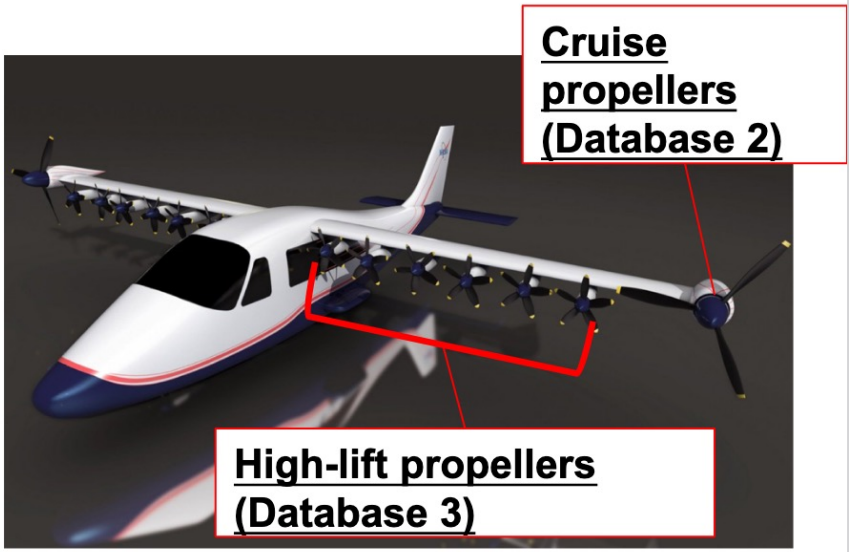


Image source:
https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170001218.pdf

AMS Seminar by Jared Duensing
https://www.nas.nasa.gov/pubs/ams/2020/10-13-20.html

X-57 CFD Analysis Objective

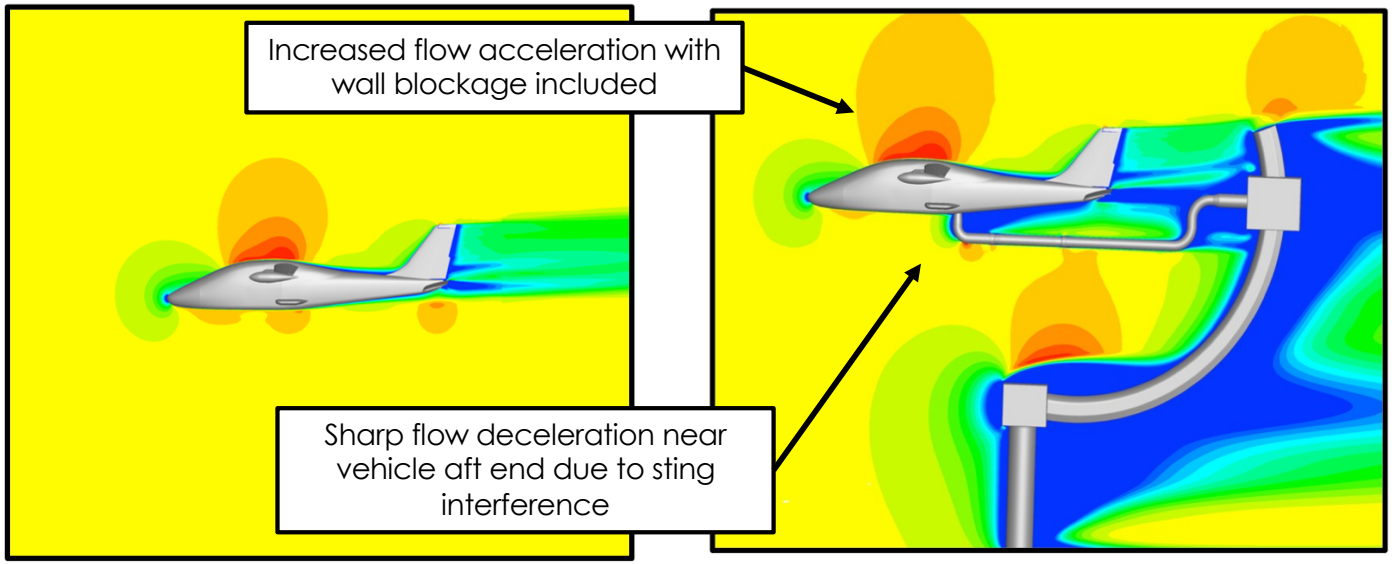
- Establish best-practices to generate aerodynamic database with LAVA and Star-CCM+
- Apply best-practices to CFD databases which cover a variety of flight conditions and aircraft configurations
  - Database 1 (188 simulations): Power-off
  - Database 2 (233 simulations): Cruise power-on
  - Database 3 (2000+ simulations): High-lift power on

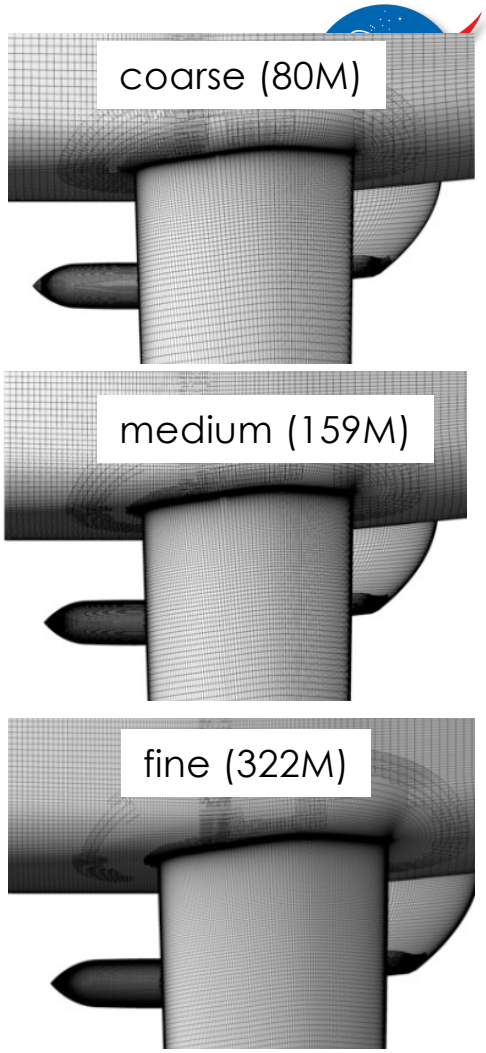


- Post-process database results to assess aircraft performance and stability for the aircraft flight demonstrator
- More information can be found in NASA AMS Seminar by Jared Duensing as well as AIAA2019-0274 and AIAA2019-3698

Verification and Validation for Power-Off Case

- Experimental data only available for power-off configuration
- Extensive validation & verification (188 Simulations[1]) performed:
  - Numerical scheme (including low Mach preconditioning)
  - Turbulence Model
  - Mesh refinement (free-air, free-air + sting, free-air + sting + wind-tunnel)

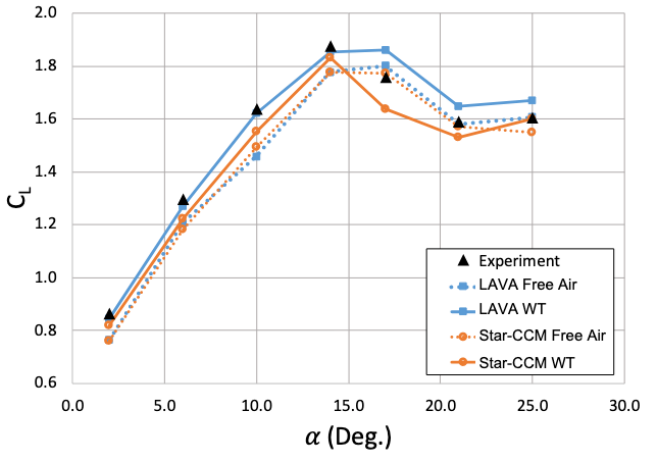


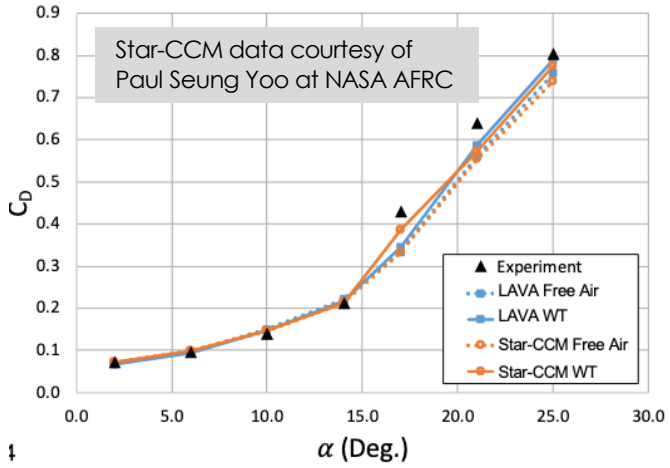


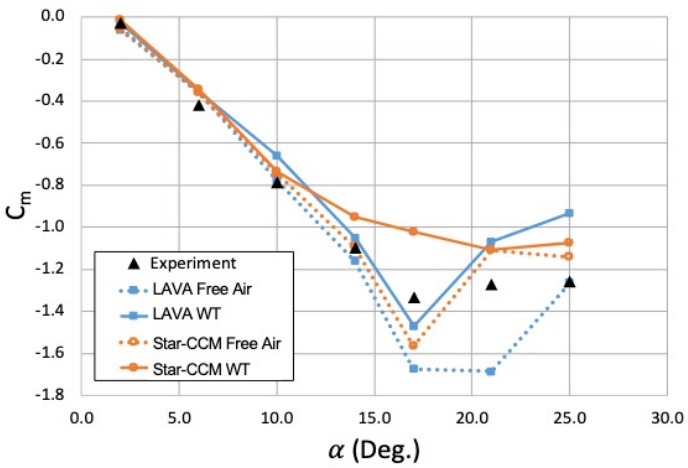
[1] Duensing et al. "Establishing Best Practices for X-57 Maxwell CFD Database Generation", AIAA SciTech 2019 Forum

Verification and Validation for Power-Off Case

- Overall **excellent agreement with experiments** in linear regime pre-stall
- Incorporating wind tunnel effects to the CFD simulation improved lift predictions
- Only minor changes in drag noted in linear regime
- Larger scatter in results observed post-stall. Limitations of RANS in stall regime well known and documented (see High Lift Prediction Workshop series https://hiliftpw.larc.nasa.gov)
- Preliminary validation study resulted in **high confidence for power-on database**





