

Implementation of a Body Force Model into OVERFLOW for Propulsor Simulations



H. Doğuş Akaydın

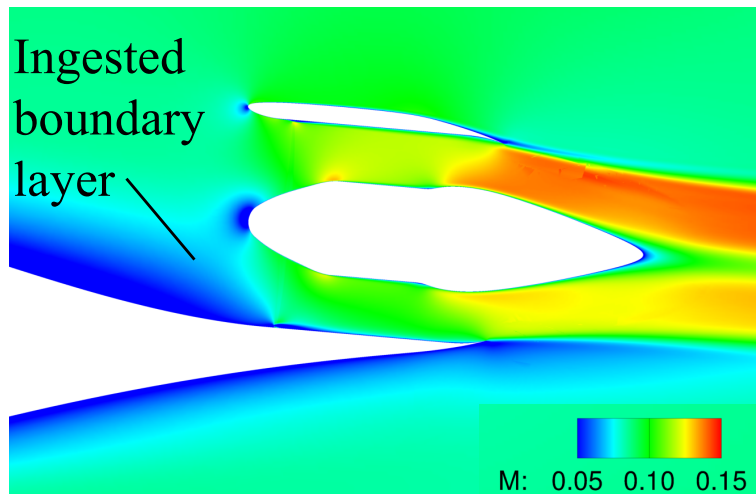
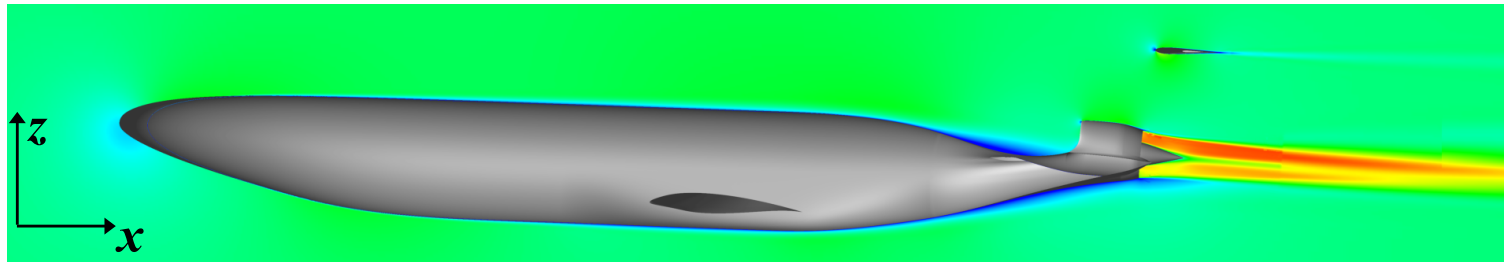
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Science and Technology Corporation
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Shishir A. Pandya

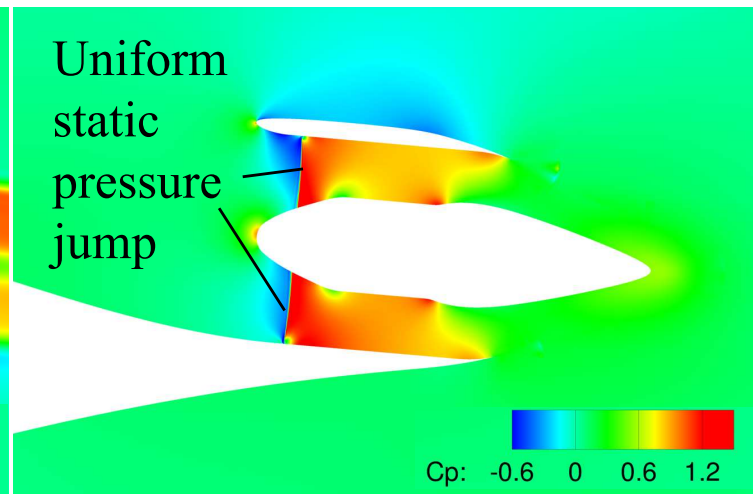
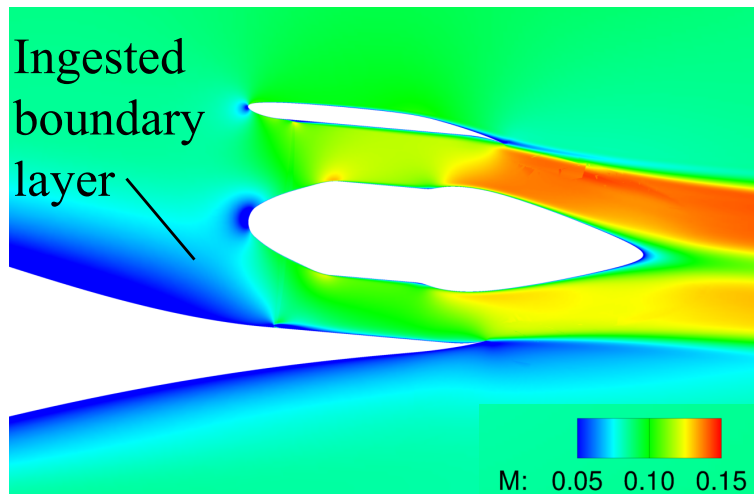
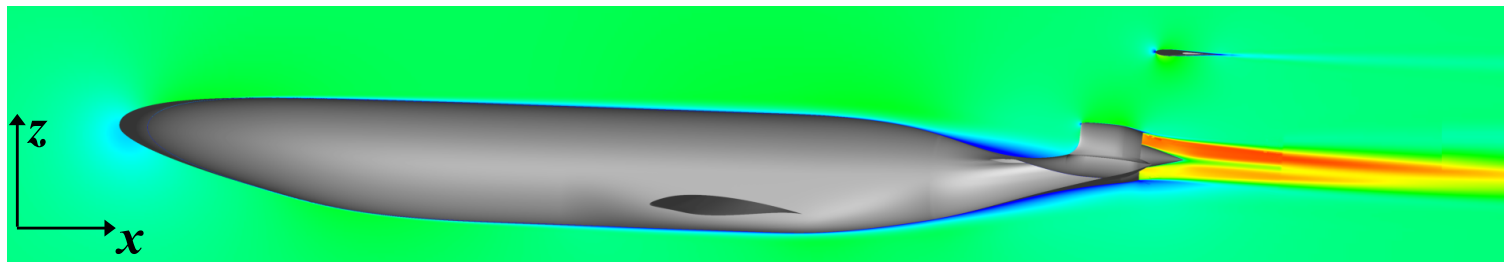
Aerospace Engineer
NASA Ames Research Center

35th Applied Aerodynamic Conference, AIAA Aviation Forum
6th June, 2017. Denver, CO.

The application: Boundary Layer Ingestion on D8 aircraft



The application: Boundary Layer Ingestion on D8 aircraft



Previous method:
Uniform static
pressure jump

$$p_{\text{avg}} = 0.5(p_J + p_{J+1})$$

$$p_J = p_{\text{avg}} - 0.5\Delta p$$

$$p_{J+1} = p_{\text{avg}} + 0.5\Delta p$$

(ρ , T are not jumped)

Literature

Variants of actuator disk or blade element models

Helicopter rotors & wind turbine applications

Fejtek and Roberts [1992]

Zori and Rajagopalan [1995]

Chaffin and Berry [1997] --> Two versions are already in Overflow

O'Brien and Smith [2005]

... many others.

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Turbomachine applications

Joo and Hynes [1997]

Kim et al. [1999]

...

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Turbomachine applications

Joo and Hynes [1997]

Kim et al. [1999]

...

A particular series of “body-force” approaches for turbomachines

Marble [1964]

...

Gong et al. [1998]

Defoe and Spakovszky [2013]

Peters et al. [2014]

Hall et al. [2017]

The implemented body force model by Hall et al.

$$\begin{aligned}\nabla \cdot (\rho \mathbf{V}) &= 0 \\ \mathbf{V} \cdot \nabla \mathbf{V} + \frac{\nabla p}{\rho} &= \mathbf{f} \\ \mathbf{V} \cdot \nabla h_t &= \mathbf{V} \cdot \mathbf{f} + \dot{e} \\ f &= \frac{2\pi\delta(\frac{1}{2}|\mathbf{W}|^2)}{\frac{2\pi r}{B}|n_\theta|} \\ \dot{e} &= T \cdot \mathbf{V} \nabla s = -\mathbf{W} \cdot \mathbf{f}\end{aligned}$$

The implemented body force model by Hall et al.

$$\nabla \cdot (\rho \mathbf{V}) = 0$$
$$\mathbf{V} \cdot \nabla \mathbf{V} + \frac{\nabla p}{\rho} = \mathbf{f}$$

$$f = \frac{2\pi\delta(\frac{1}{2}|\mathbf{W}|^2)}{\frac{2\pi r}{B}|n_\theta|}$$

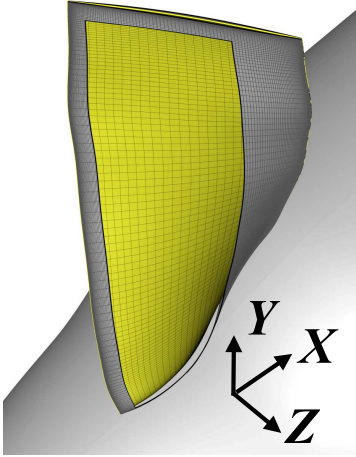
$$\mathbf{V} \cdot \nabla h_t = \mathbf{V} \cdot \mathbf{f} + \dot{e}$$

$$\dot{e} = T \cdot \mathbf{V} \nabla s = -\mathbf{W} \cdot \mathbf{f}$$

$$\mathbf{W} \cdot \mathbf{f} = 0 \text{ (Isentropic flow turning)}$$

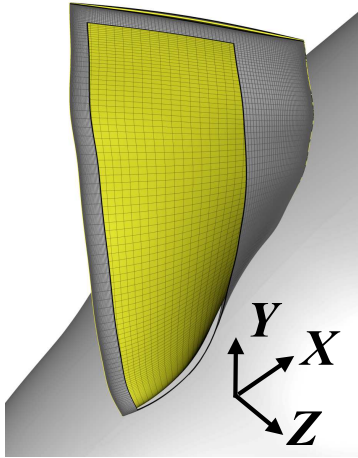
Implementation of the body force model

1. Define:

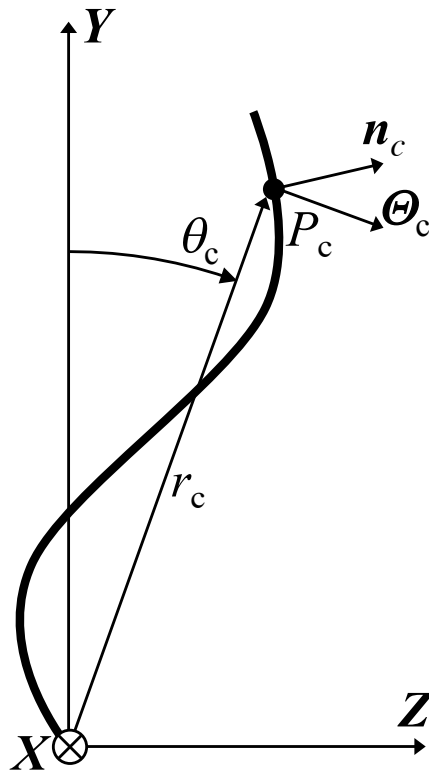
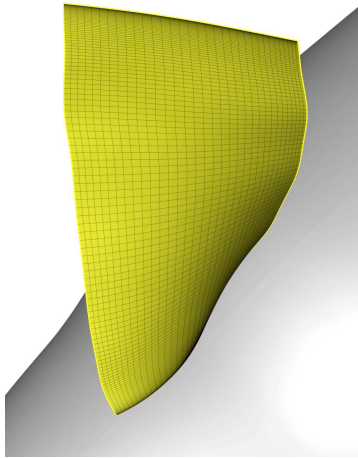


Implementation of the body force model

1. Define:



2. Extract:

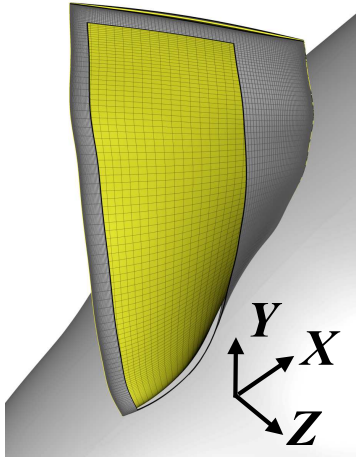


$$\mathbf{W} = \mathbf{V} - \mathbf{U} = \mathbf{V} - \Omega r \Theta$$

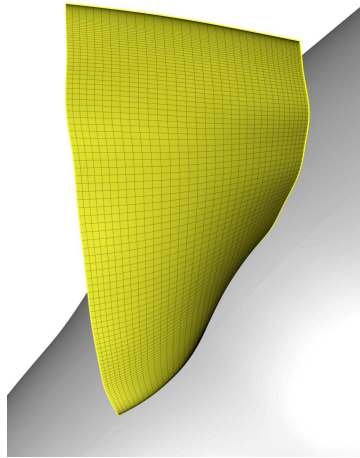
$$\delta = \arcsin \left(\frac{\mathbf{W} \cdot \mathbf{n}}{|\mathbf{W}| \cdot |\mathbf{n}|} \right)$$

Implementation of the body force model

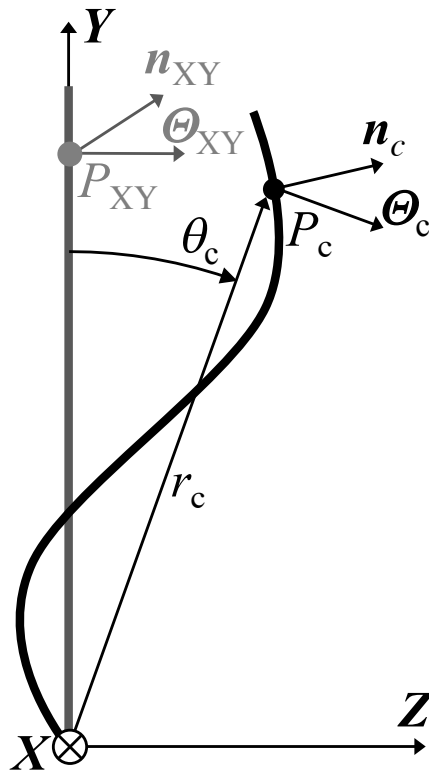
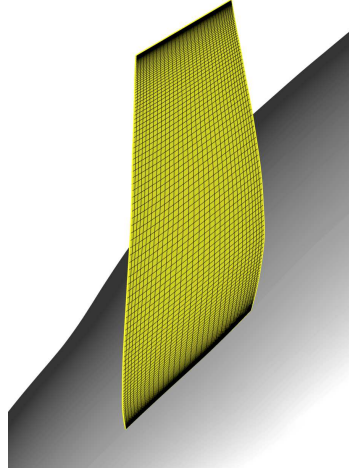
1. Define:



2. Extract:



3. Flatten:

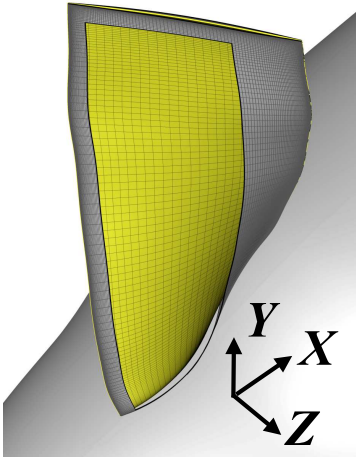


$$\mathbf{W} = \mathbf{V} - \mathbf{U} = \mathbf{V} - \Omega r \mathbf{\Theta}$$

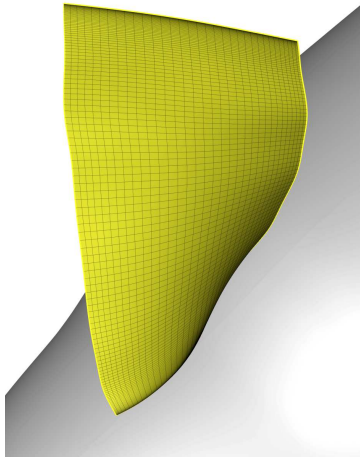
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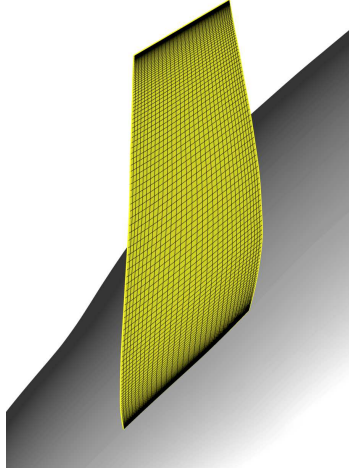
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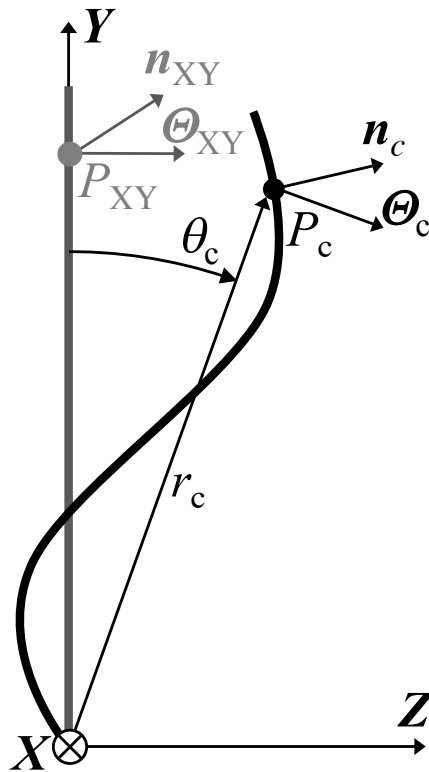
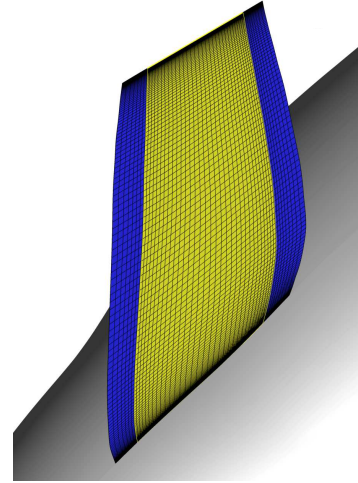
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3. Flatten:

