Implementation of a Body Force Model into OVERFLOW for Propulsor Simulations

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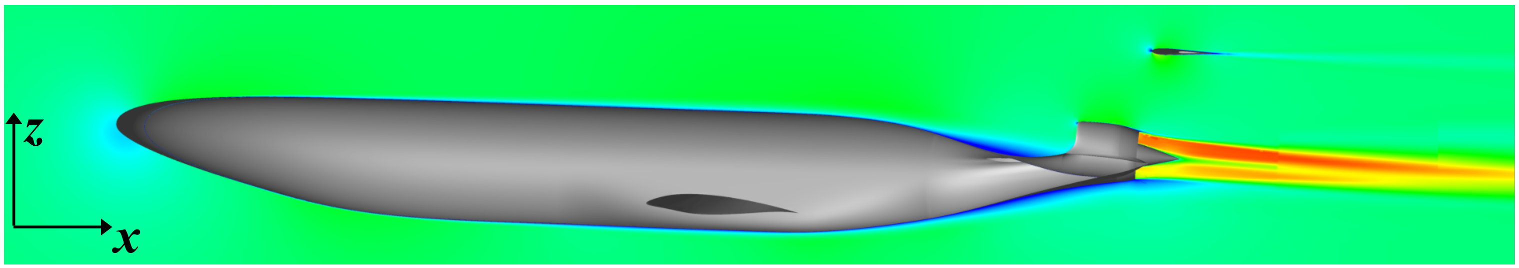
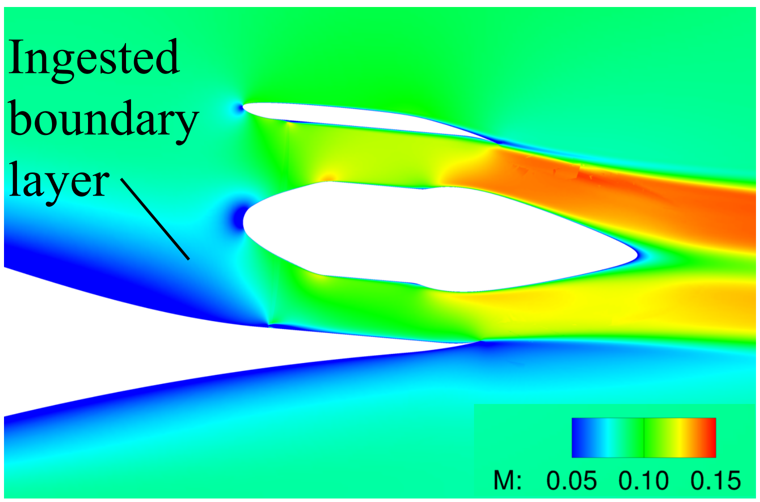
The application: Boundary Layer Ingestion on D8 aircraft