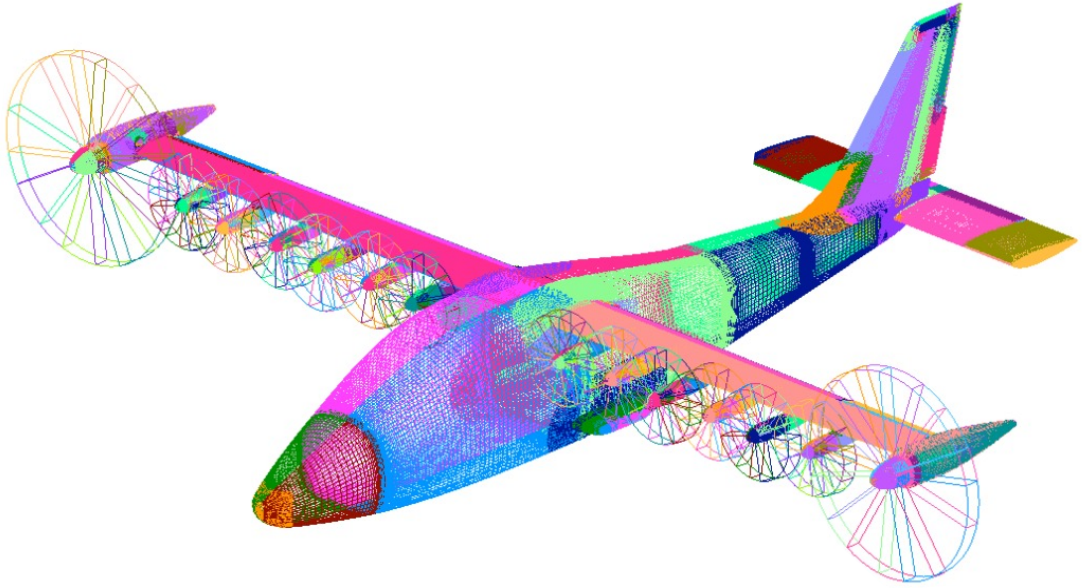


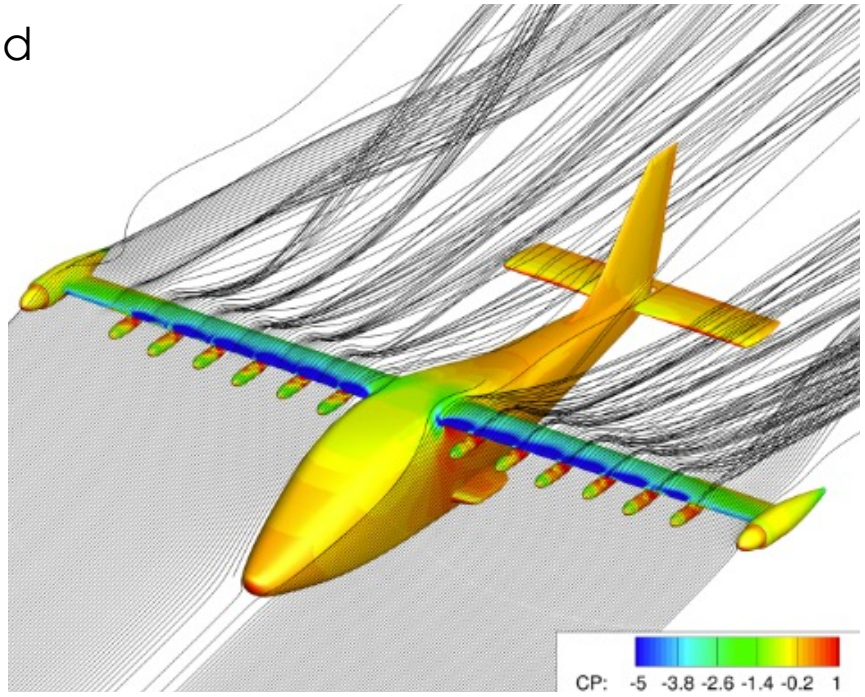
[1] Duensing et al. "Establishing Best Practices for X-57 Maxwell CFD Database Generation", AIAA SciTech 2019 Forum

WT = Wind Tunnel Walls + Sting + C-Strut

X-57 Power-On Configuration

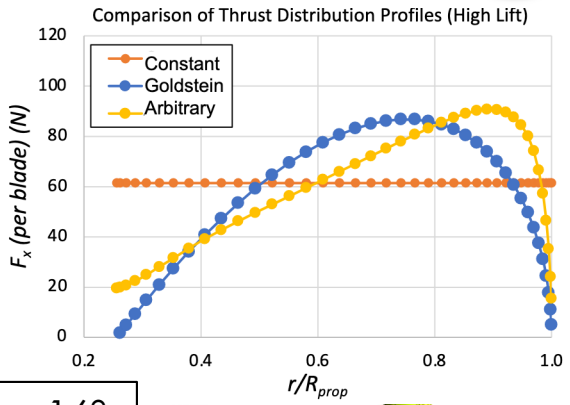
- Structured curvilinear overset mesh consisting of 350 zones with 160-180M grid points
- For power-on configuration only **free-air simulations** considered
- Actuator zones model the momentum imparted from the propeller to the surrounding flow field without the computational cost of simulating the moving blade
- Several different thrust and torque profiles studied



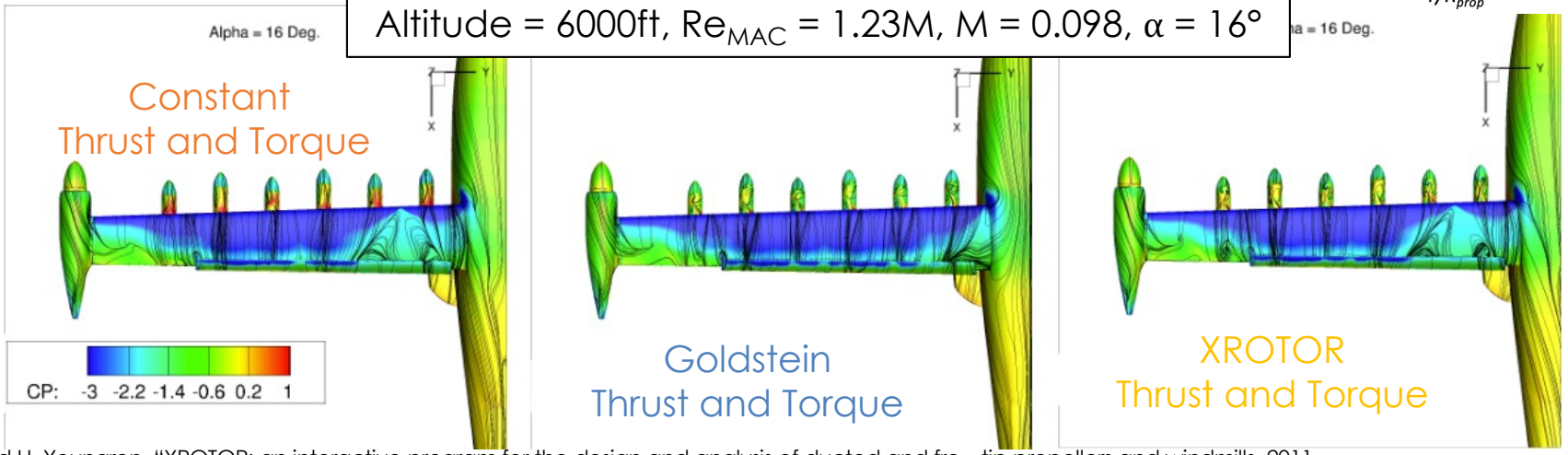


Selecting Actuator Zone Loading Distributions

- For high-lift propulsion cases, XROTOR[2] data was available to define an arbitrary radial thrust and torque distribution
- Initial CFD simulations were performed using LAVA to understand impact of thrust and torque distributions on the solution
- Separation behavior at high AoA highly depends on load distribution



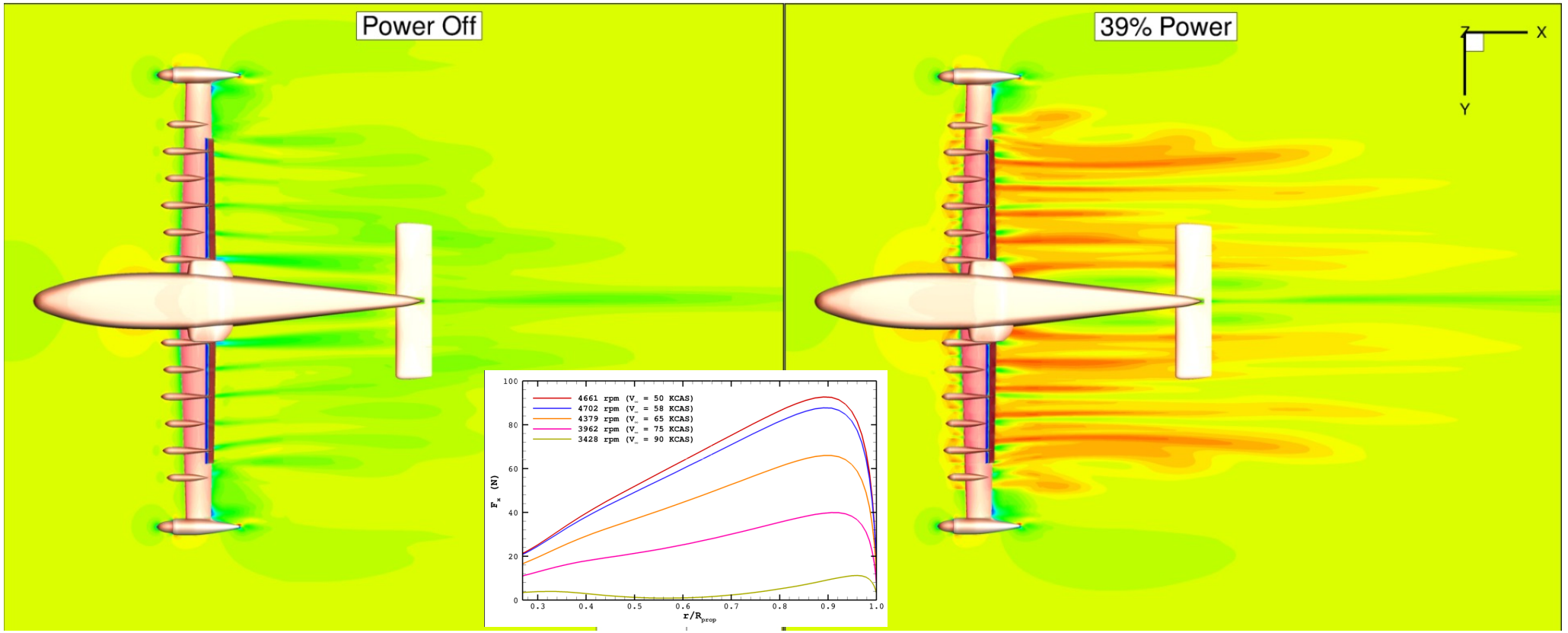
Altitude = 6000ft, Re_{MAC} = 1.23M, M = 0.098, α = 16°



[2] Drela, M. and H. Youngren. "XROTOR: an interactive program for the design and analysis of ducted and fre—tip propellers and windmills, 2011. [Software] Available at: https//web.mit.edu/drela"

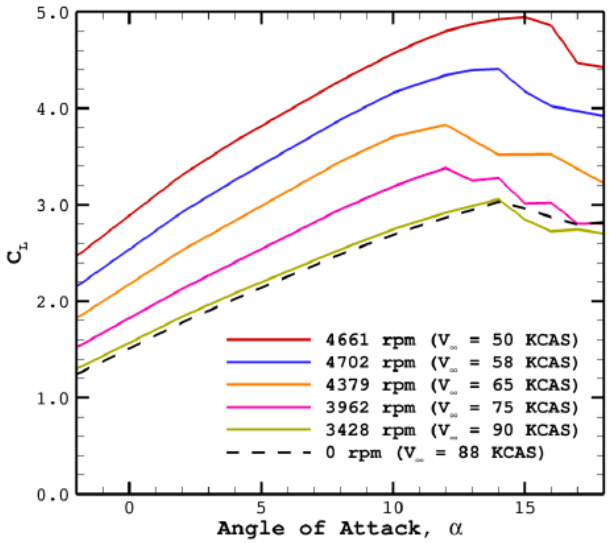
X-57 Sample Power on vs Power off Flow Visualizations