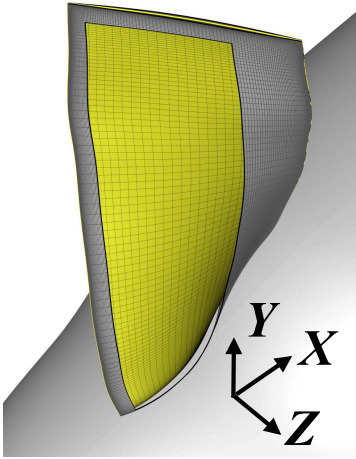


4. Extend:

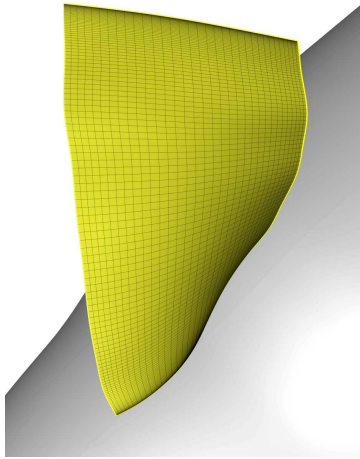


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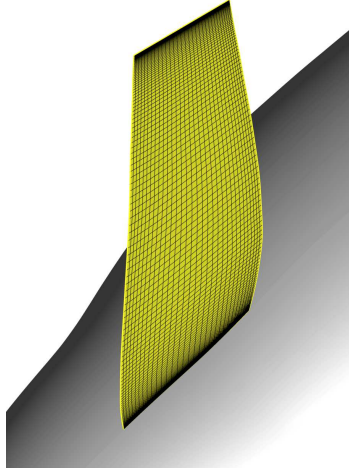
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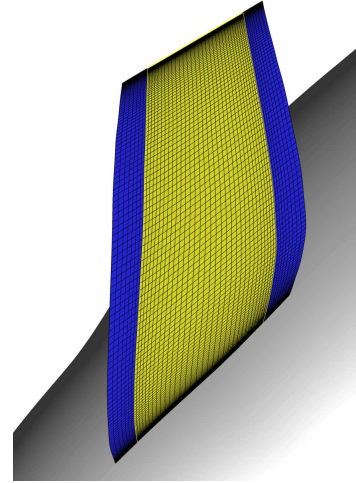
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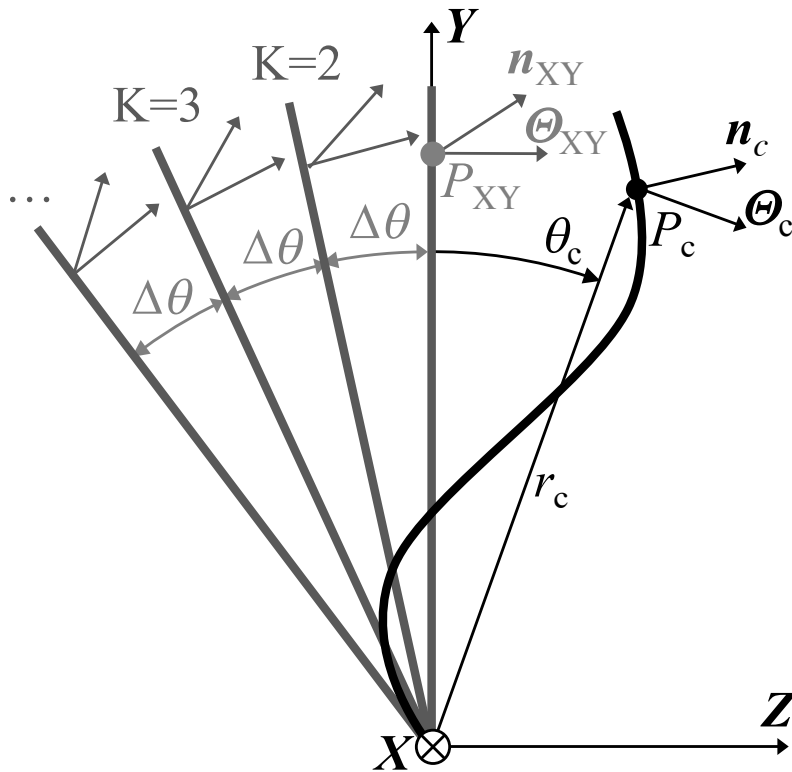
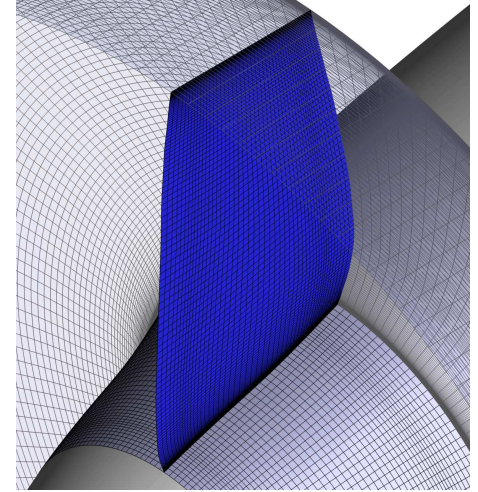
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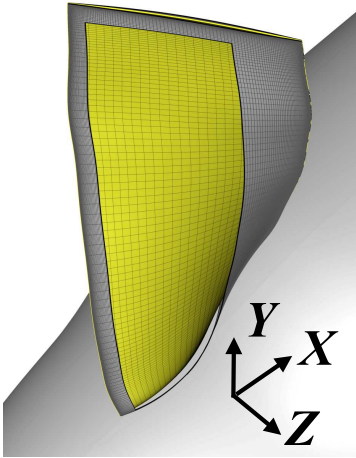


5. Revolve:

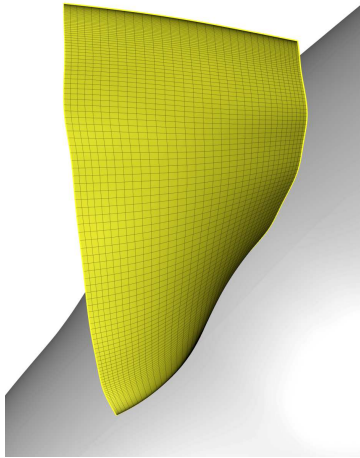


Implementation of the body force model

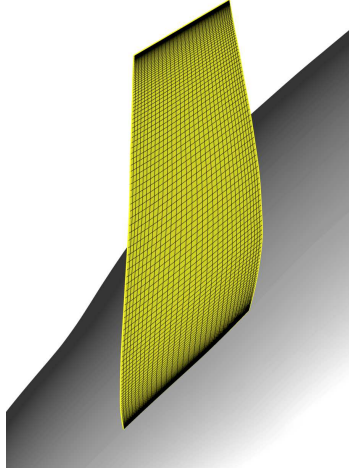
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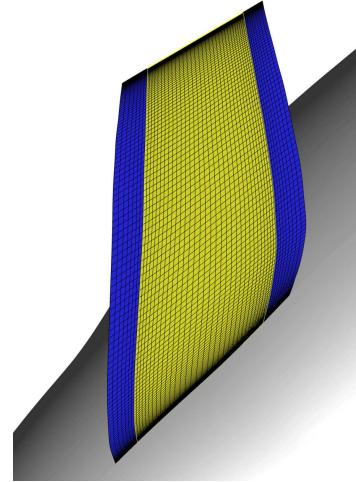
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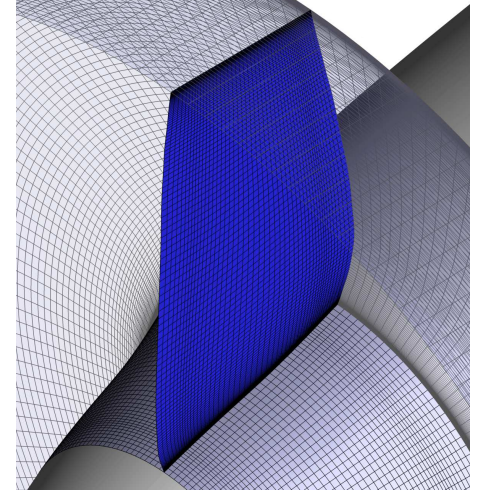
3. Flatten:



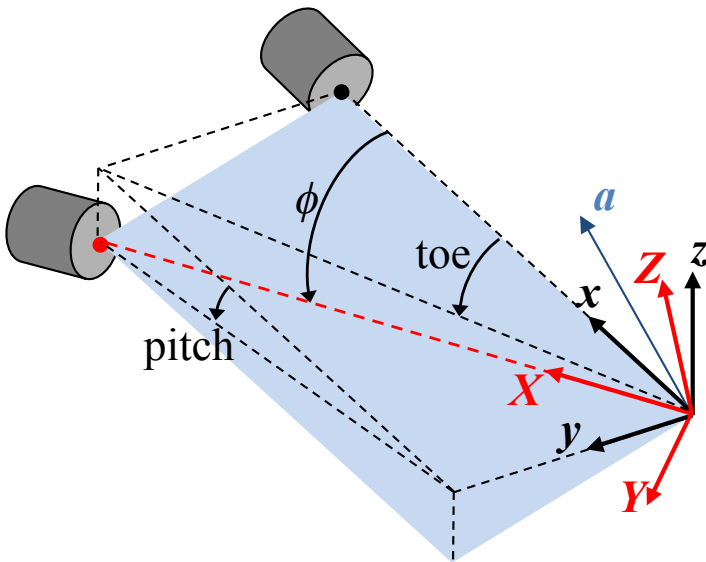
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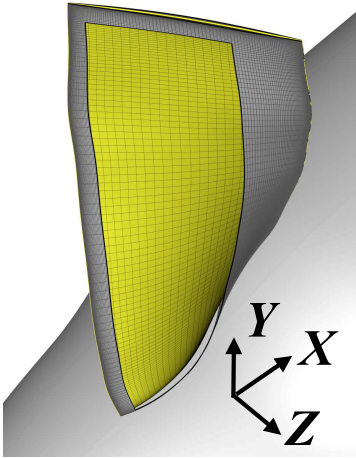


6. Rotate:

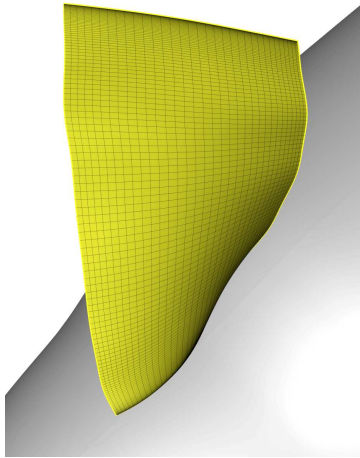


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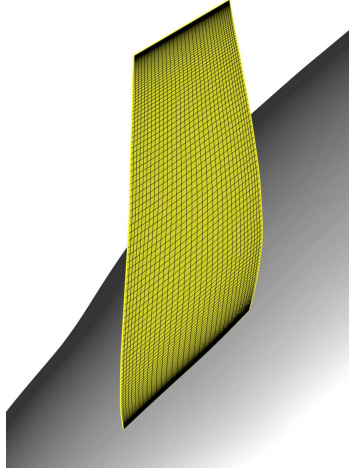
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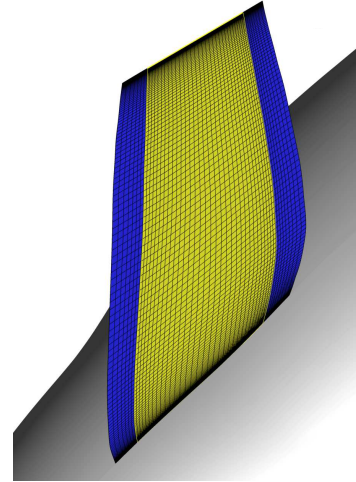
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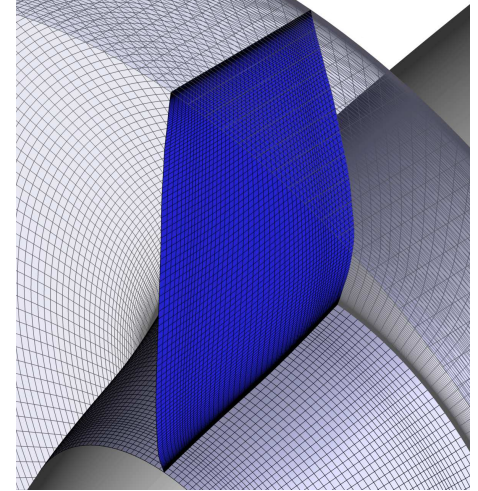
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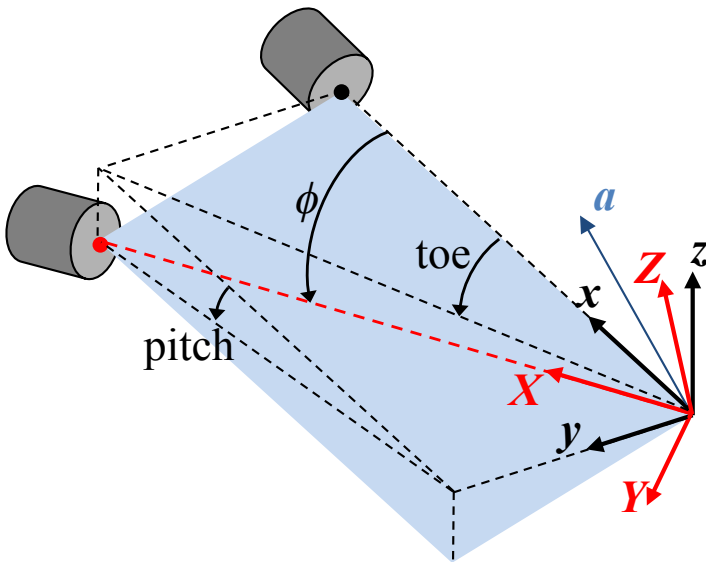
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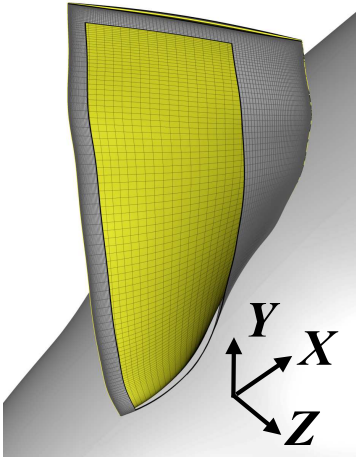