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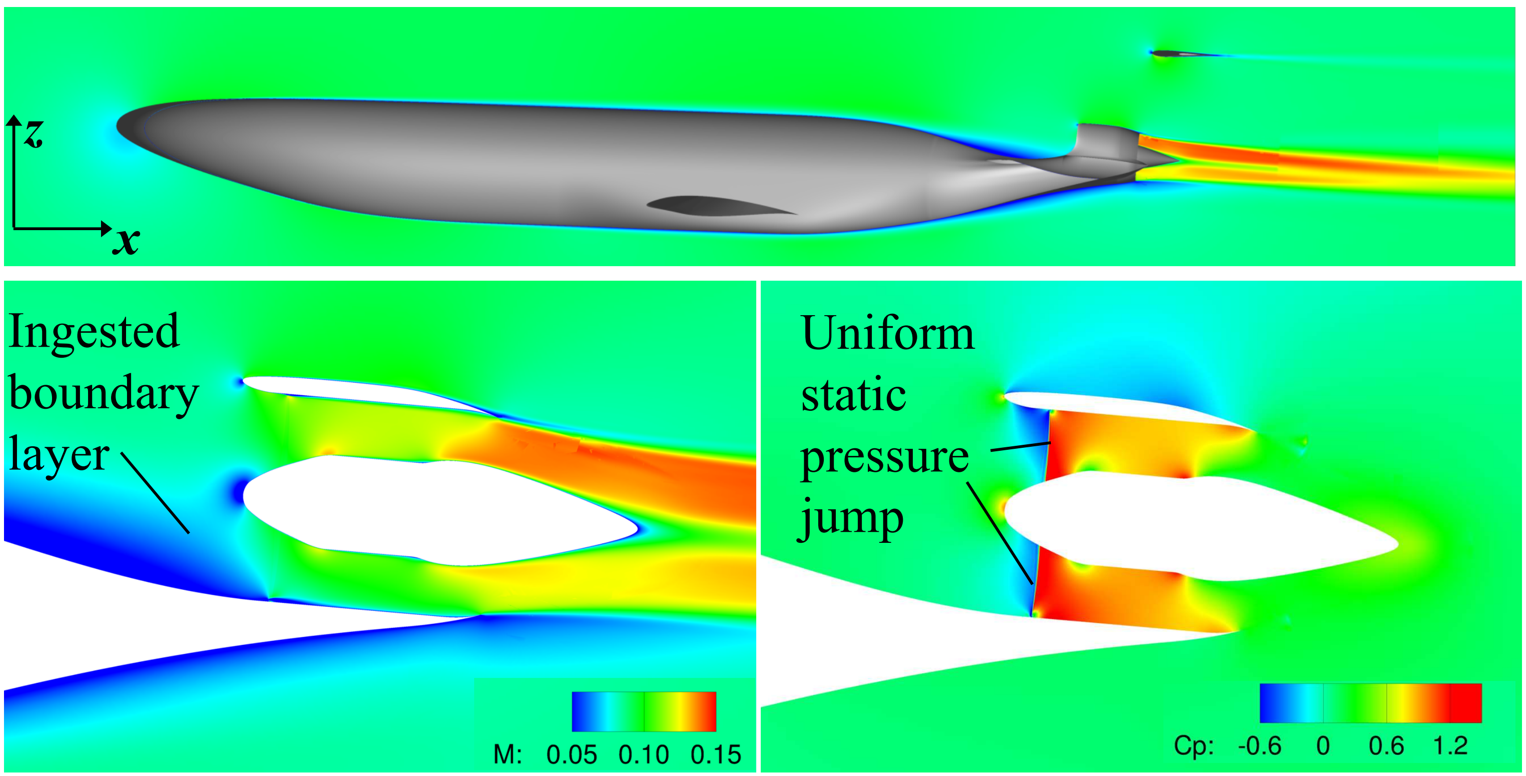

Previous method: Uniform static pressure jump

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

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

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

(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]

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Turbomachine applications

Joo and Hynes [1997]

Kim et al. [1999]

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… many others.

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.

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

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

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

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

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

Hall et al. “Analysis of Fan Stage Conceptual Design Attributes for Boundary Layer Ingestion”, 2017, ASME J. Turbomach.

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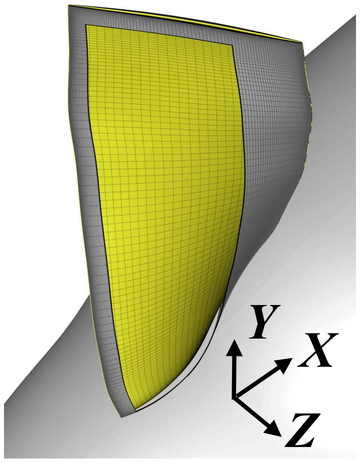
$$\mathbf{W} \cdot \mathbf{f} = 0 \text{ (Isentropic flow turning)}$$

Hall et al. "Analysis of Fan Stage Conceptual Design Attributes for Boundary Layer Ingestion", 2017, ASME J. Turbomach.