- Altitude: 2,500ft, Mach = 0.119, Re_{MAC} = 1.6M, Flaps = 30°
- Dimensionless streamwise velocity (U/U_{ref}) is shown on slice, C_p on aircraft surface

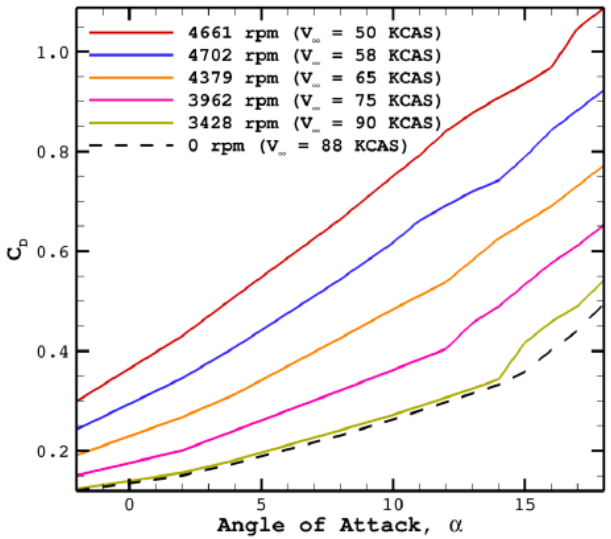


X-57 Steady-State RANS Database Summary

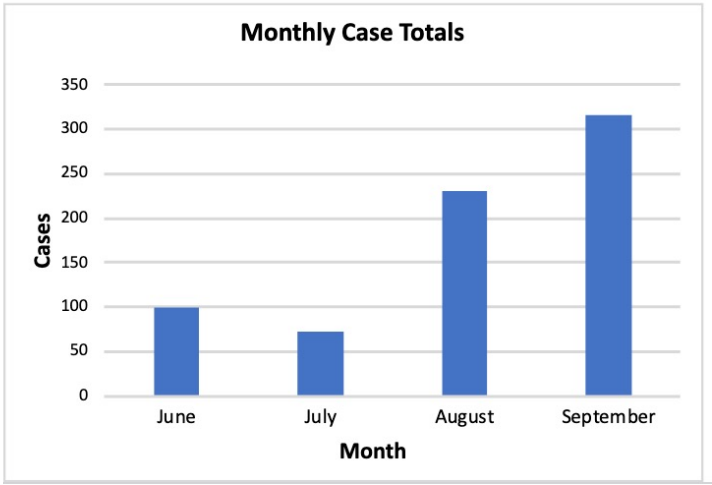
- Over 3000 RANS simulations have been conducted in support of X-57
- Code to code comparison showed < 5% difference in integrated lift and drag



(a) Lift



(b) Drag



AMS Seminar by Jared Duensing and Gaetan Kenway
https://www.nas.nasa.gov/pubs/ams/2020/10-13-20.html

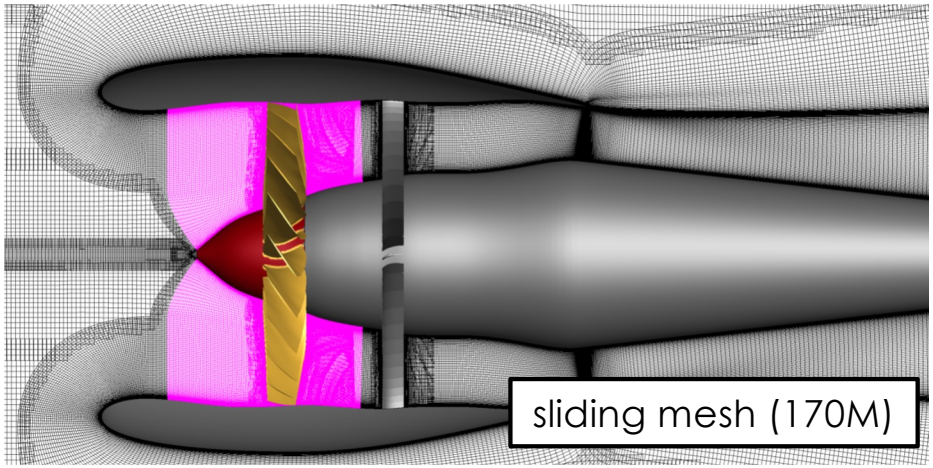
Condition: Altitude: 2,500 ft, Mach = 0.119, Re_{MAC} = 1,682,000, Flaps = 30°



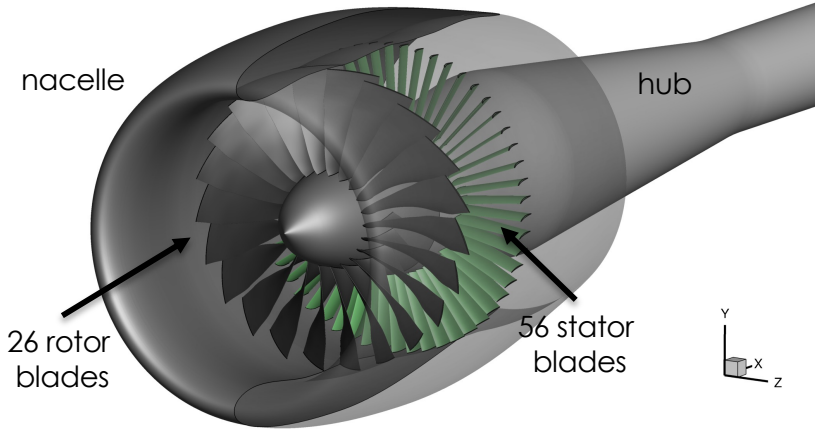
Aircraft Noise Reduction (ANR)
R4 Noise Source Diagnostic Test (SDT)

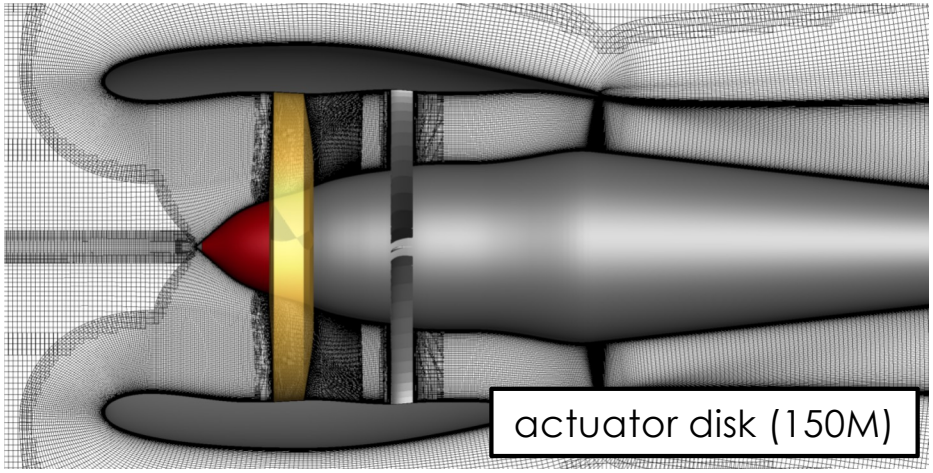
Work Supported by NASA Advanced Air Transport Technology (AATT)

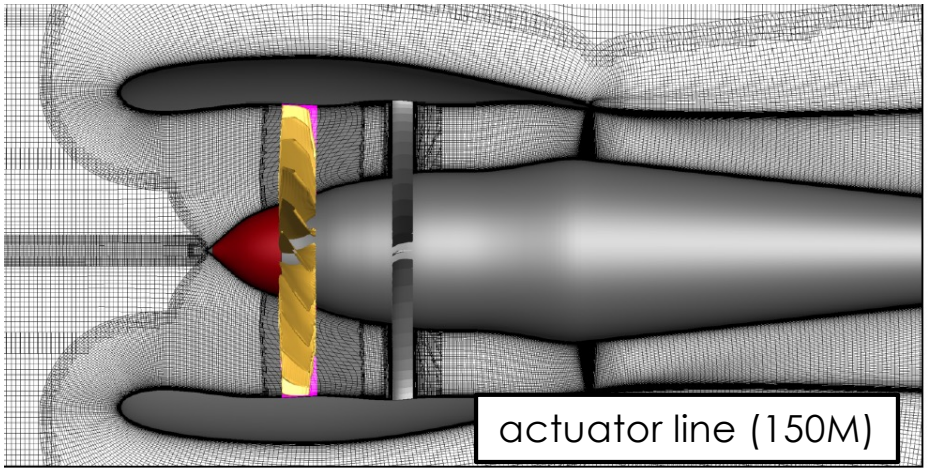
R4 Noise Source Diagnostic Test (SDT) at Approach Speed



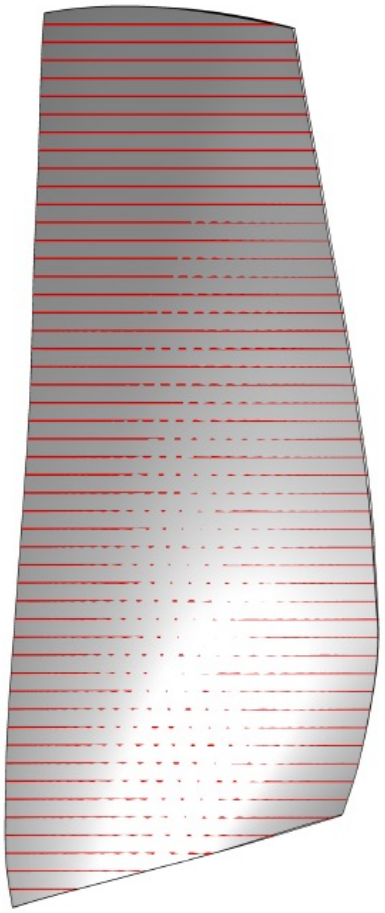
M_∞ = 0.1 ; 7808 RPM (67% cruise speed)