7. Save:

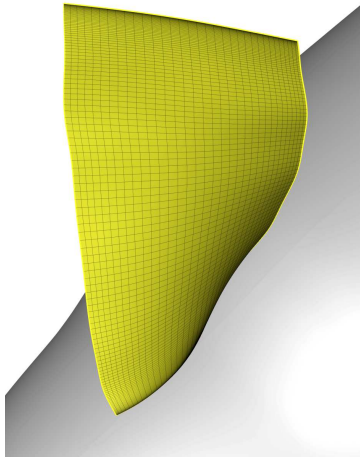
r
 n_x
 n_y
 n_z
 n_θ
 Θ_x
 Θ_y
 Θ_z

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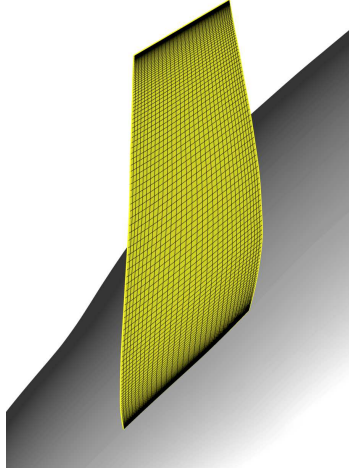
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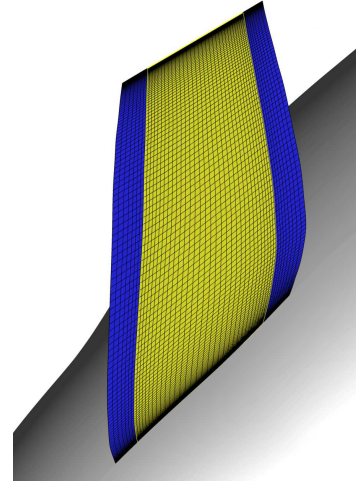
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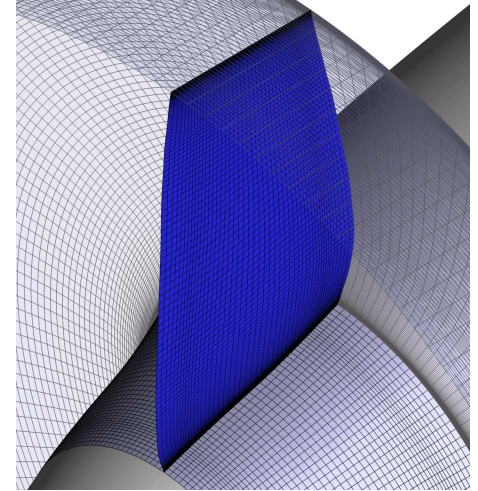
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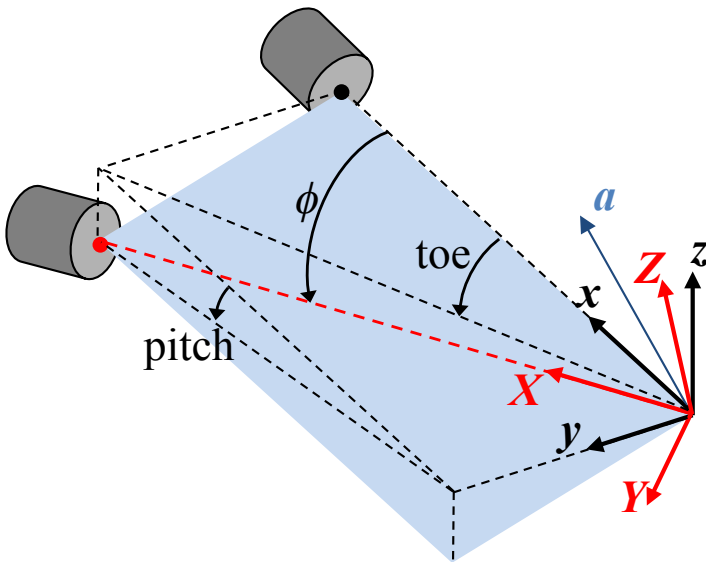
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5. Revolve:



6. Rotate:



7. Save:

r
 n_x
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 Θ_x
 Θ_y
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8. Read in Overflow, compute the source terms each in iteration

$$f = \frac{2\pi\delta(\frac{1}{2}|\mathbf{W}|^2)}{\frac{2\pi r}{B}|n_\theta|}$$

$$\nabla \cdot (\rho \mathbf{V}) = 0$$

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$$\mathbf{V} \cdot \nabla h_t = \mathbf{V} \cdot \mathbf{f} + \dot{e}$$

Flow solution methods

Grid Generation: *Chimera Grid Tools (CGT)*

Steps 1 to 7 are automated by routines added to CGT codebase

Solver: *Overflow 2.2/*

An implicit RANS solver for body-fitted structured overset grid systems.

Simulations here used

- Diagonalized approximate factorization scheme [Pulliam and Chaussee 1981]
- Central difference in Euler terms
- Steady-state simulations with constant CFL number
- Matrix dissipation
- Spalart Allmaras (SA) turbulence model
- Body force method grids and metric files are automatically split
- No multigrid when the body force model is used
- Jacobians of source terms are not added to left hand side
(Hence no low Mach preconditioning when the body force model is used)

Test Cases



A stand-alone Source Diagnostics Test (SDT)
fan with R4 rotor blades

Test Cases



A stand-alone Source Diagnostics Test (SDT) fan with R4 rotor blades



A stand-alone TF8000 propulsor

Test Cases



A stand-alone Source Diagnostics Test (SDT) fan with R4 rotor blades



A stand-alone TF8000 propulsor



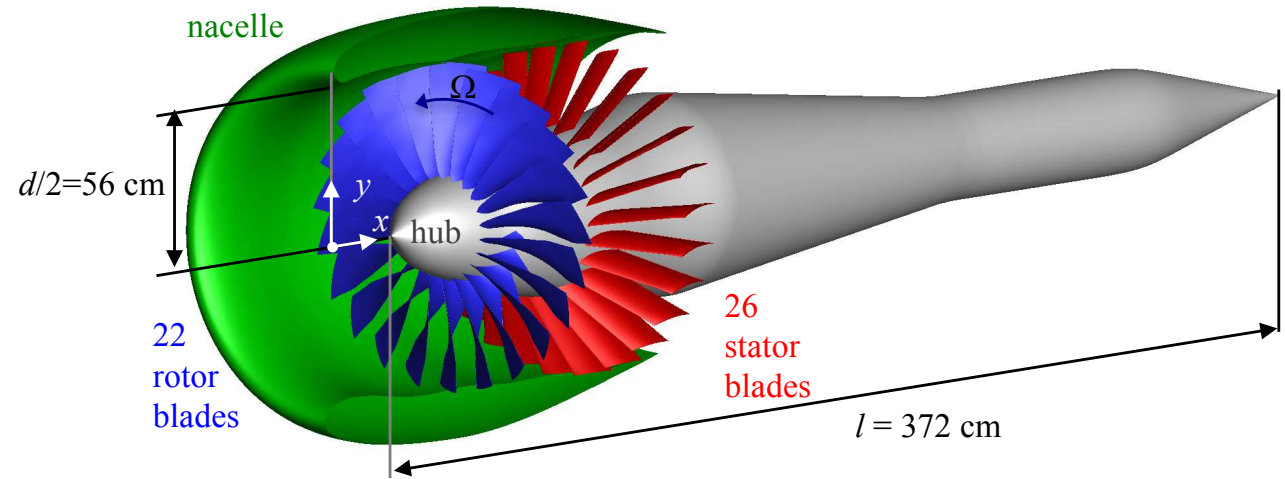
The D8 aircraft model in a wind tunnel

Source Diagnostics Test (SDT) fan with R4 Rotors



$M_\infty=0.1$

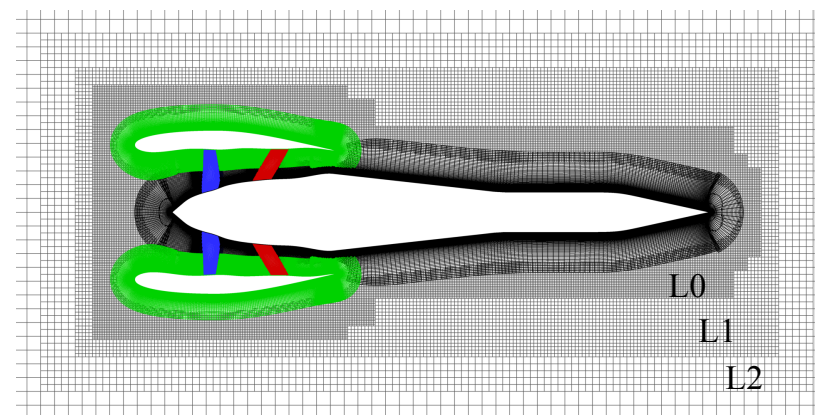
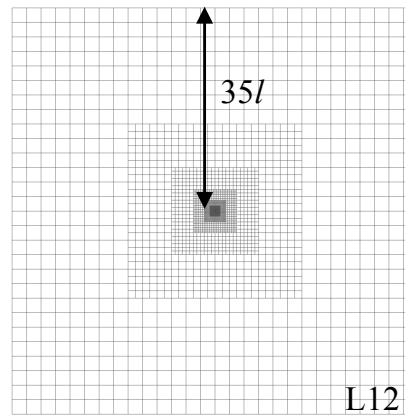
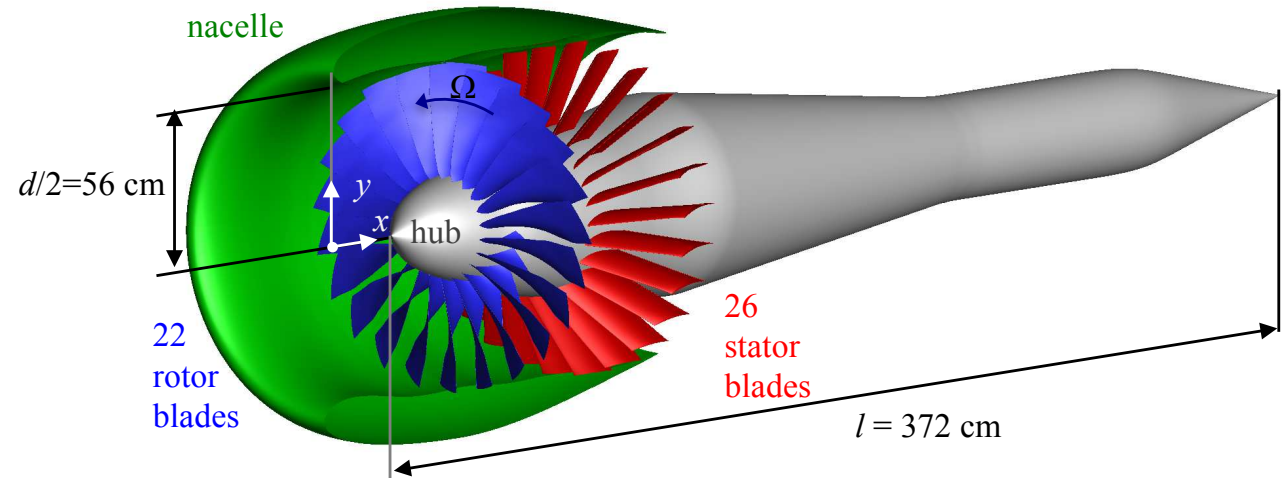
Envia, E., "Fan Noise Source Diagnostic Test Completed and Documented,"
NASA Tech. Memo. TM-2003-211990



Source Diagnostics Test (SDT) fan with R4 Rotors

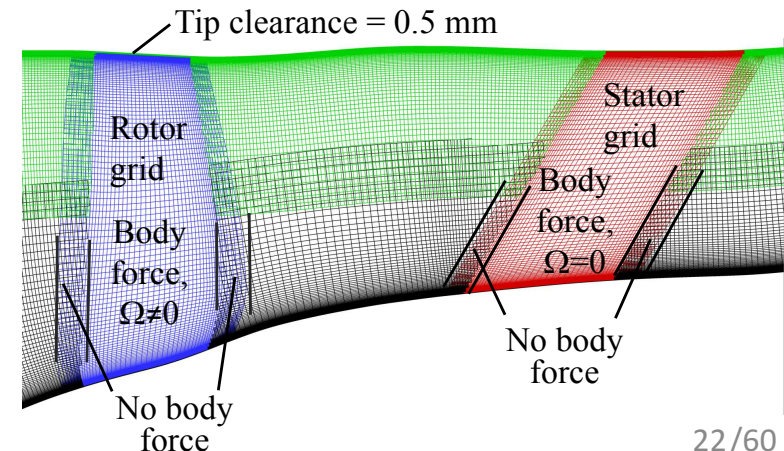
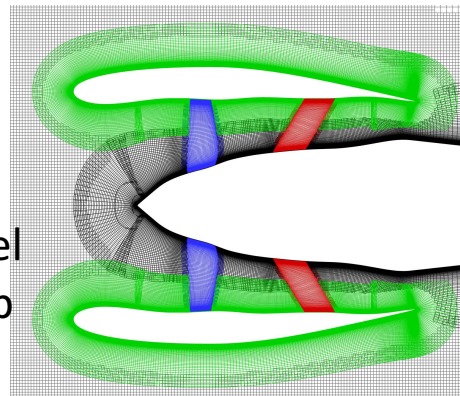


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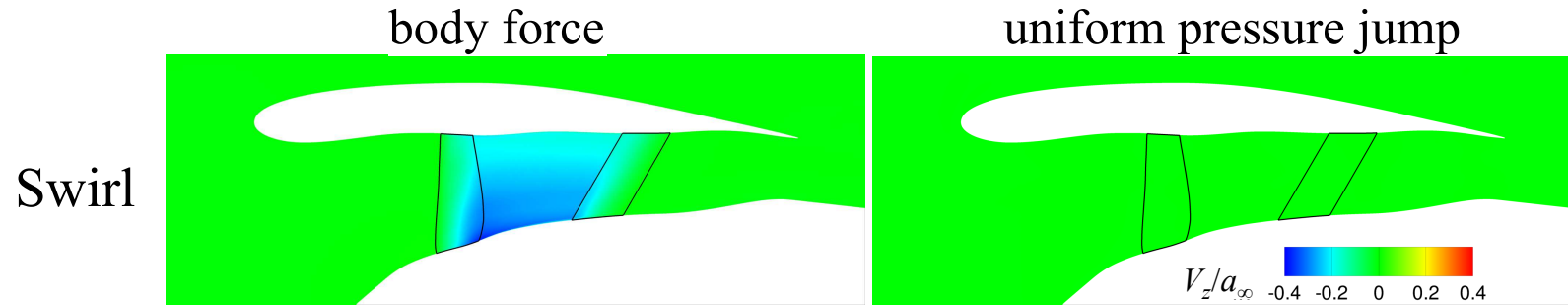


35 million vertices, $y^+ \approx 1$
4 to 8 hours on 128 Haswell cores

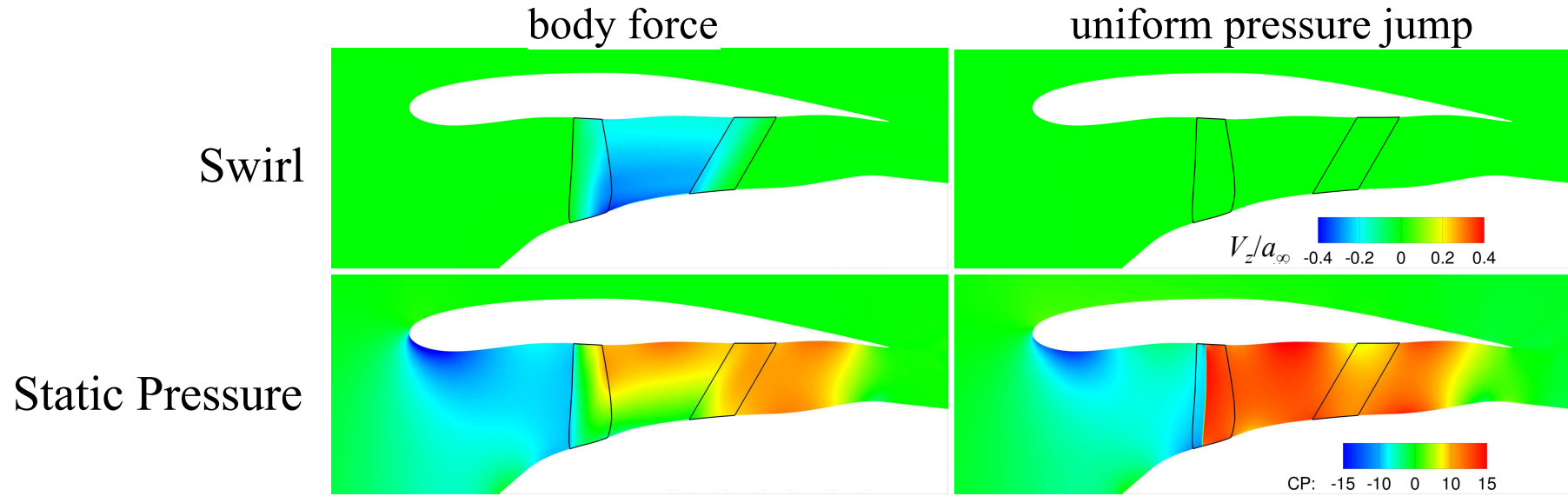
Full convergence with body force model
Partial convergence with pressure jump