Implementation of the body force model

1. Define:



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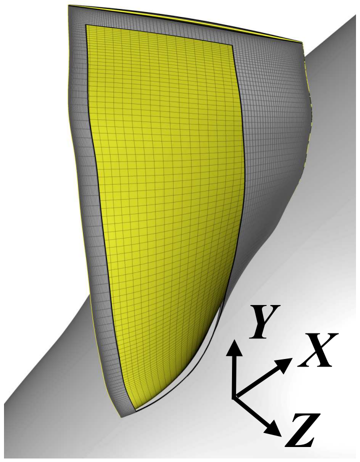
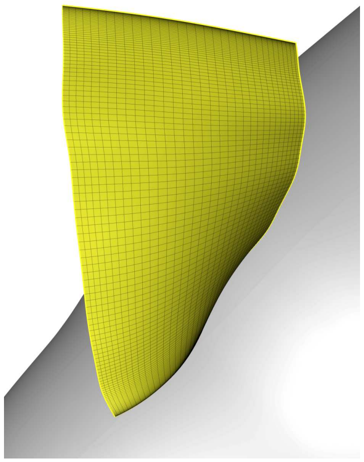
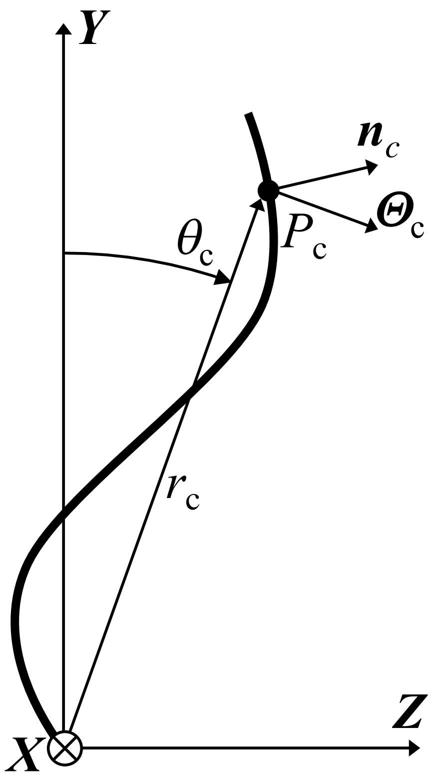


2. Extract:



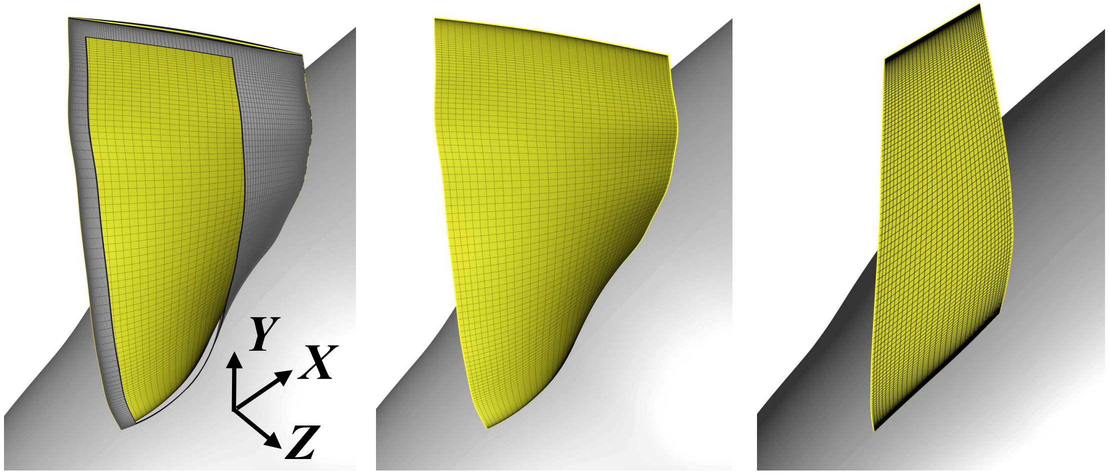


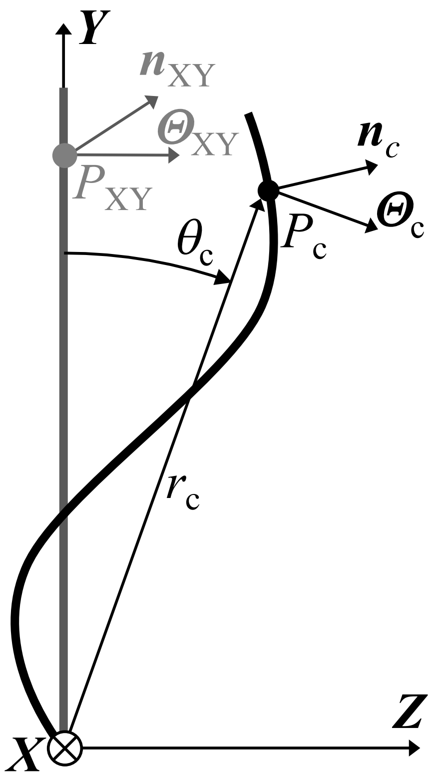
$$\mathbf{W} = \mathbf{V} - \mathbf{U} = \mathbf{V} - \Omega r \mathbf{\Theta}$$