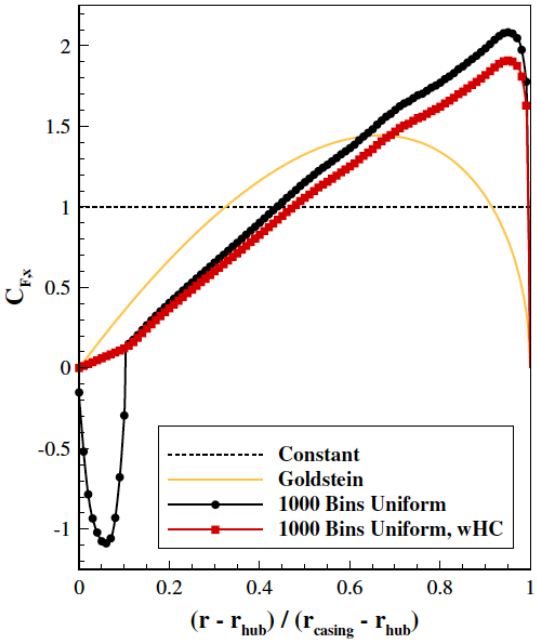




R4 SDT: Procedure to Compute Blade Load Distribution



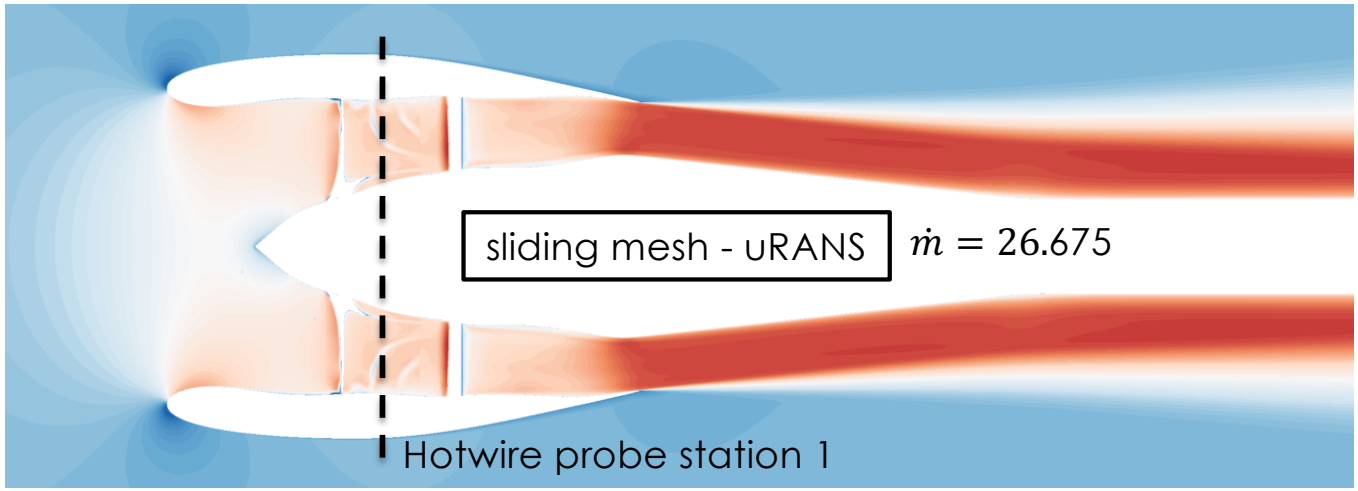
- Loads are obtained from sliding mesh simulation using NASA's Chimera Grid Tools OVERINT and MIXSUR
- Surface pressures averaged over 10revs from uRANS to compute thrust (4040N) and torque (904Nm)

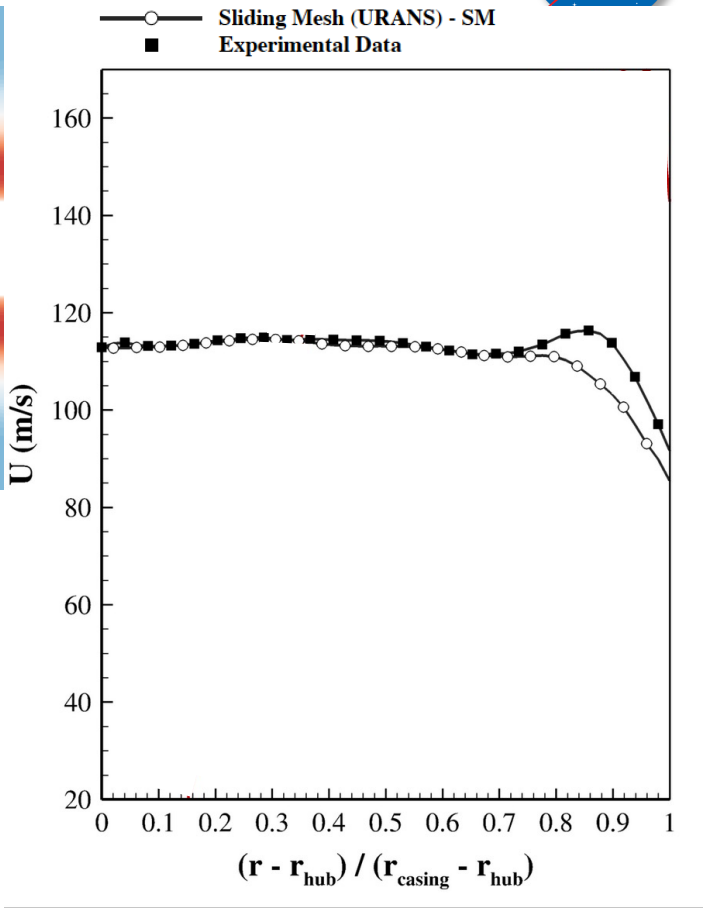


Load Distribution

- TRILOAD: Surface divided in 1000bins to get load distribution
- Correction applied at hub (wHC) to account for negative thrust
- Constant and Goldstein Optimum loading used for comparison

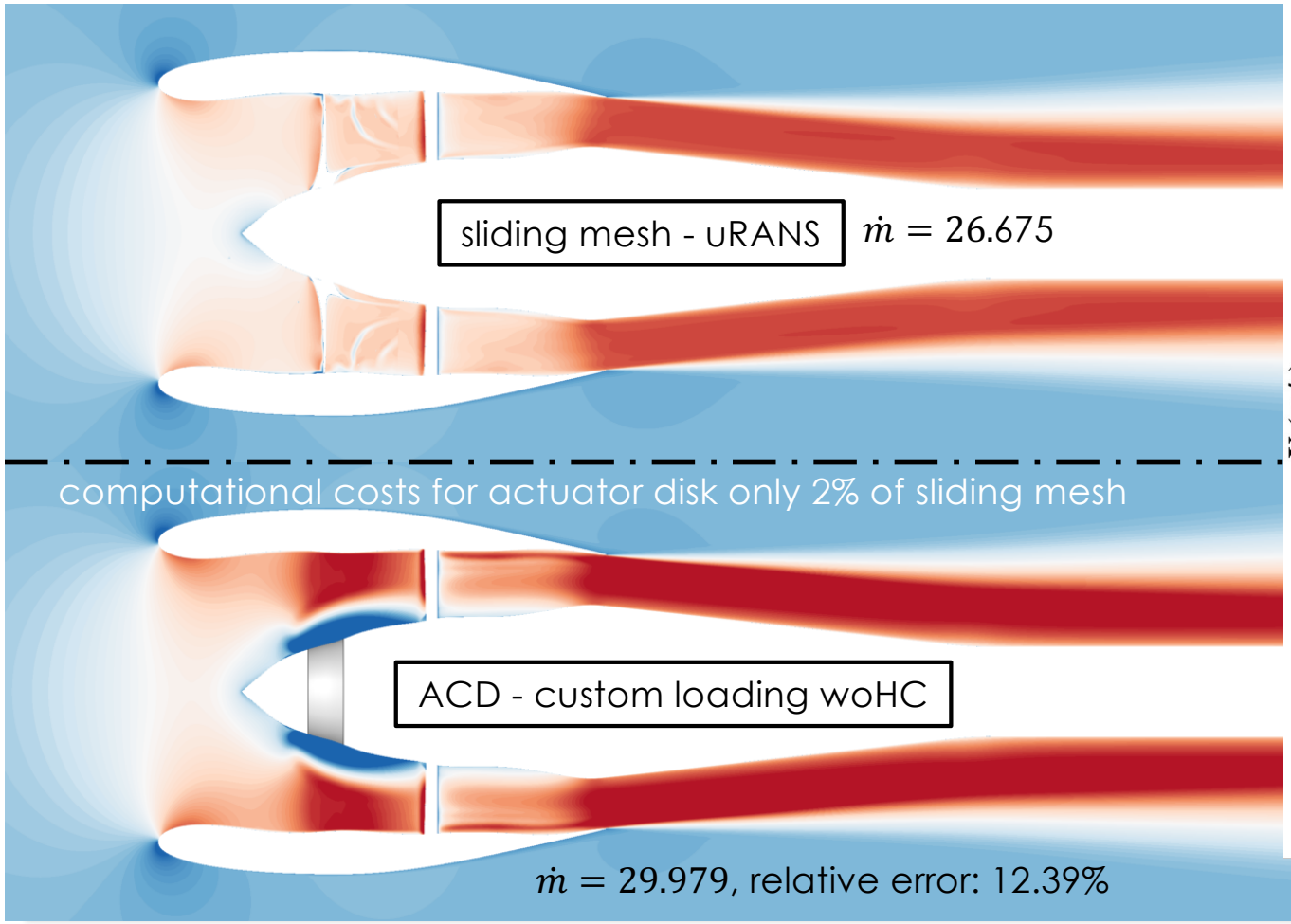
R4 SDT: Streamwise Velocity Contour Plots

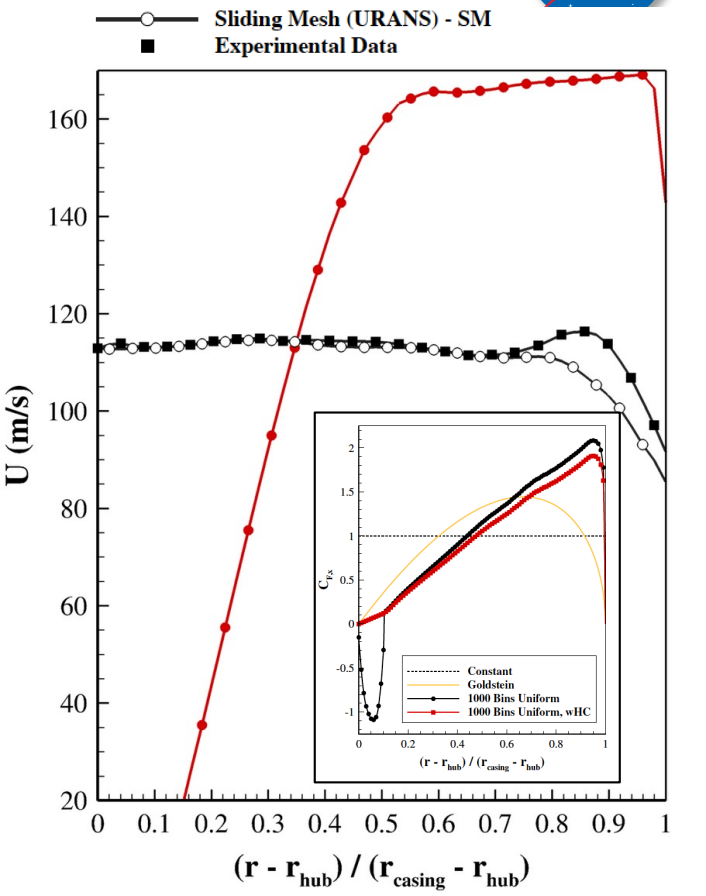




- Baseline: uRANS sliding mesh configuration
- Comparison of mass flow rate $\dot{m}_{exp} = 26.535$ kg/s
- Comparison of mass-averaged total pressure and temperature ratio
- Excellent agreement with hot-wire probe at station 1
- Sliding mesh shows different behavior at blade tip