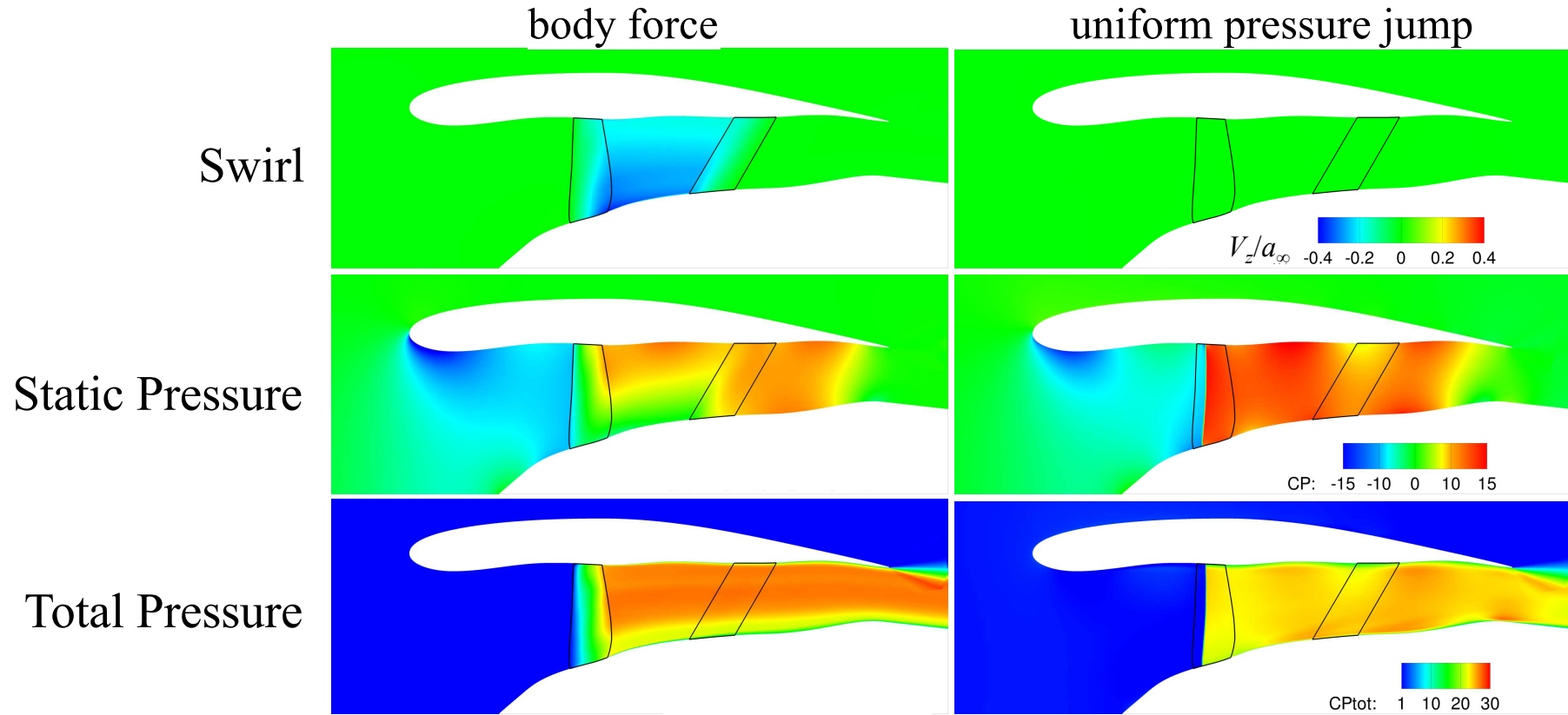
SDT fan results



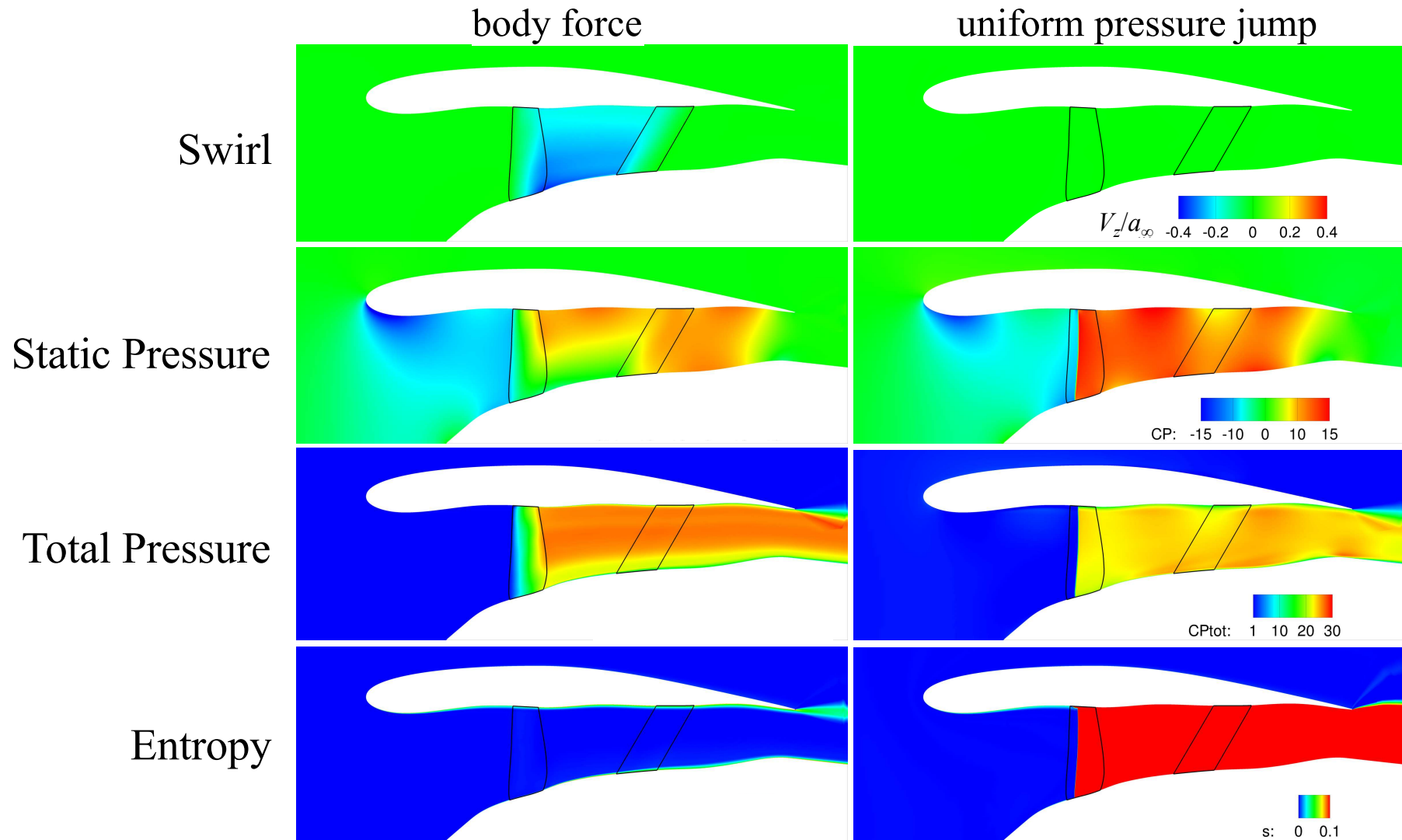
SDT fan results



SDT fan results



SDT fan results

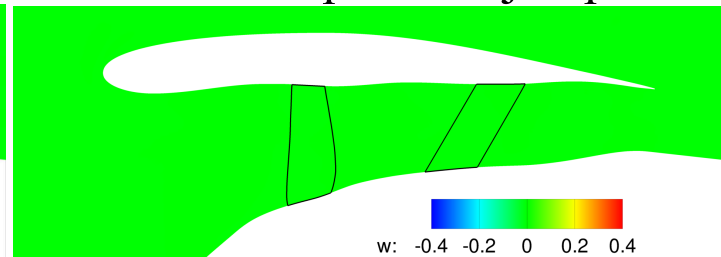
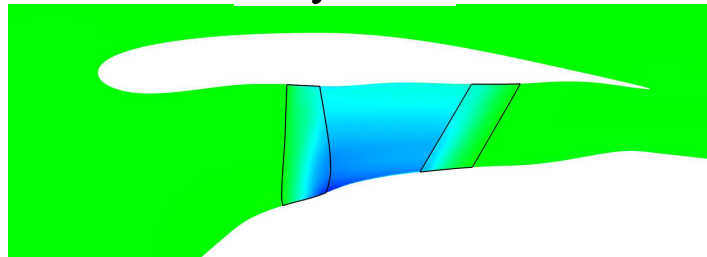


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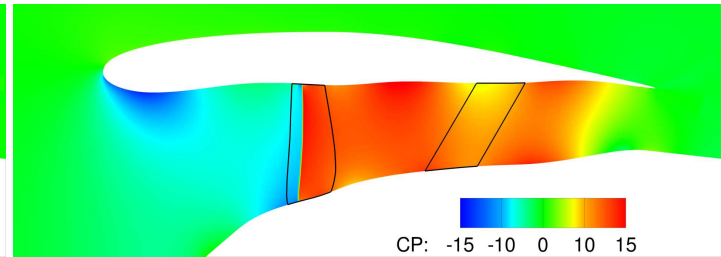
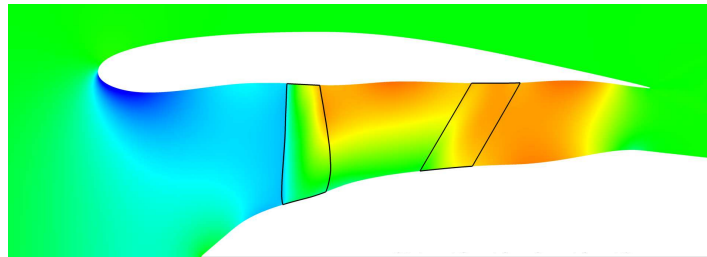
body force

uniform pressure jump

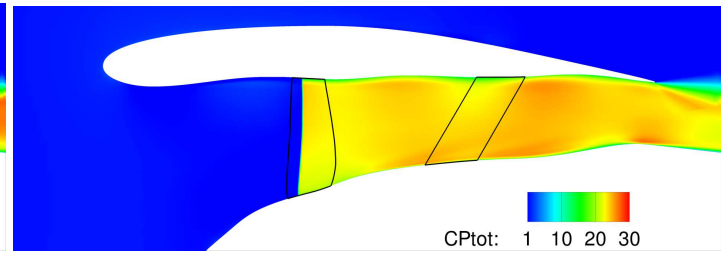
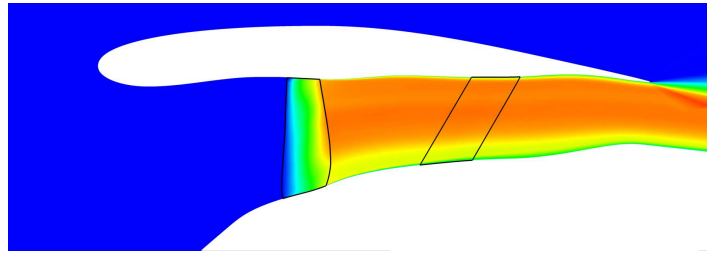
Swirl



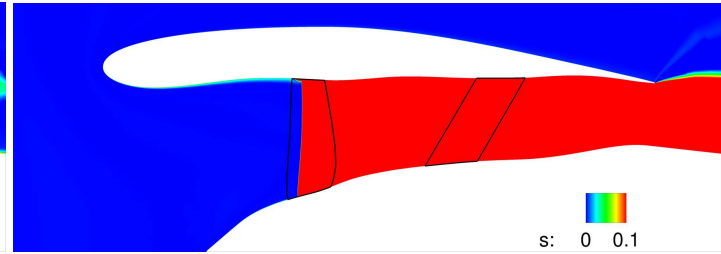
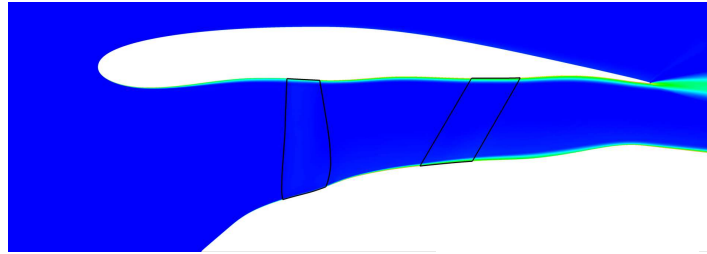
Static Pressure



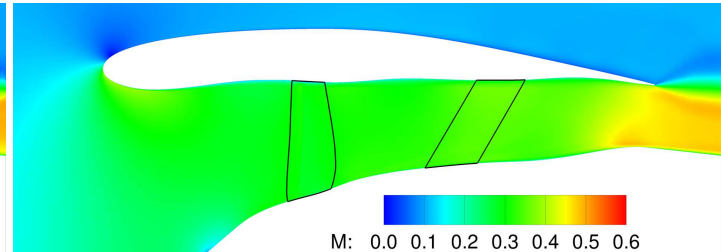
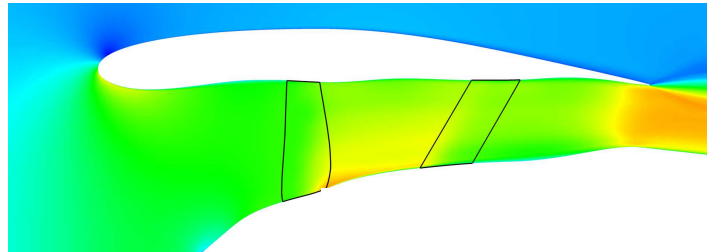
Total Pressure