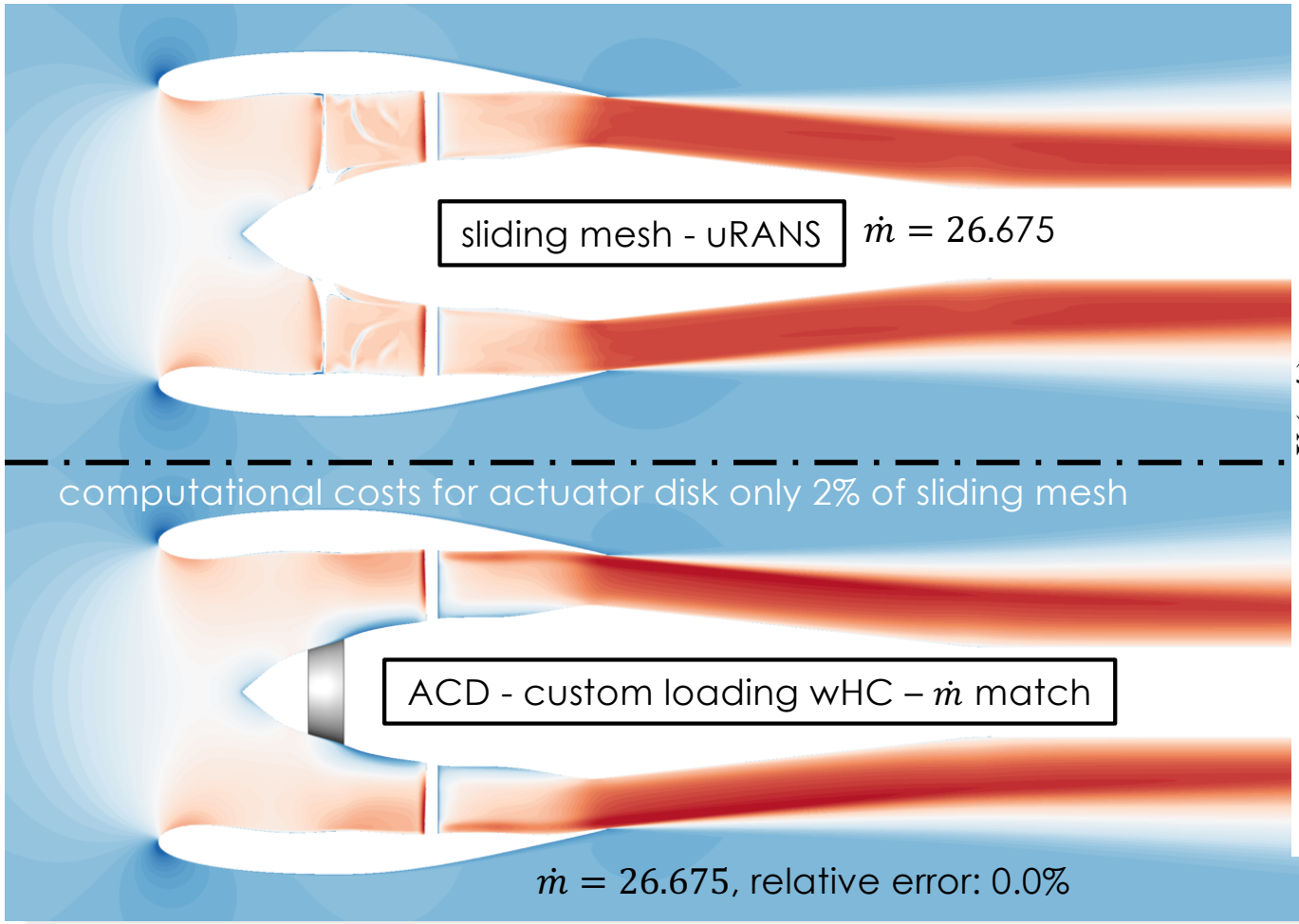
R4 SDT: Actuator Disk with Custom Profile no Hub Correction

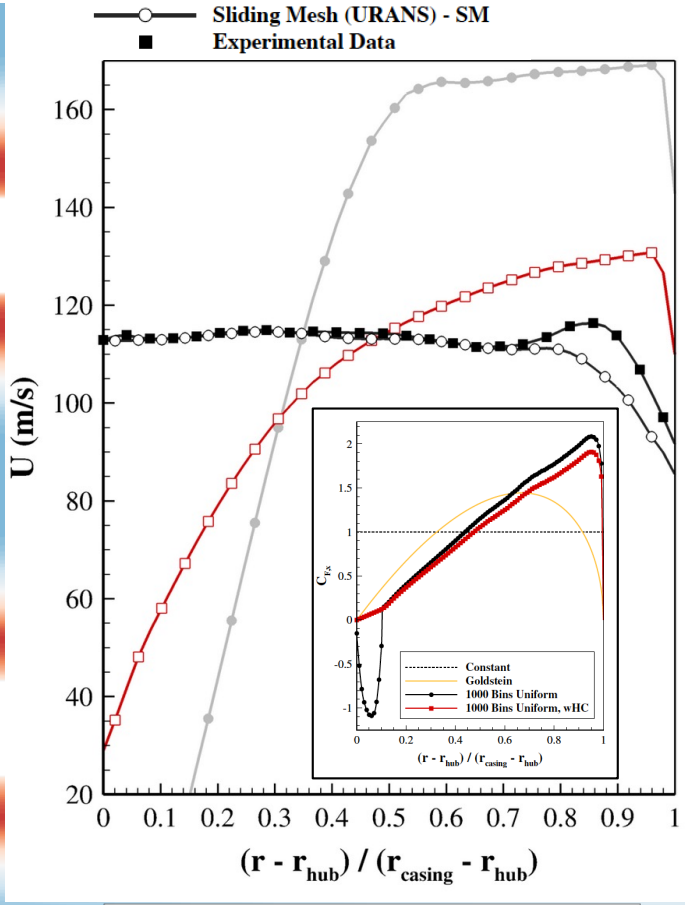




RANS, Actuator Zone - AR-nU Grid
Target Thrust/Torque, woHC, Custom Load Distribution

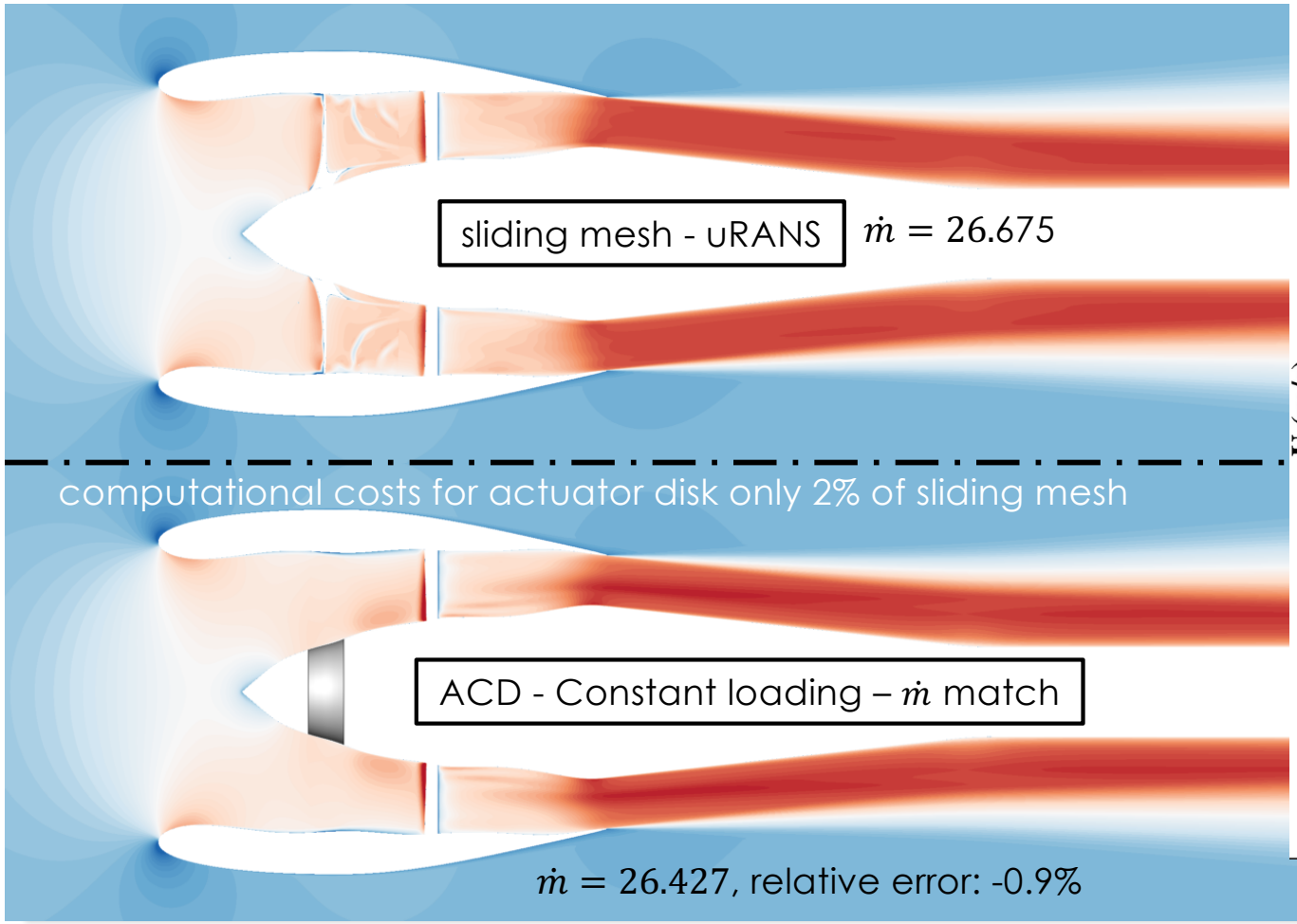
R4 SDT: Actuator Disk with mass flow matching

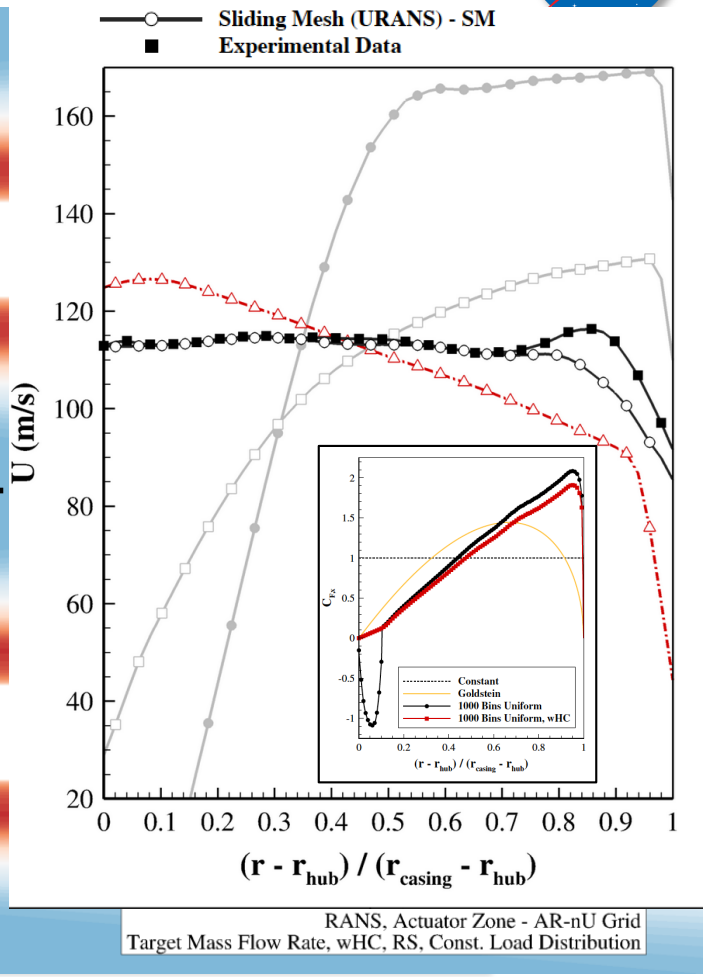




RANS, Actuator Zone - AR-nU Grid
Target Mass Flow Rate, wHC, RS, Custom Load Distribution