Entropy

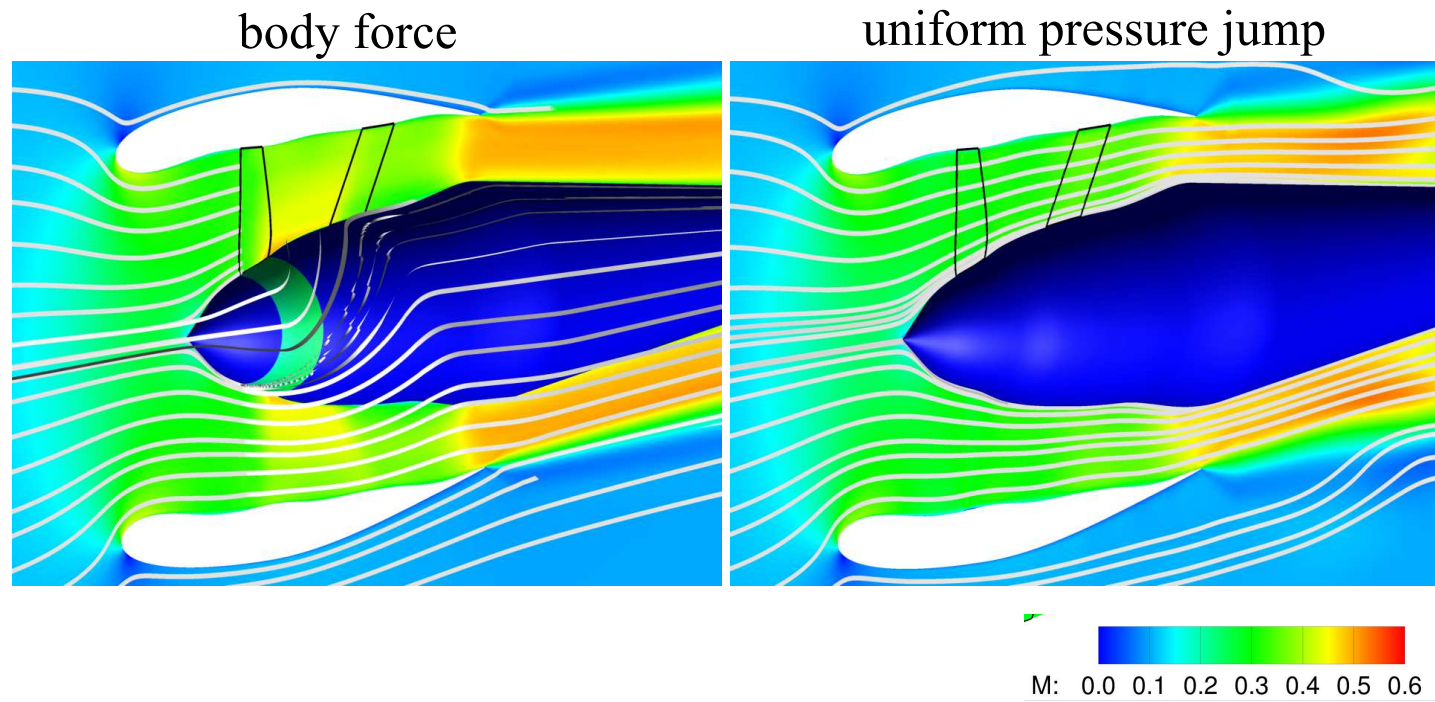


Mach number

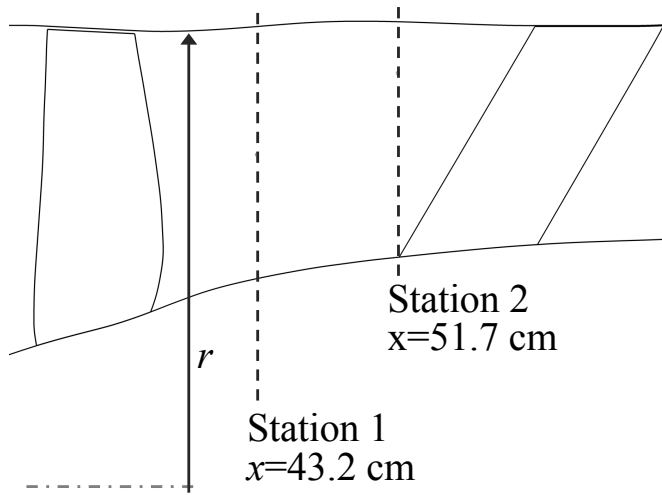


SDT fan results

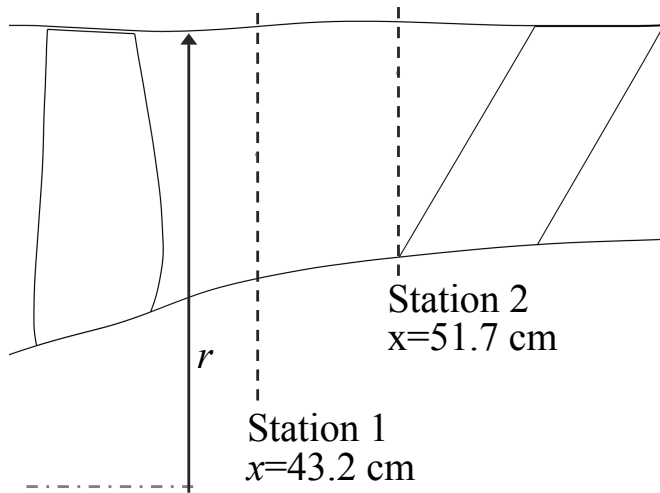
Streamlines



SDT fan results



SDT fan results



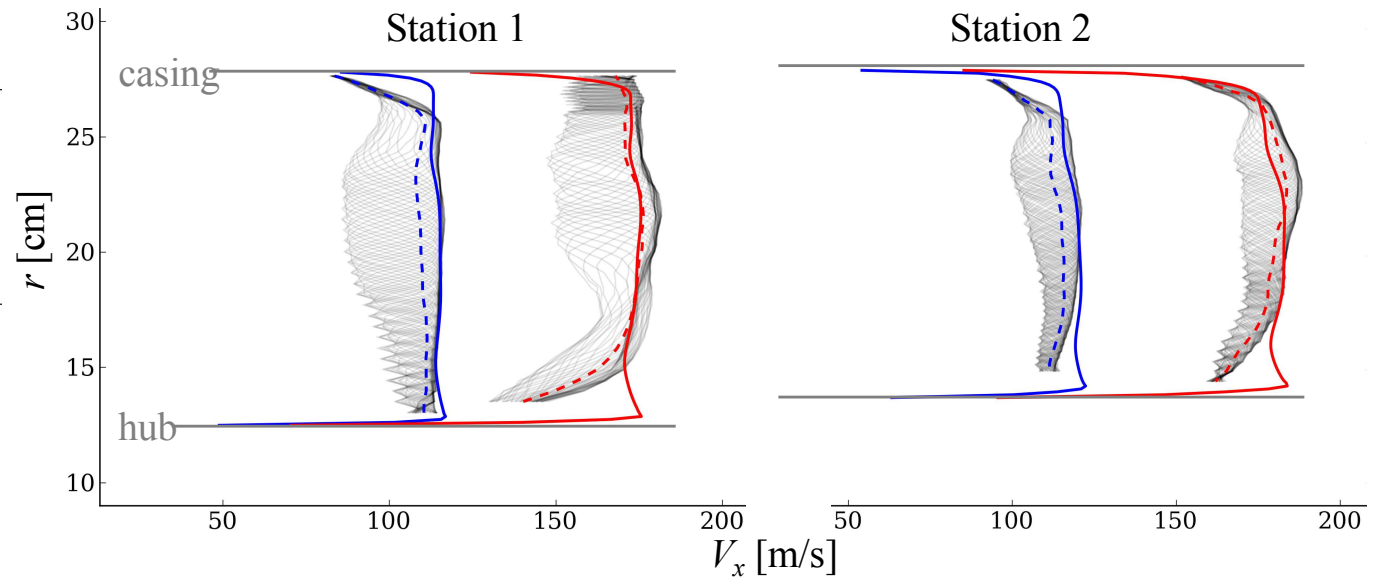
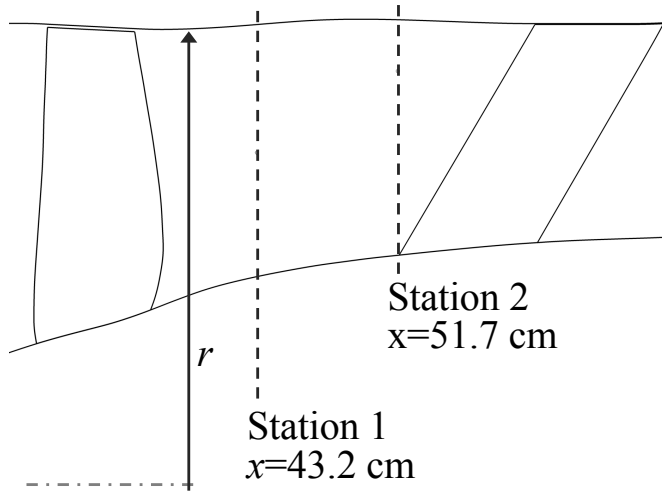
7,808 rpm 12,657 rpm

—	—	Experiment (phase-avg.)
- - -	- - -	Experiment (mean of phase-avg.)
—	—	Simulation (body force model)

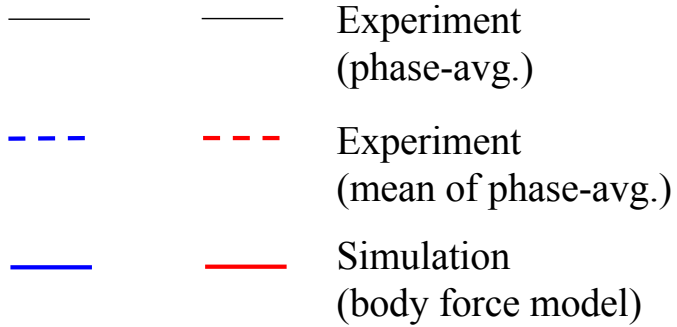


SDT campaign at NASA Glenn Research Center
POC: Dr. Ed Envia

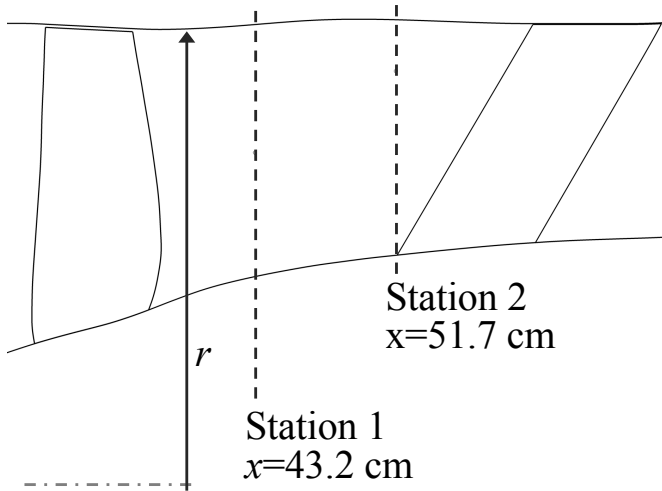
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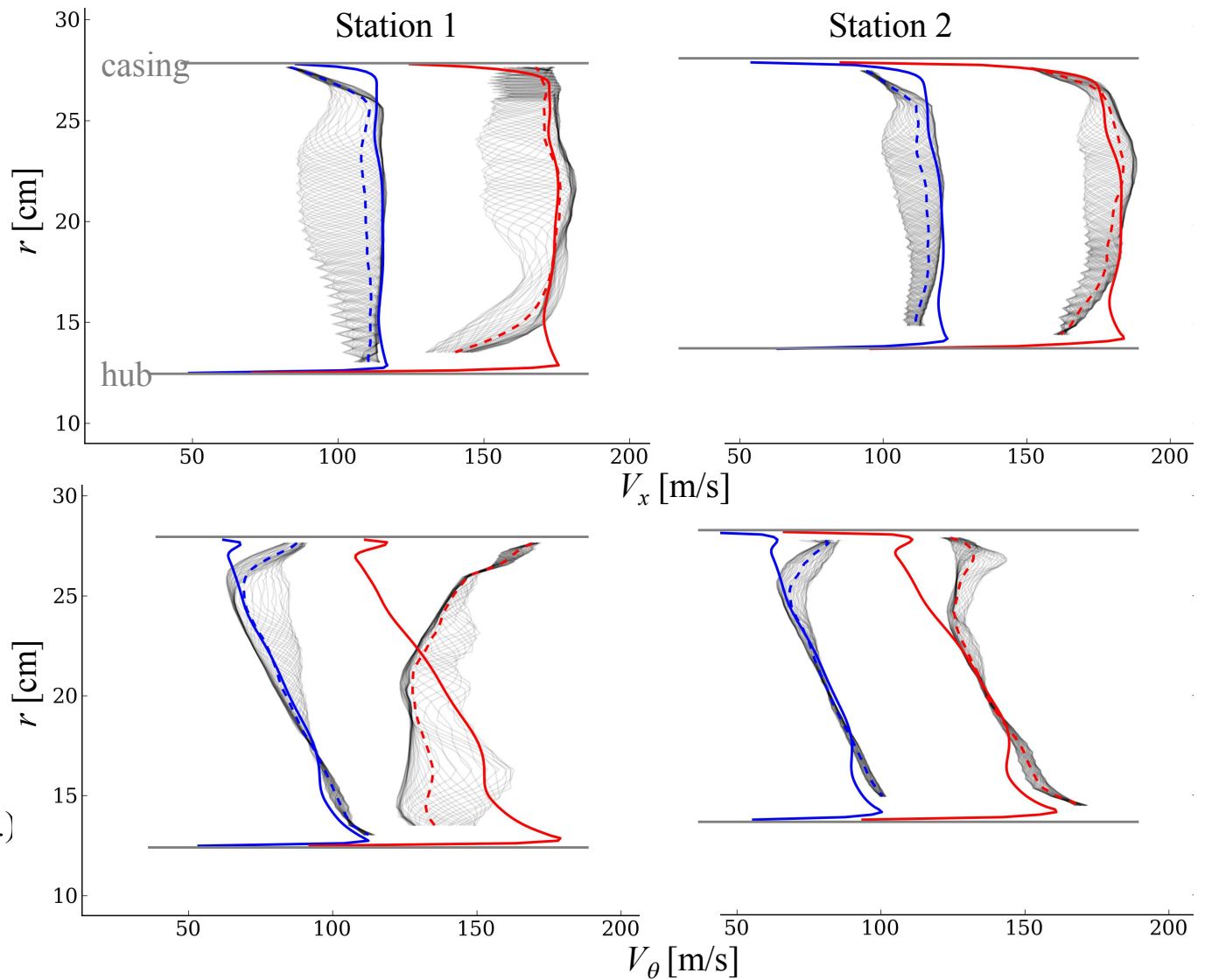
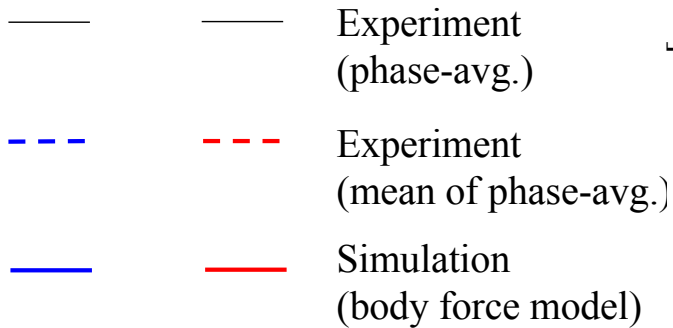
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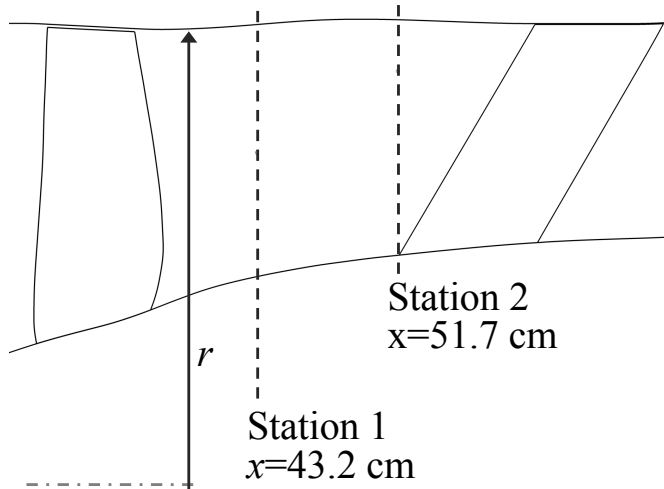
SDT fan results



7,808 rpm 12,657 rpm

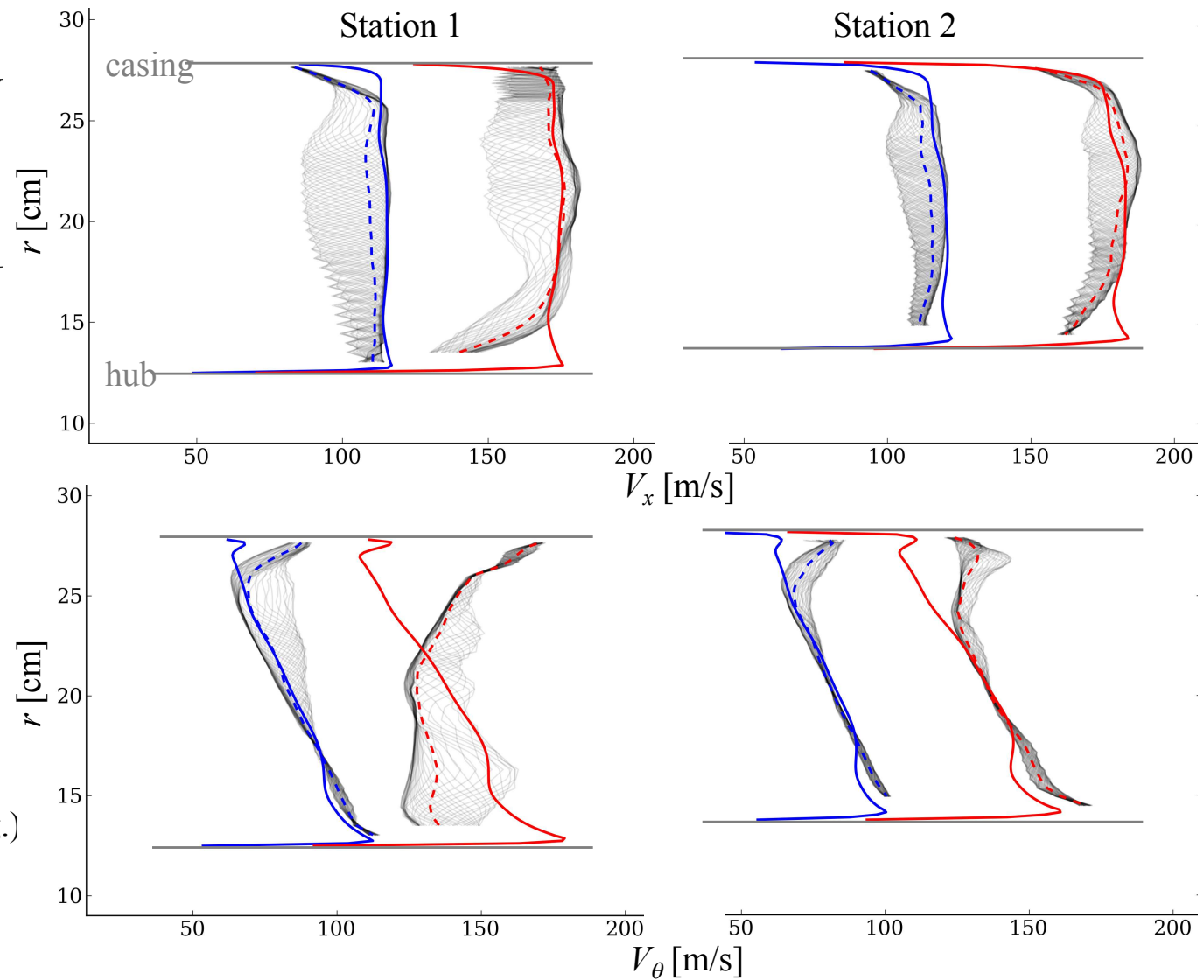


SDT fan results



7,808 rpm 12,657 rpm

— Experiment (phase-avg.)
 - - - Experiment (mean of phase-avg.)
 — Simulation (body force model)



at Station 1, 12,657 rpm	$\bar{V}_x$ [m/s]	$\bar{V}_\theta$ [m/s]	$P_{o,1} / P_{o,\infty}$
Experiment	171	138	1.509
Body Force Model	172	133	1.491

Hughes et al., 2005

The D8 aircraft in wind tunnel

Experiment: NASA Langley 14x22ft Wind Tunnel



Uranga *et al.*, *Preliminary Experimental Assessment of the Boundary Layer Ingestion Benefit for the D8 Aircraft*, AIAA-2014-0906

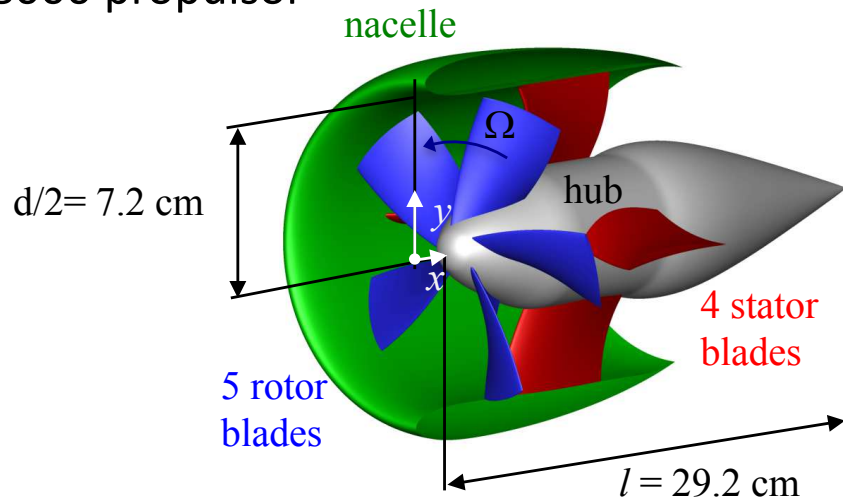
CFD: Simulation of the model in the wind tunnel including the contraction and diffuser sections



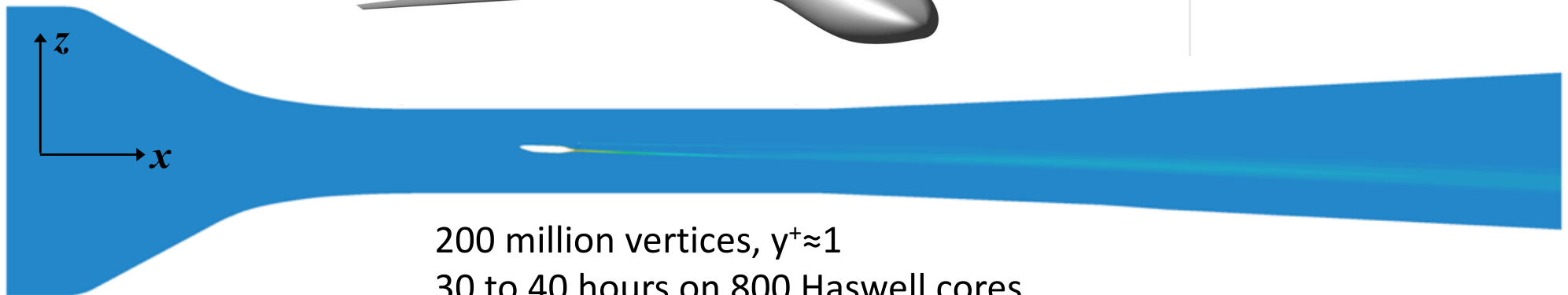
Pandya, *External Aerodynamics Simulations for the MIT D8 "Double-Bubble" Aircraft Design*, 2012, ICCFD7-4304

TF8000 propulsor on D8

TF8000 propulsor

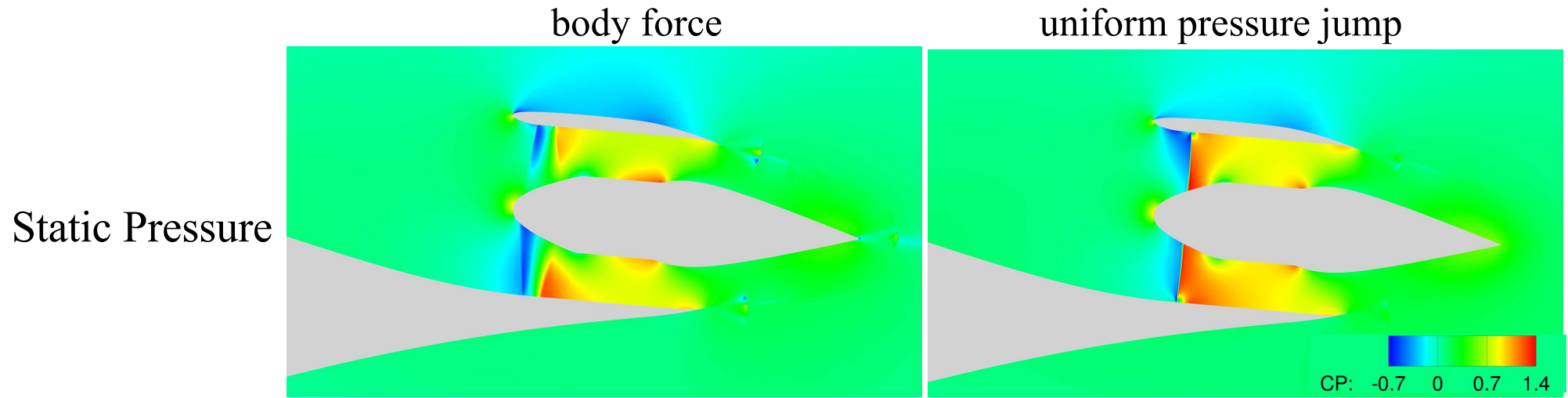


D8 aircraft in wind tunnel

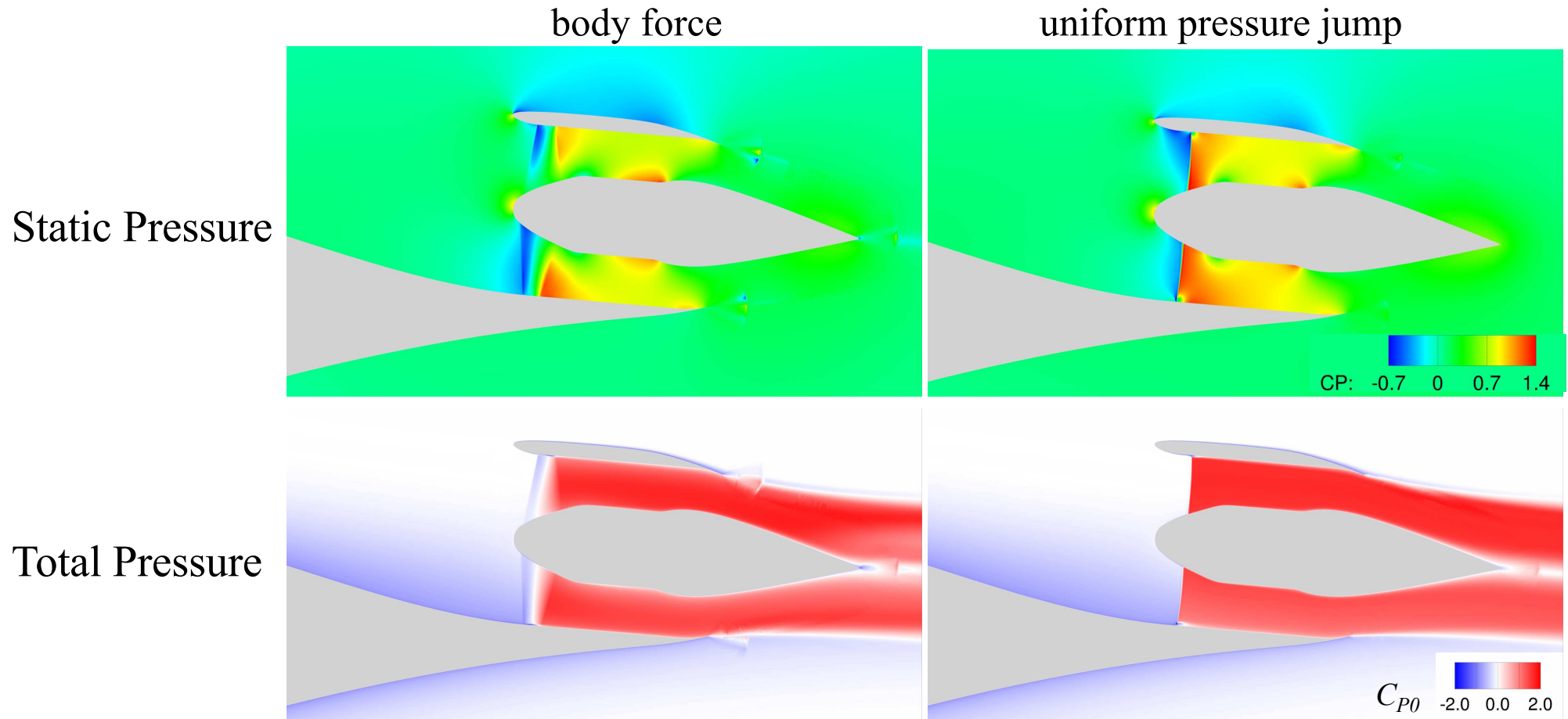


200 million vertices, $y^+ \approx 1$
30 to 40 hours on 800 Haswell cores

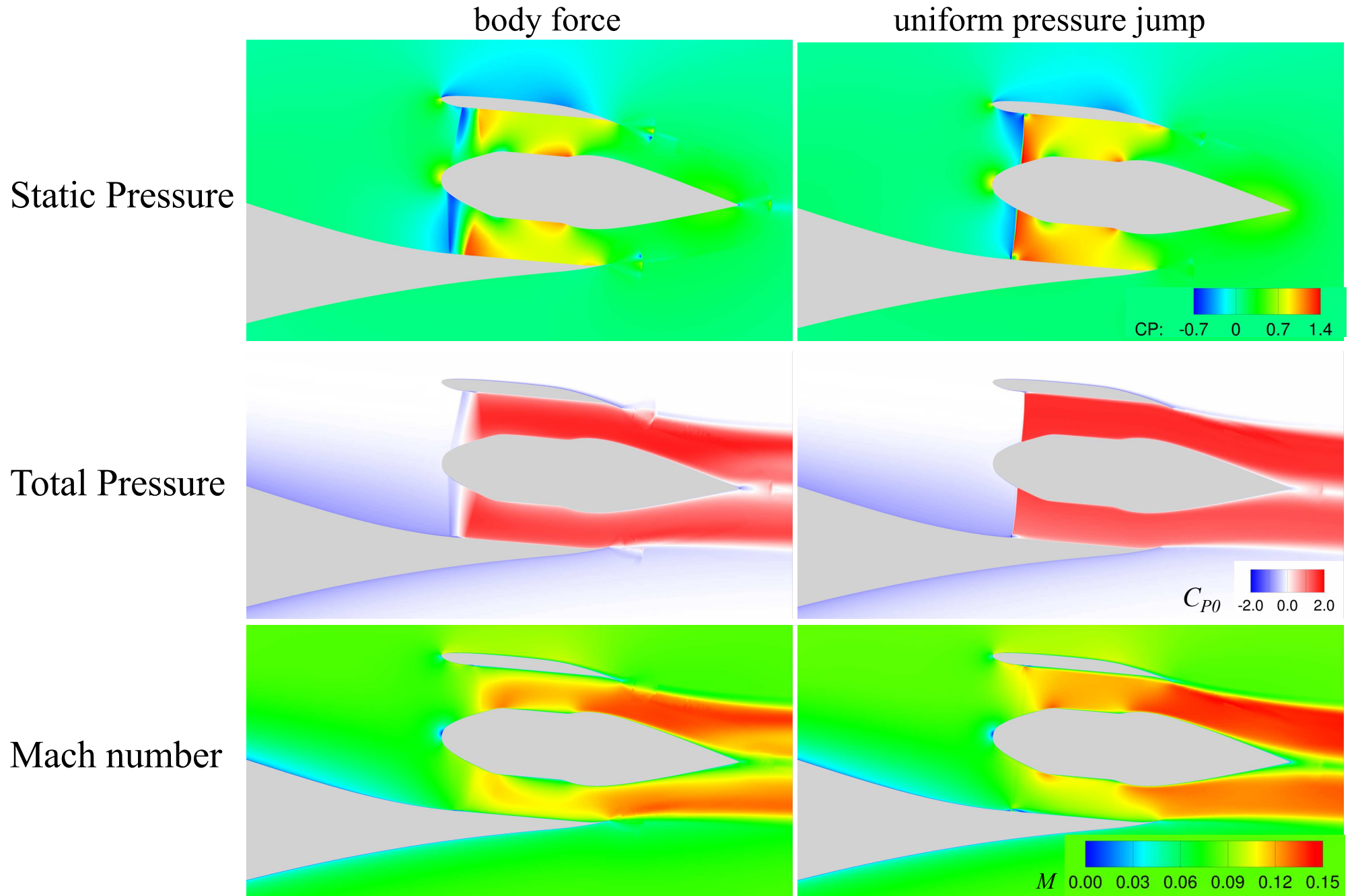
TF8000 propulsor on D8 -- Results



TF8000 propulsor on D8 -- Results

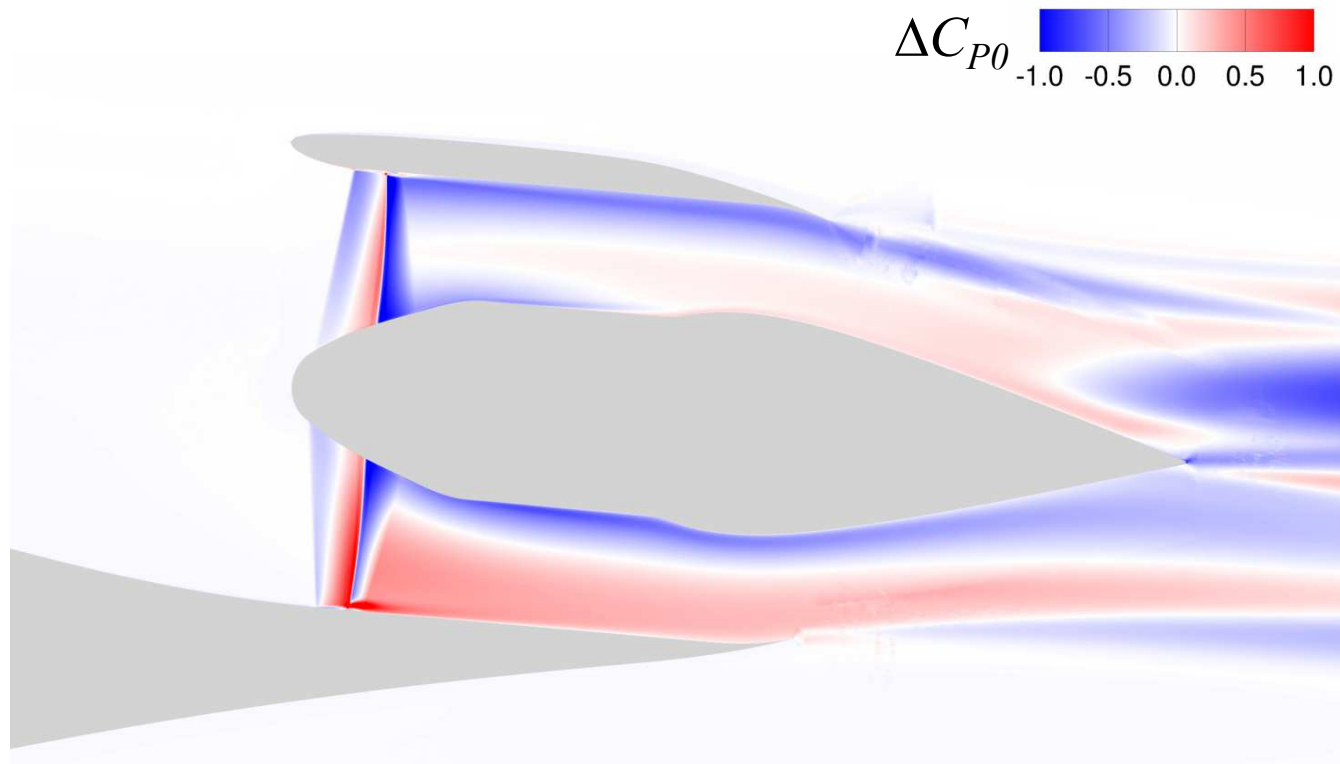


TF8000 propulsor on D8 -- Results

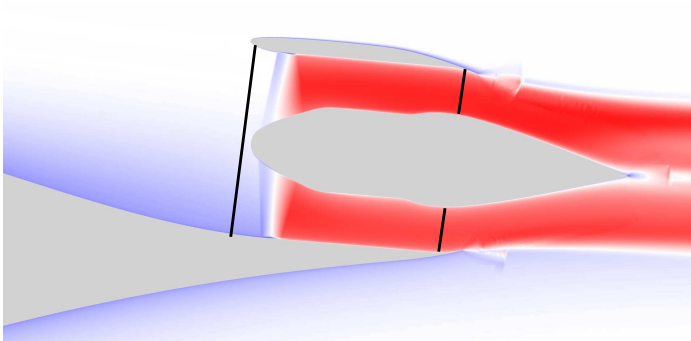
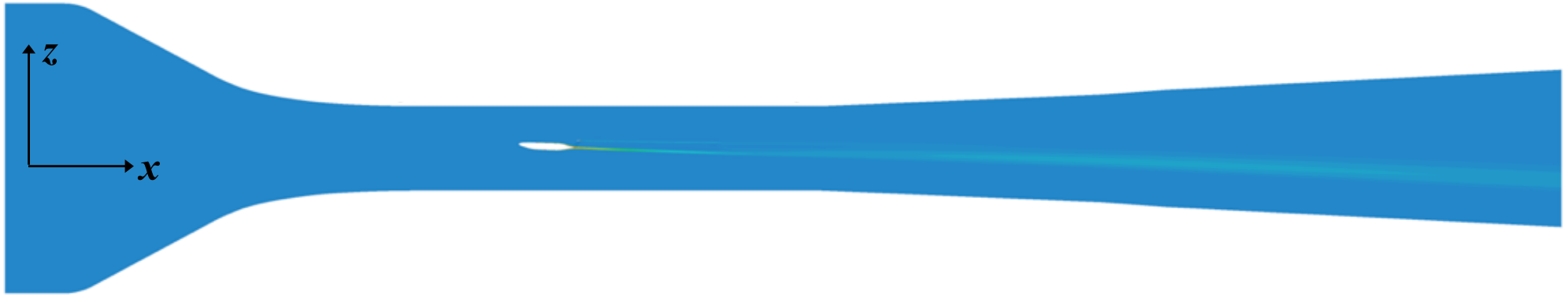