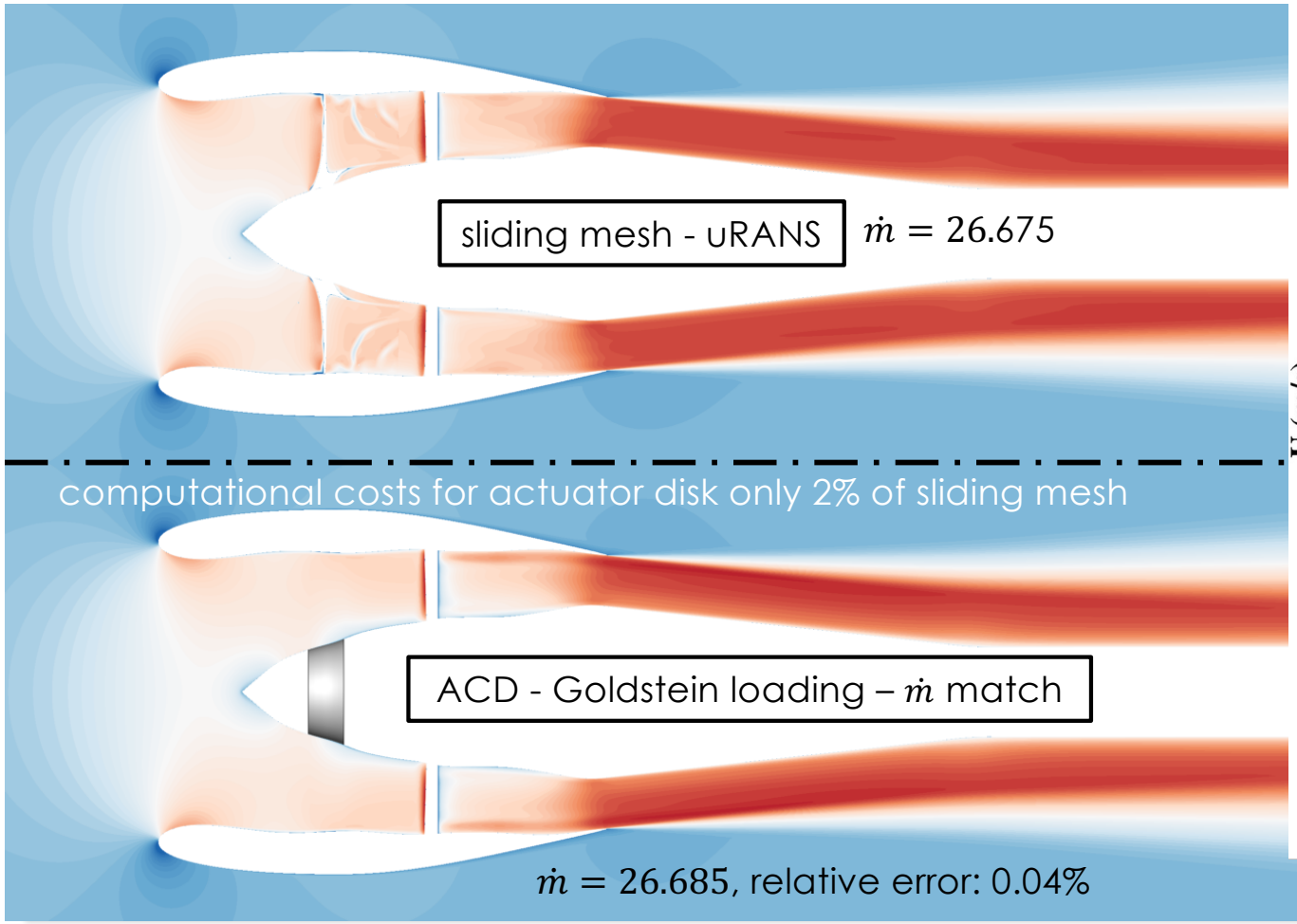
R4 SDT: Actuator Disk with Goldstein and $\dot{m}$ Matching

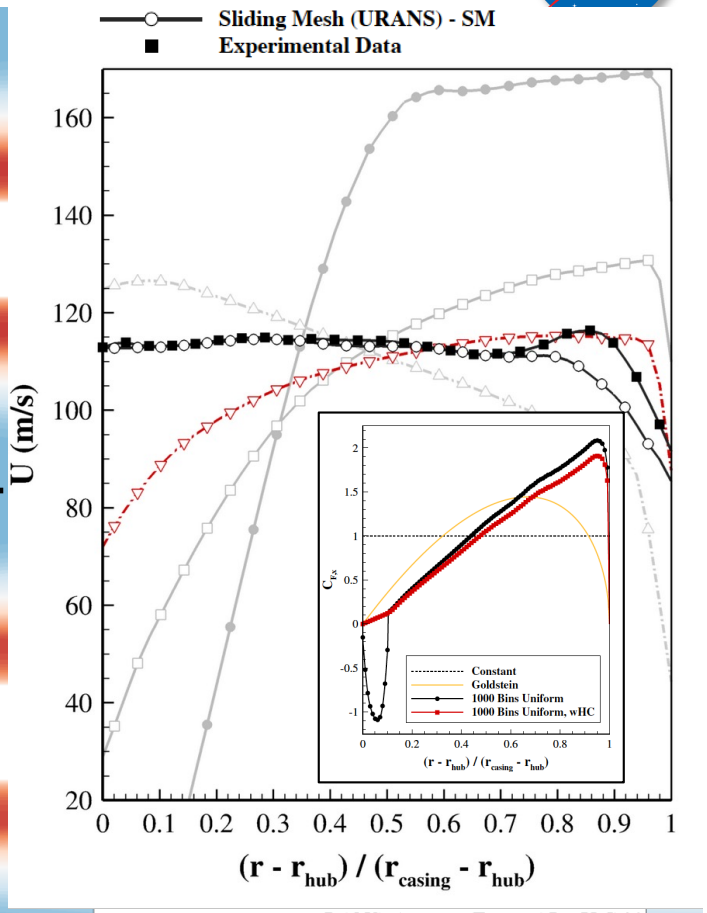




RANS, Actuator Zone - AR-nU Grid
Target Mass Flow Rate, wHC, RS, Const. Load Distribution

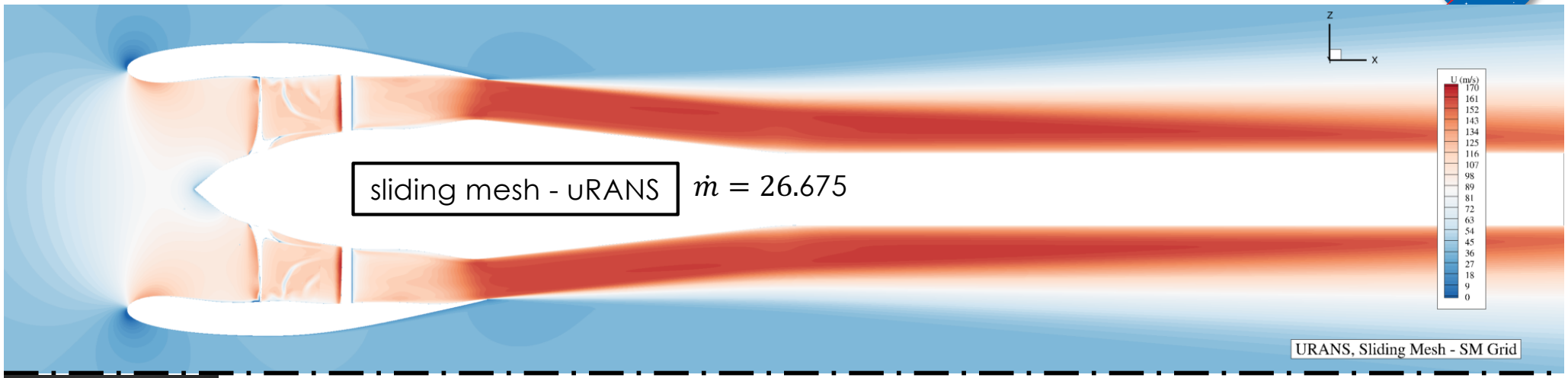
R4 SDT: Actuator Disk with Goldstein and $\dot{m}$ Matching

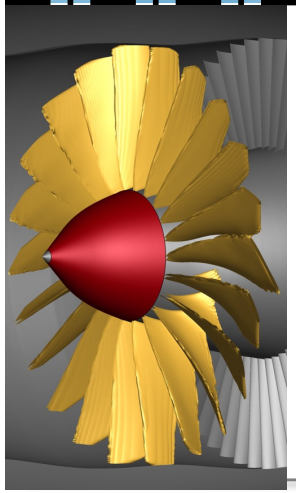




RANS, Actuator Zone - AR-nU Grid
Target Mass Flow Rate, wHC, RS, Goldstein Load Distribution