TF8000 propulsor on D8 -- Results

$$\Delta C_{P0} = C_{P0, \text{body force}} - C_{P0, \text{pressure jump}}$$

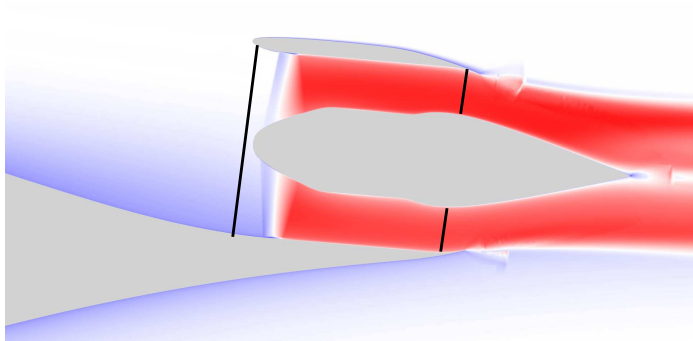
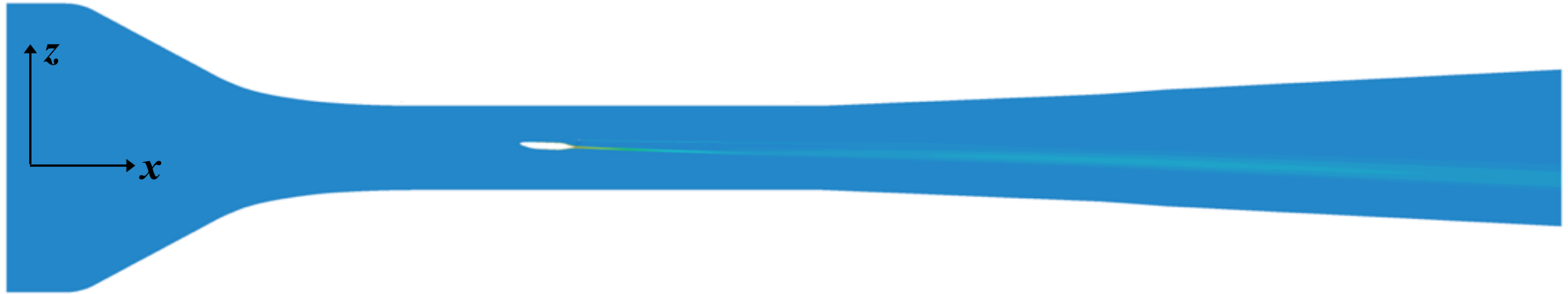


TF8000 propulsor on D8 -- Results



$$C_{PK} = \frac{\int_{fan} (p_{t,\infty} - p_t)(\mathbf{V} \cdot \mathbf{n}) dA}{q_{\infty} V_{\infty} S_{ref}}$$

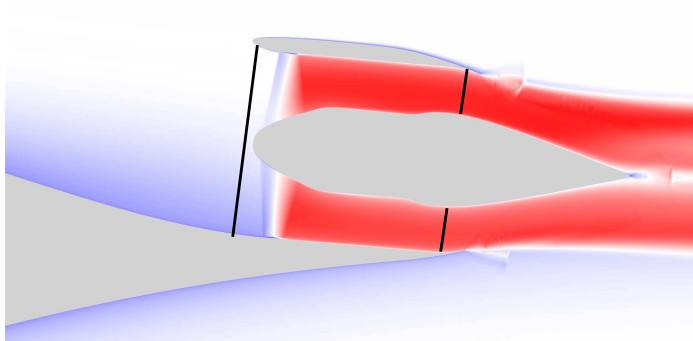
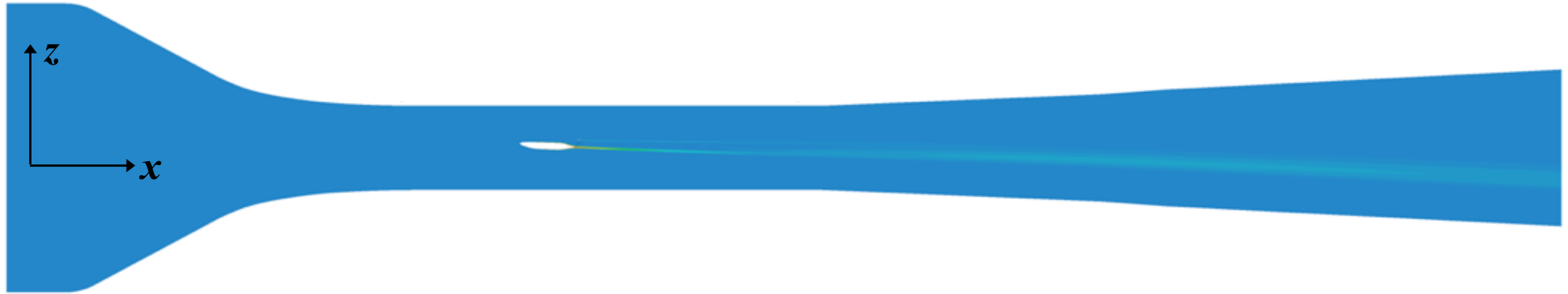
TF8000 propulsor on D8 -- Results



$$C_{PK} = \frac{\int_{fan} (p_{t,\infty} - p_t)(\mathbf{V} \cdot \mathbf{n}) dA}{q_\infty V_\infty S_{ref}}$$

Method	C_x	C_z	C_{PK}	C_m
Experiment	0.0000 ± 0.0006	0.644 ± 0.001	0.045 ± 0.001	0.0267 ± 0.0006
Uniform Pressure Jump	0.0002	0.651	0.045	0.0282

TF8000 propulsor on D8 -- Results



$$C_{PK} = \frac{\int_{fan} (p_{t,\infty} - p_t)(\mathbf{V} \cdot \mathbf{n}) dA}{q_\infty V_\infty S_{ref}}$$

Method	C_x	C_z	C_{PK}	C_m
Experiment	0.0000 ± 0.0006	0.644 ± 0.001	0.045 ± 0.001	0.0267 ± 0.0006
Uniform Pressure Jump	0.0002	0.651	0.045	0.0282
Body Force, 11,450 rpm	0.0005	0.678	0.043	0.0281

Summary & Discussion

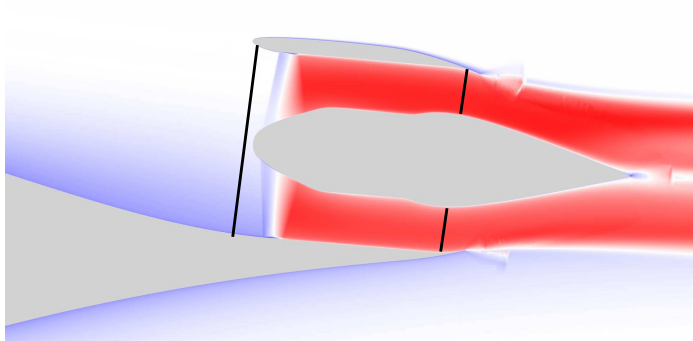
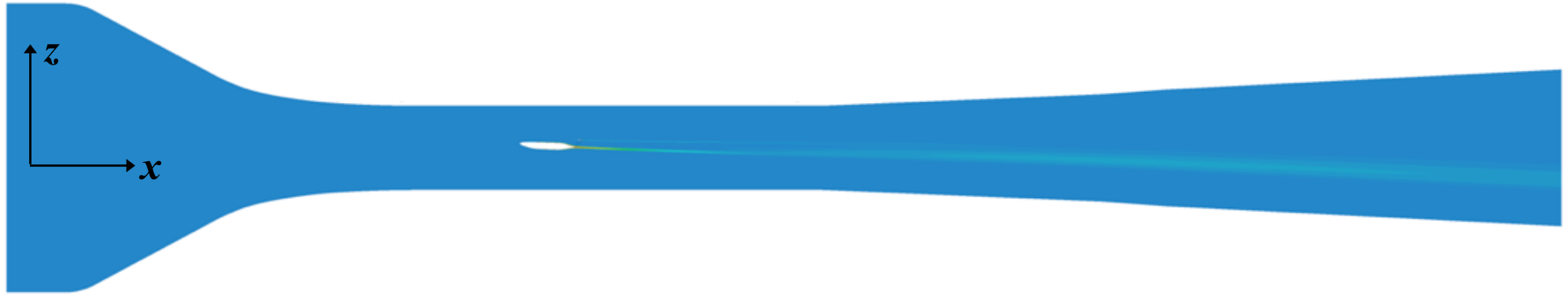
- The body force model by Hall et al. predicted integrated quantities within a few percent on SDT with R4 rotor blades.
- In TF8000 propulsor cases the predictions were a bit more off, possibly due to certain uncharacterized sources of error across CFD and experiments
- The body force model provided detailed insights on the buildup of mechanical power throughout the propulsor
- Further work will include adding compressibility, blade blockage and endwall corrections into the model
- Further work will also include implementing propulsor models of various fidelities to assess the modeling fidelity sufficient for a given modeling goal

Acknowledgements

- Dr. David K. Hall of the MIT Gas Turbine Laboratory provided a description of the source term computation algorithm.
- Dr. Edmane Envia of NASA Glenn Research Center provided the SDT aerodynamic data and geometry definition files.
- NASA Advanced Air Transport Technology (AATT) project provided the funding for this work.
- NASA Advanced Supercomputing (NAS) Division at NASA Ames Research Center provided computing resources.

Backup Slides

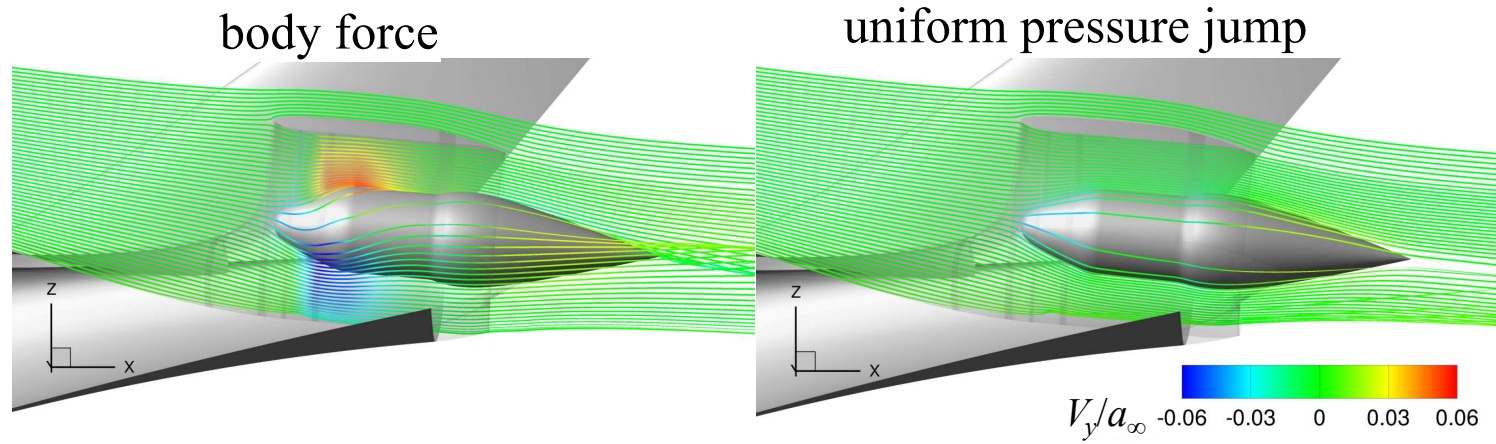
TF8000 propulsor on D8 -- Results



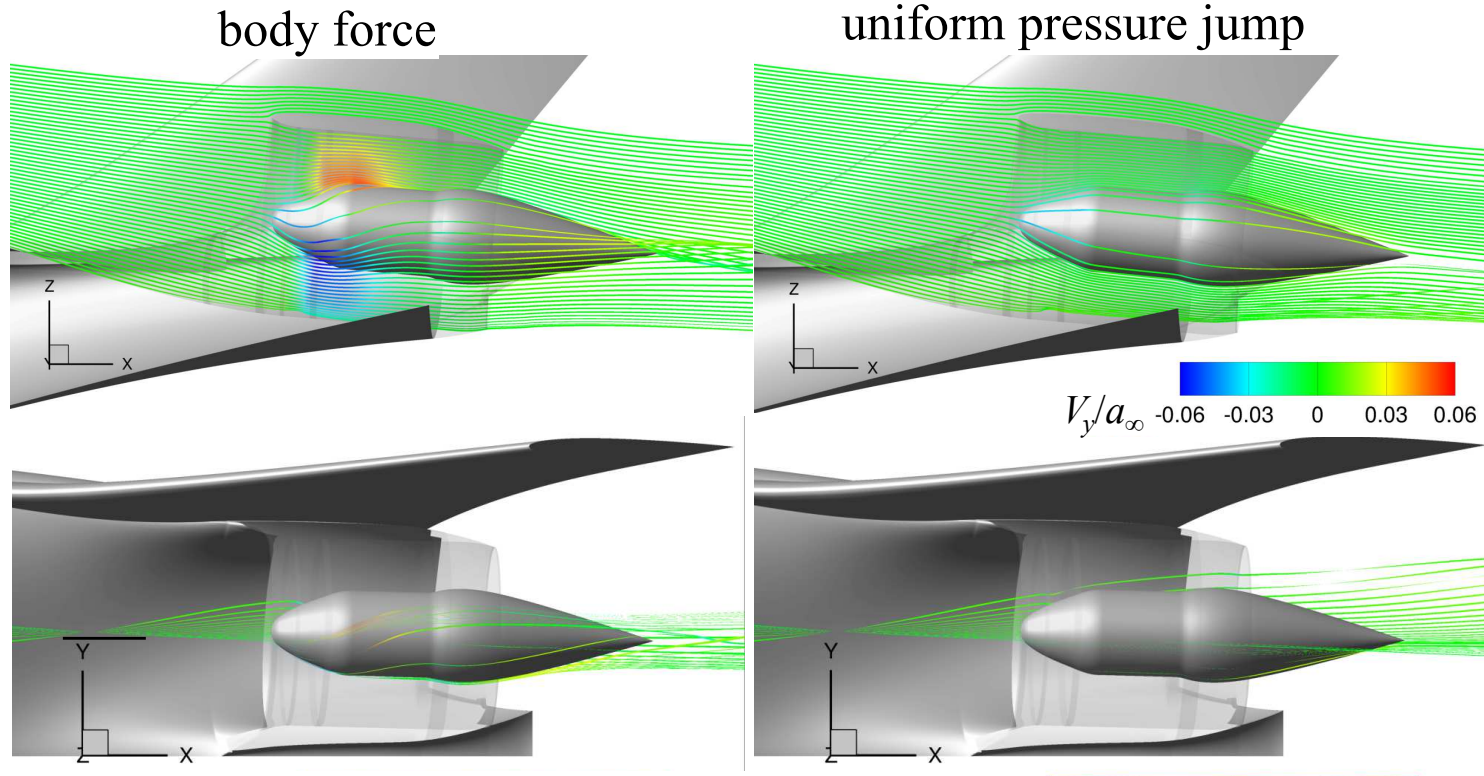
$$C_{PK} = \frac{\int_{fan} (p_{t,\infty} - p_t)(\mathbf{V} \cdot \mathbf{n}) dA}{q_\infty V_\infty S_{ref}}$$