R4 SDT: Actuator Line with Goldstein and $\dot{m}$ Matching



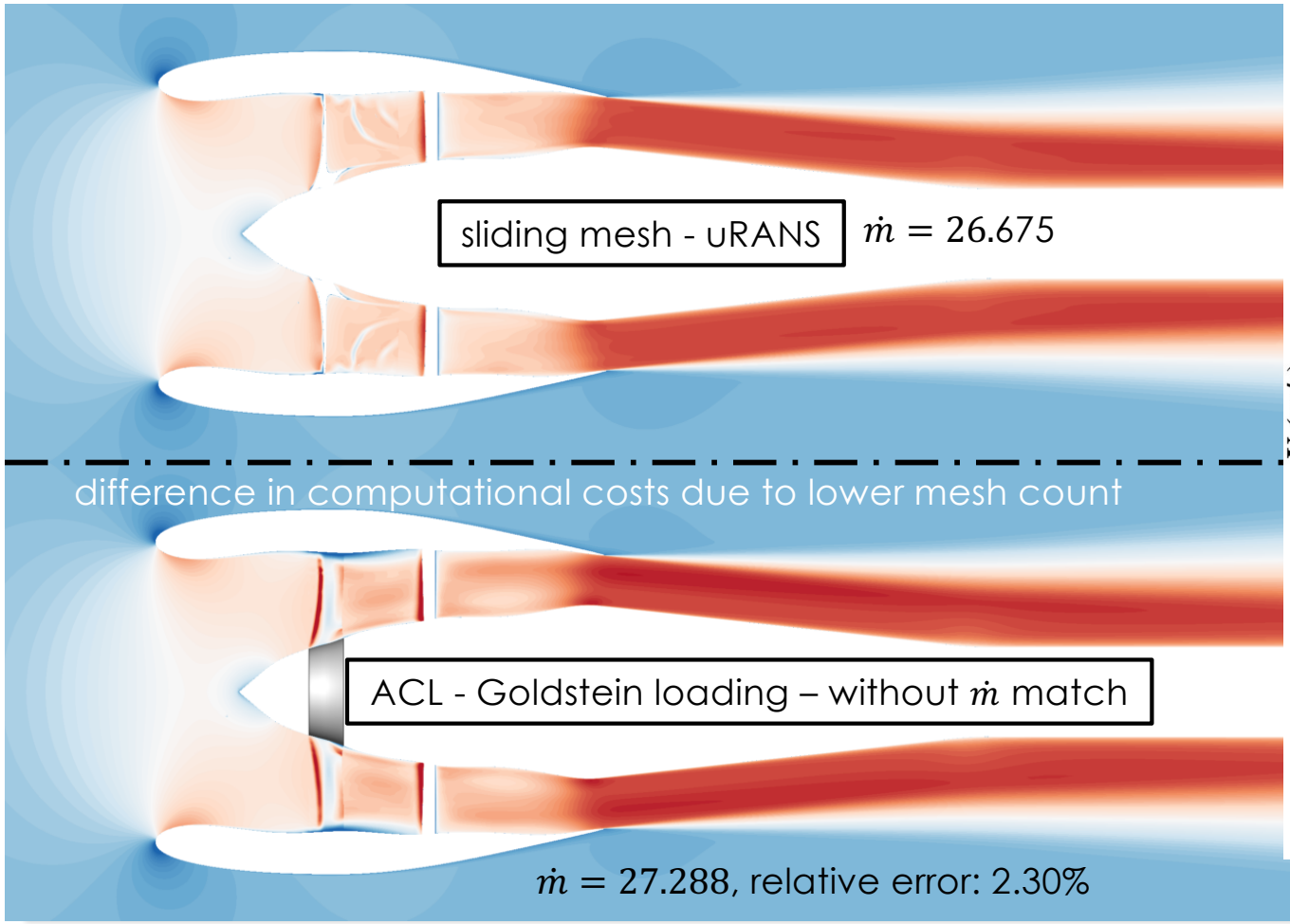


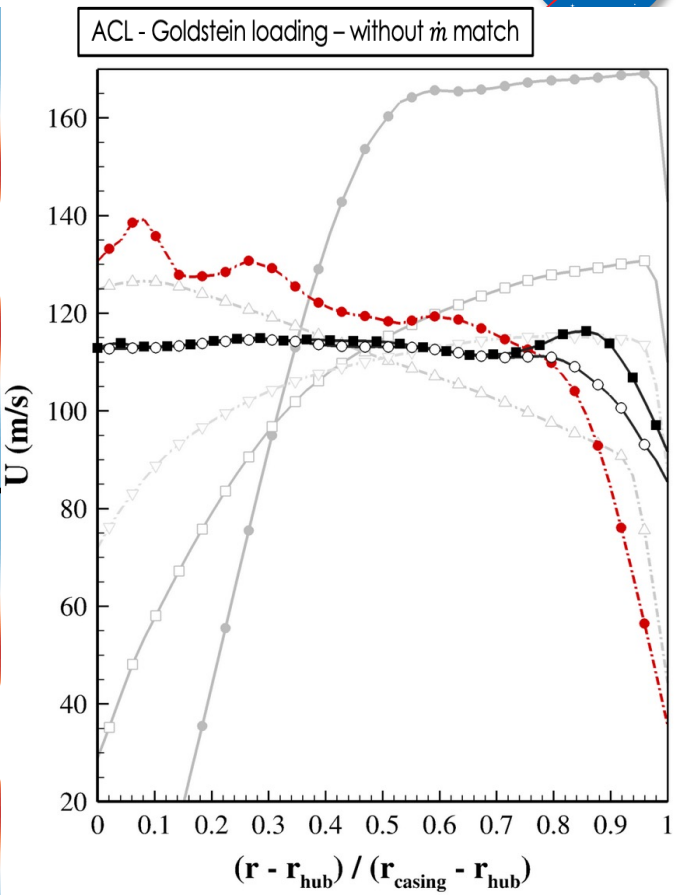
- Source term applied around 3D control points using non uniform gaussian distribution:

$$\Theta(x_c, x_t, x_r) = \frac{1}{\epsilon_c \epsilon_t \epsilon_r \pi^{3/2}} \exp\left(\frac{(x_c - x_{c,0})^2}{\epsilon_c^2} - \frac{(x_t - x_{t,0})^2}{\epsilon_t^2} - \frac{(x_r - x_{r,0})^2}{\epsilon_r^2}\right)$$

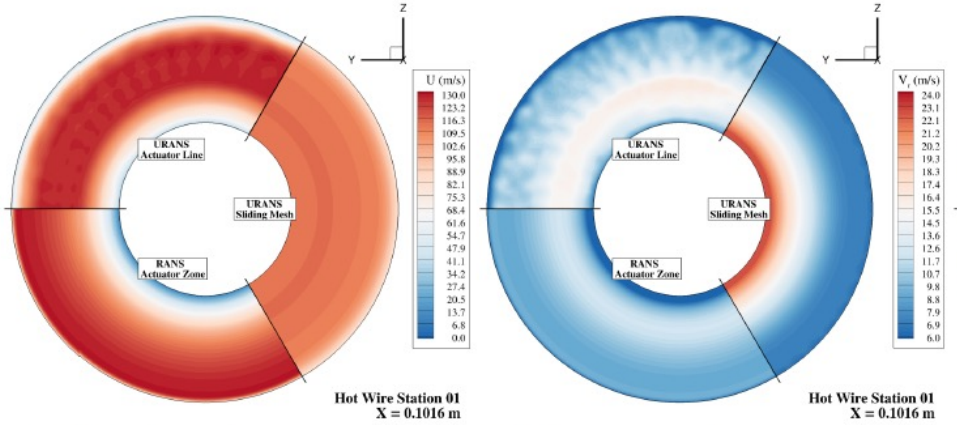
- Gaussian width depends on local mesh and local blade thickness (For this study: 3e-4 D_{rotor})

R4 SDT: Actuator Line with Goldstein Loading without $\dot{m}$ Match



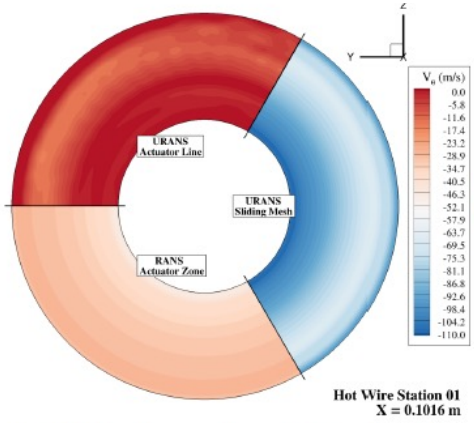


R4 SDT: Hot wire probe station 1

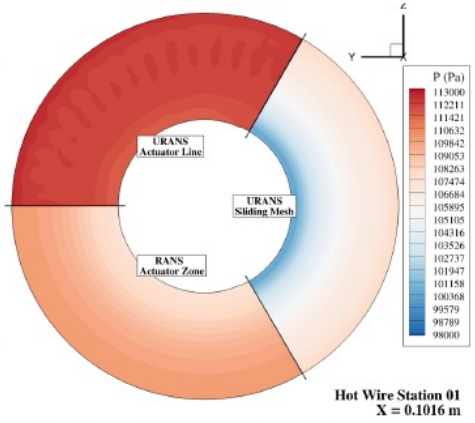


(a) Hot wire probe station 1 - U.

(b) Hot wire probe station 1 - V_r.

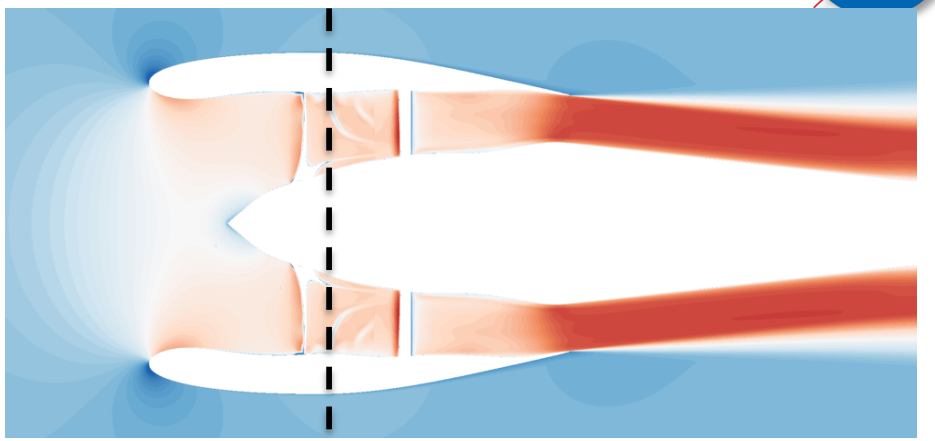


(c) Hot wire probe station 1 - V_θ.



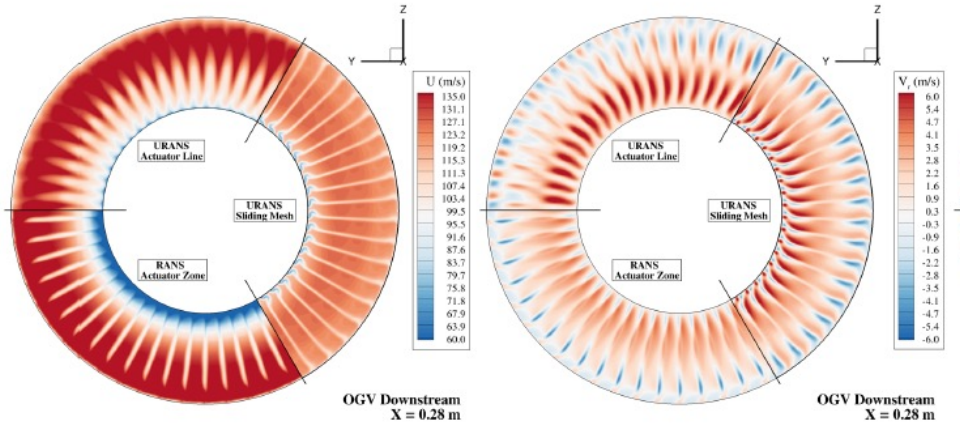
(d) Hot wire probe station 1 - P.

Custom wHC, m-match

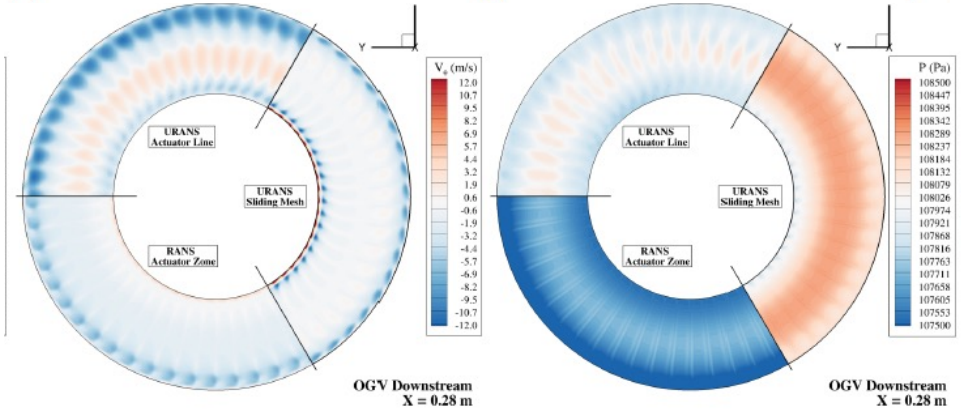


- Biggest difference in flow field observed downstream of rotor
- Actuator models show low velocity region close to hub
- Actuator line and disk method under-predict tangential and radial velocity components

R4 SDT: OGV downstream station

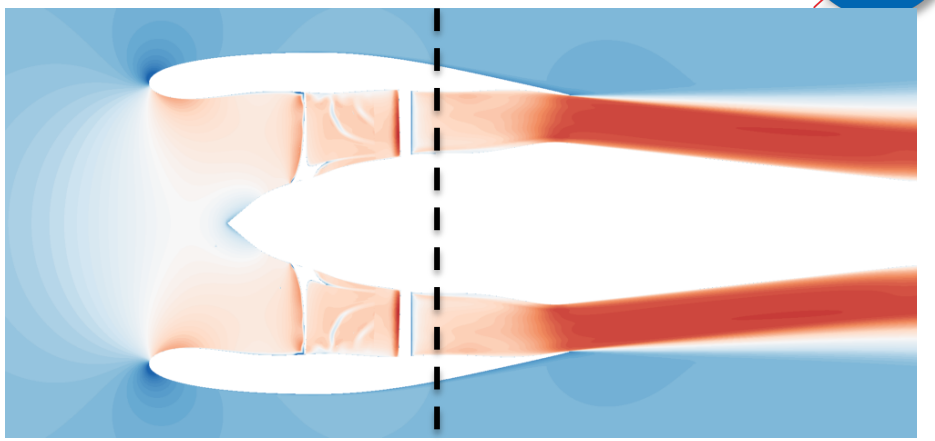


(f) OGV downstream station - U. (g) OGV downstream station - V_r.