Method	C_x	C_z	C_{PK}	$C_{\dot{m}}$
Experiment	0.0000 ± 0.0006	0.644 ± 0.001	0.045 ± 0.001	0.0267 ± 0.0006
Uniform Pressure Jump	0.0002	0.651	0.045	0.0282
Body Force, 11,450 rpm	0.0005	0.678	0.043	0.0281
Body Force, 11,100 rpm	0.0028	0.672	0.039	0.0275

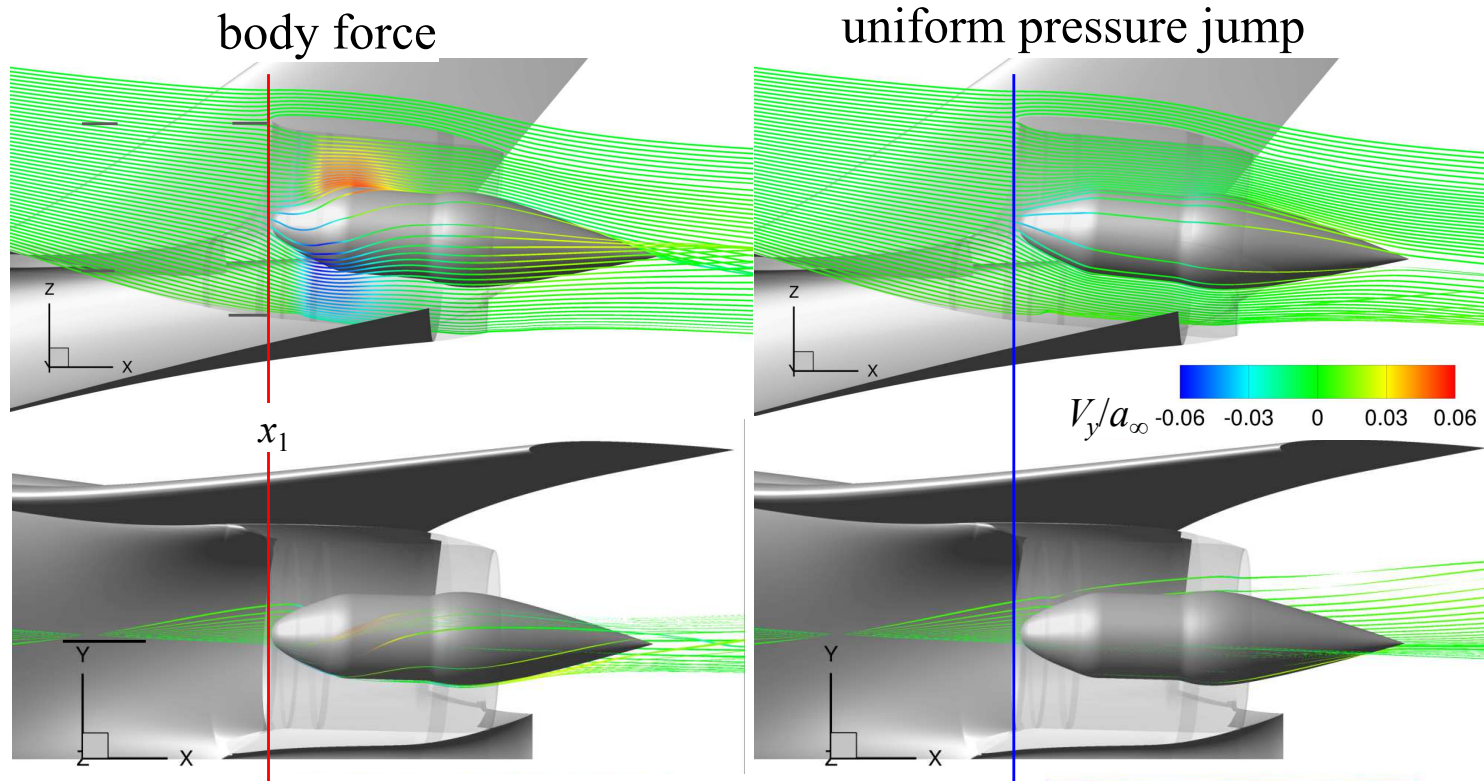
TF8000 propulsor on D8 -- Results



TF8000 propulsor on D8 -- Results

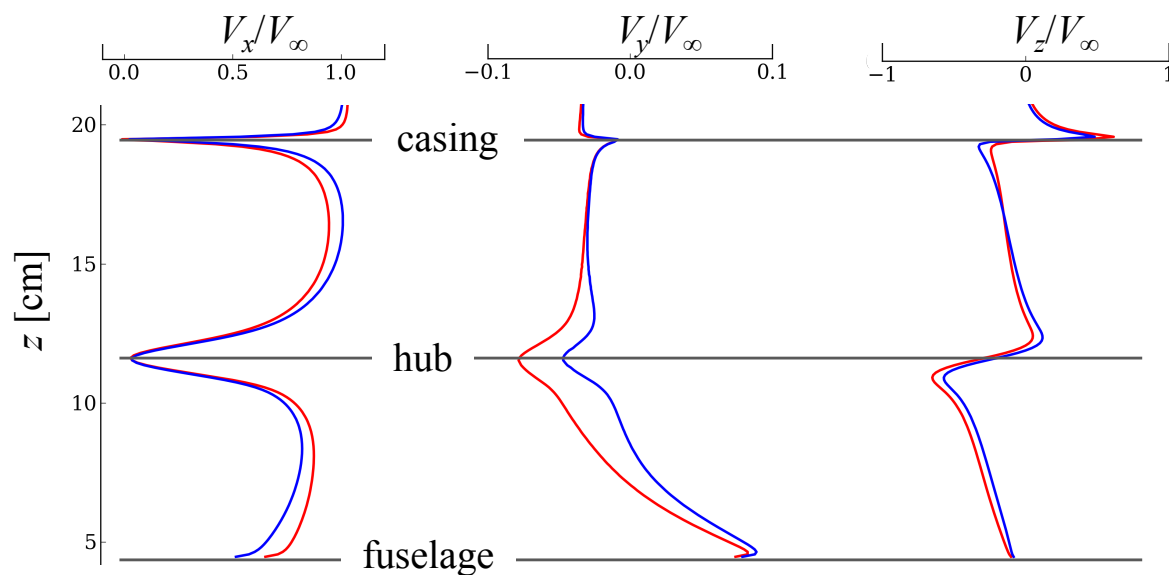
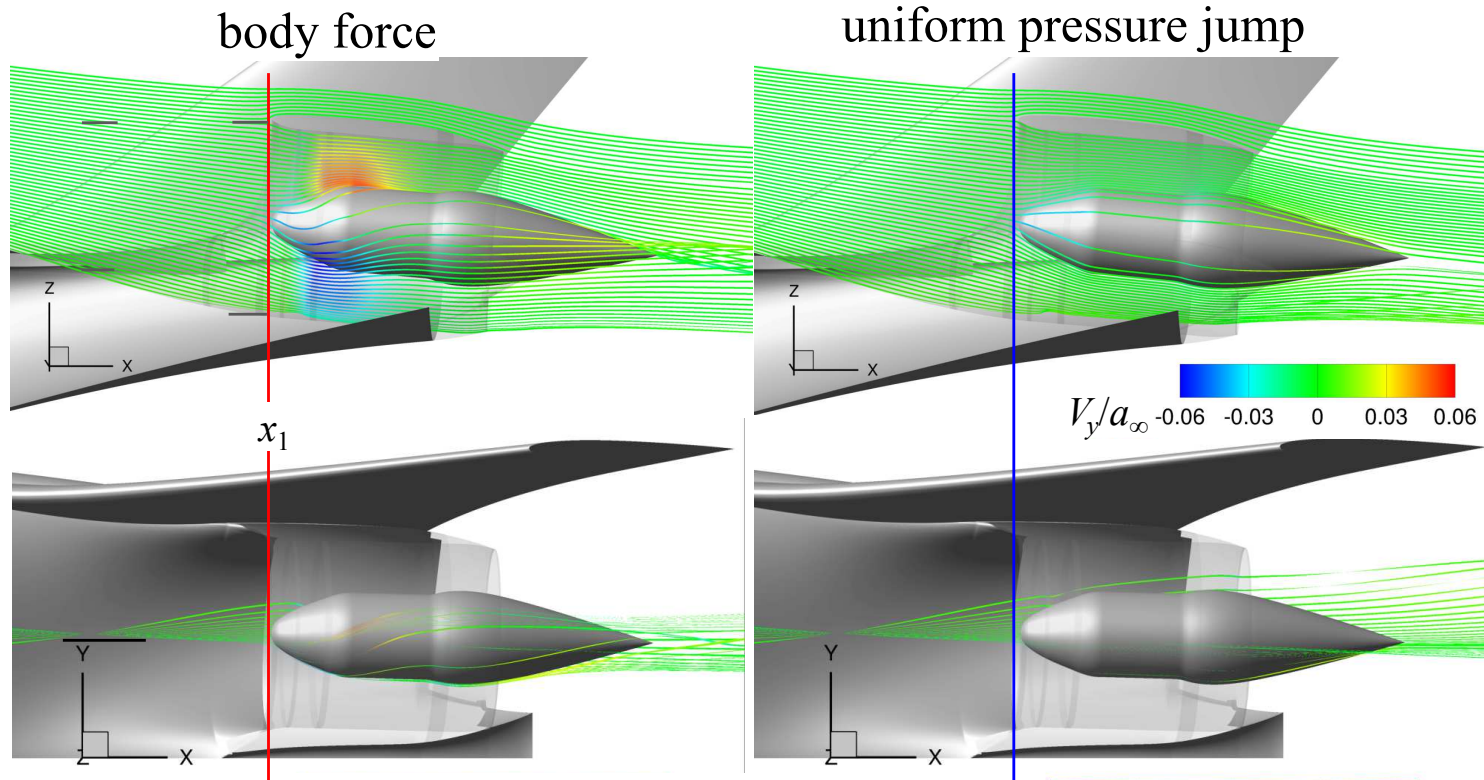


TF8000 propulsor on D8 -- Results



— body force model
— pressure jump model

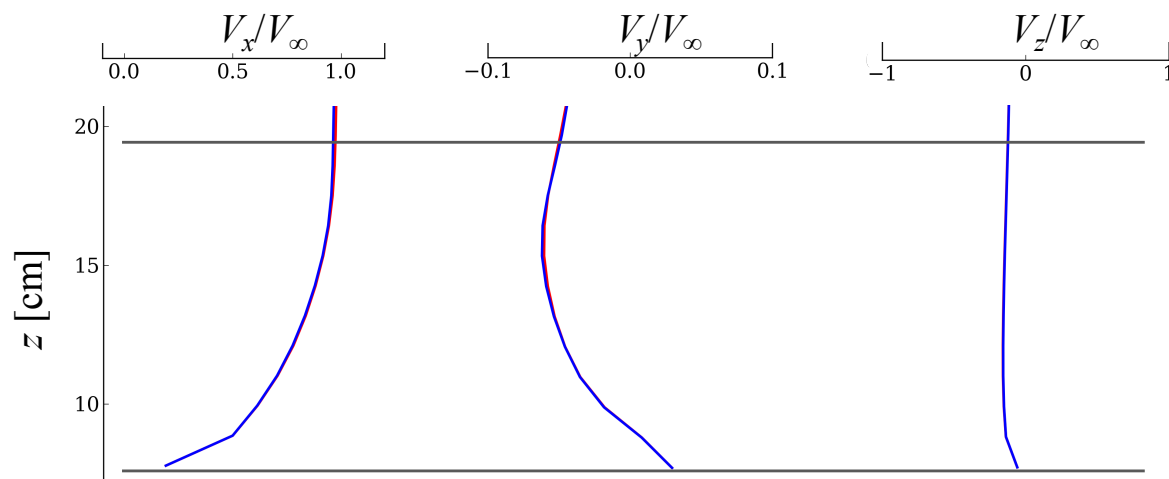
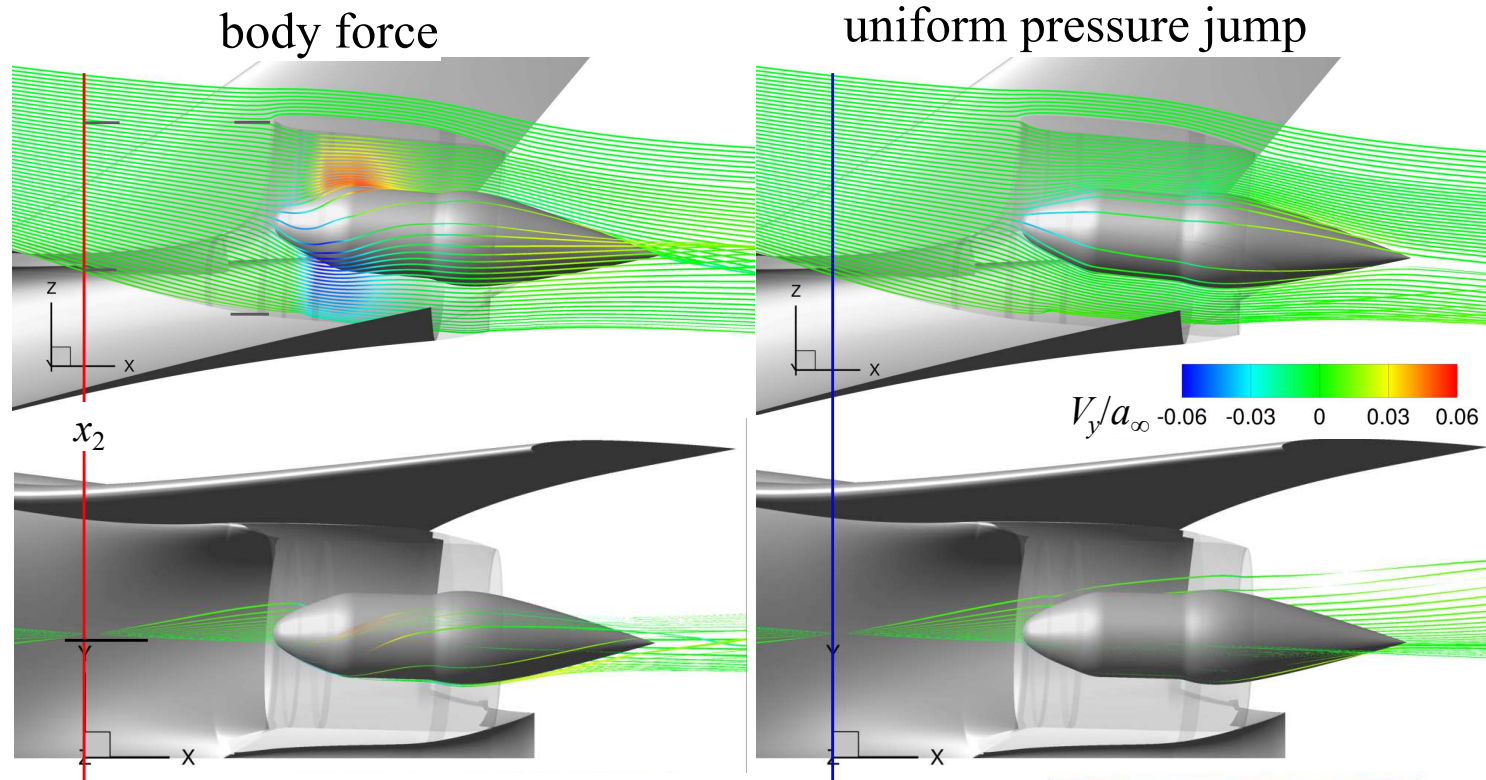
TF8000 propulsor on D8 -- Results



$x_1=2.79$ m:
(fan face)

— body force model
— pressure jump model

TF8000 propulsor on D8 -- Results



$x_2=2.67$ m:
($0.88d$ upstream)

— body force model
— pressure jump model

TF8000 propulsor, standalone



D8



D8, podded variant (non-BLI)

TF8000 propulsor, standalone



D8, podded variant (non-BLI)

TF8000 propulsor, standalone



Standalone TF8000 propulsor