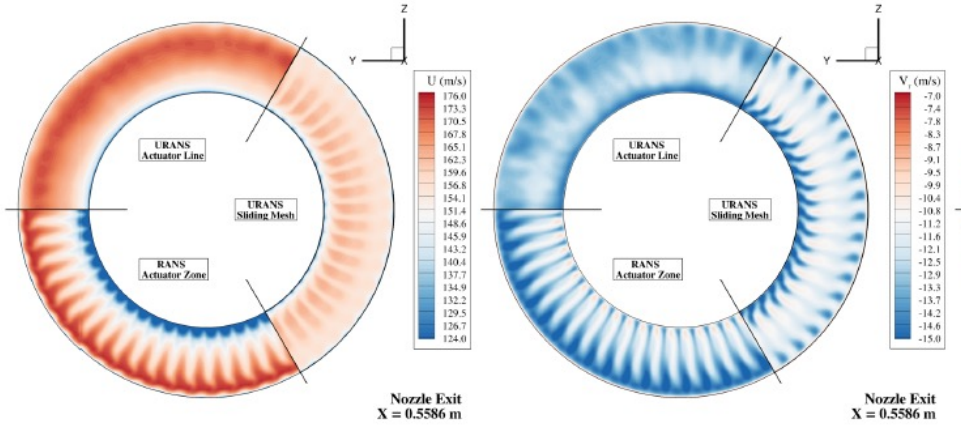
(h) OGV downstream station - V_θ. (i) OGV downstream station - P.

Custom wHC, m-match



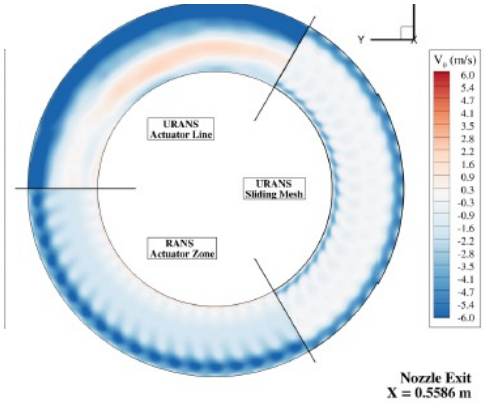
- Low axial velocity region remains throughout OGV
- Actuator line method shows prevalent tangential velocity component
- Actuator disk and sliding mesh mostly swirl free

R4 SDT: Nozzle exit station

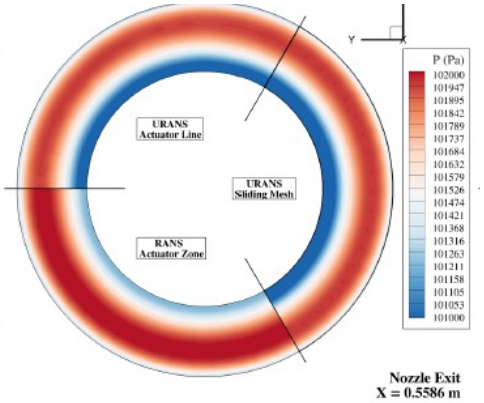


(k) Nozzle exit station - U.

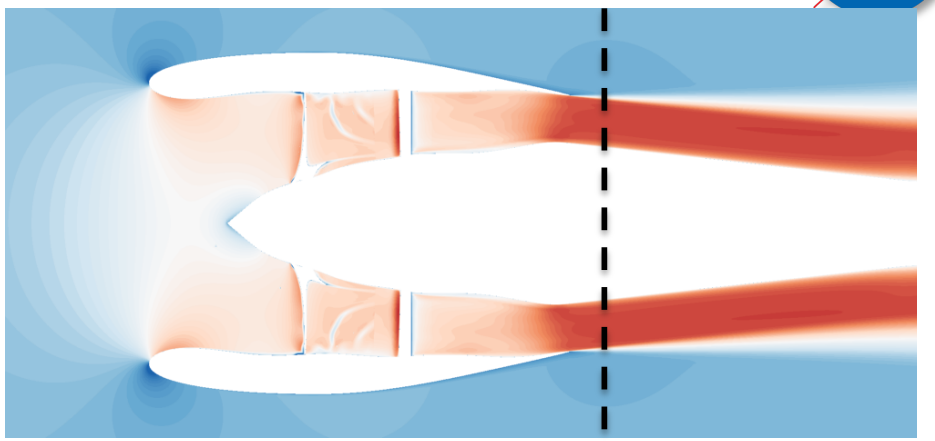
(l) Nozzle exit station - V_r.



(m) Nozzle exit station - V_θ.



(n) Nozzle exit station - P.

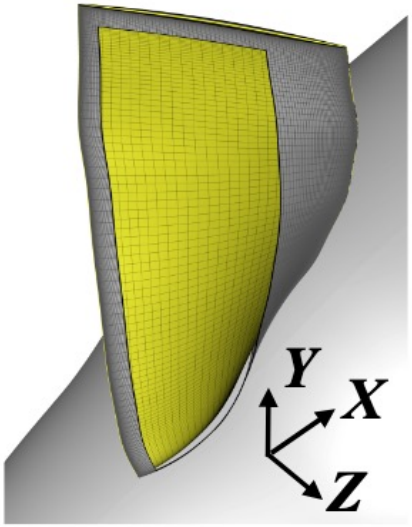


- While mass averaged quantities (pressure, temperature) agree within 1% of experiment flow field qualitatively quite different
- Further improvements to implemented propulsion method necessary to include radial and tangential source contributions

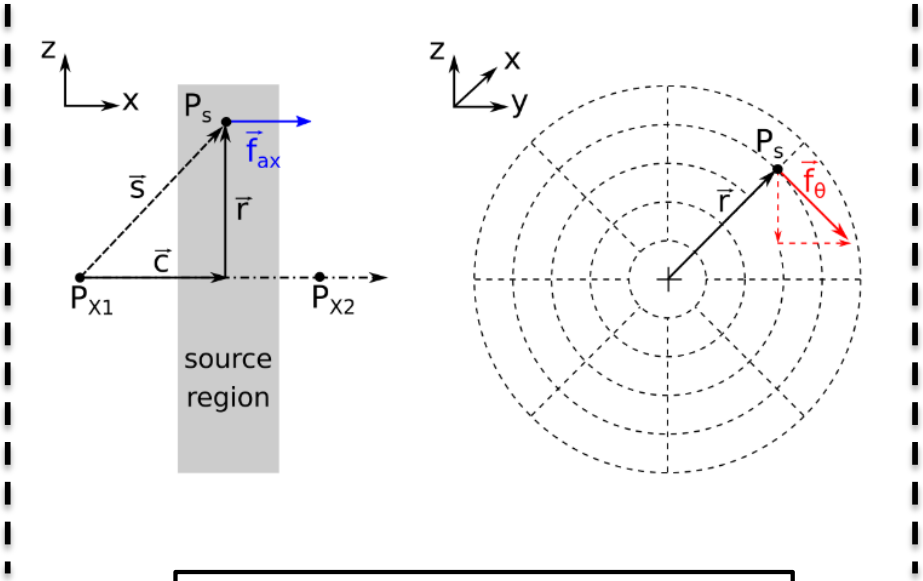
Improvements to Actuator Modelling

Useful if Blade Geometry Not Available for CFD

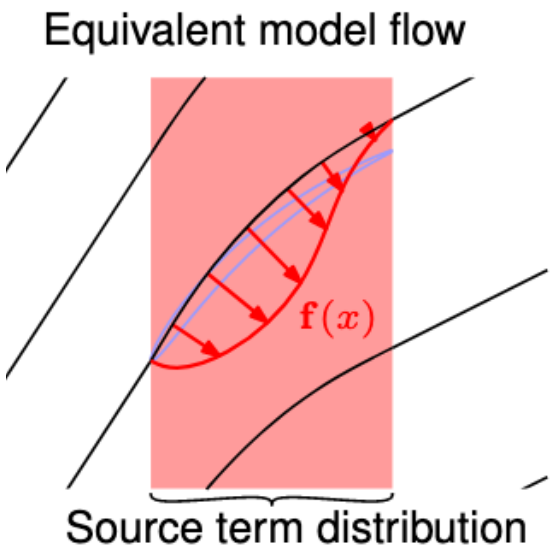
- Blades of Turbomachinery Fans strongly twisted
- Applying force in axial and tangential direction only might be too simple
- Utilizing a more blade conforming model could improve results (e.g. David Hall)
  (Hall et.al. " Analysis of Fan Stage Conceptual Design Attributes for Boundary Layer Ingestion", 2017 ASME J. Turbomachinery)



R4 Blade surface



Simple source Term Distribution



David K. Hall Model

Summary and Future Direction

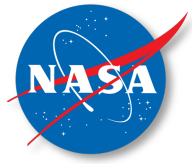


- Demonstrated that **actuator disk/line methods accelerate** propulsion airframe integration (PAI) **design and analysis** when blade geometry is not available yet
- Good agreement with simple canonical test-cases for actuator disk methods
  - **Importance of a realistic load distribution** has been highlighted
- Actuator disk methods have been demonstrated to be a powerful tool to include propulsion effects during the generation of a large database
  - **Computational cost only 2%** compared to unsteady sliding mesh method
- Simple source distribution method seems to result in non-physical separation on Hub, improved body force methods have potential to correct this behavior
- Actuator line method can be utilized to include **unsteady effects if exact blade shape not known/available**
- Actuator line method resulted in cost savings compared to sliding disk method mainly due to decreased mesh resolution
- **Sliding disk method results in significantly improved accuracy** and gives best physical representation while only being 30% more computational expensive.

Acknowledgments

- This work is supported in part by the Advanced Air Transportation Technology (AATT) project and Flight Demonstrations and Capabilities (FDC) project
- Computer time has been provided by the NASA Advanced Supercomputing (NAS) facility at NASA Ames Research Center.
- Leonardo Machado, Timothy Chau and other LAVA group members for helpful discussions and advice

Questions?



POC: gerrit-daniel.stich@nasa.gov (Propulsor Modeling Methods)

jared.c.duensing@nasa.gov (X-57 Maxwell Simulations)

luismiguel.dossantosfernandes@nasa.gov (NASA R4 SDT Simulations)

cetin.c.kiris@nasa.gov (LAVA Framework)