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

Implementation of the body force model

1. Define: 2. Extract: 3. Flatten:





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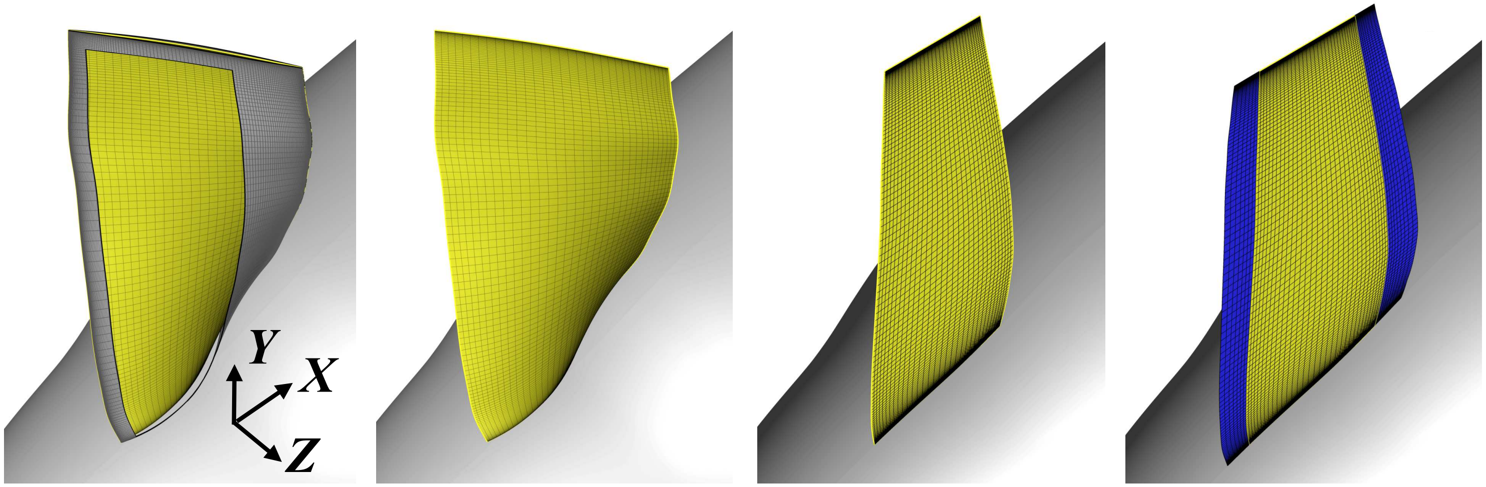

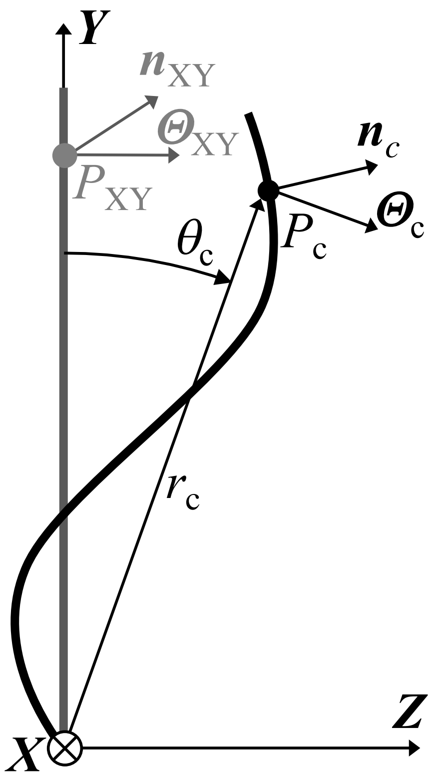

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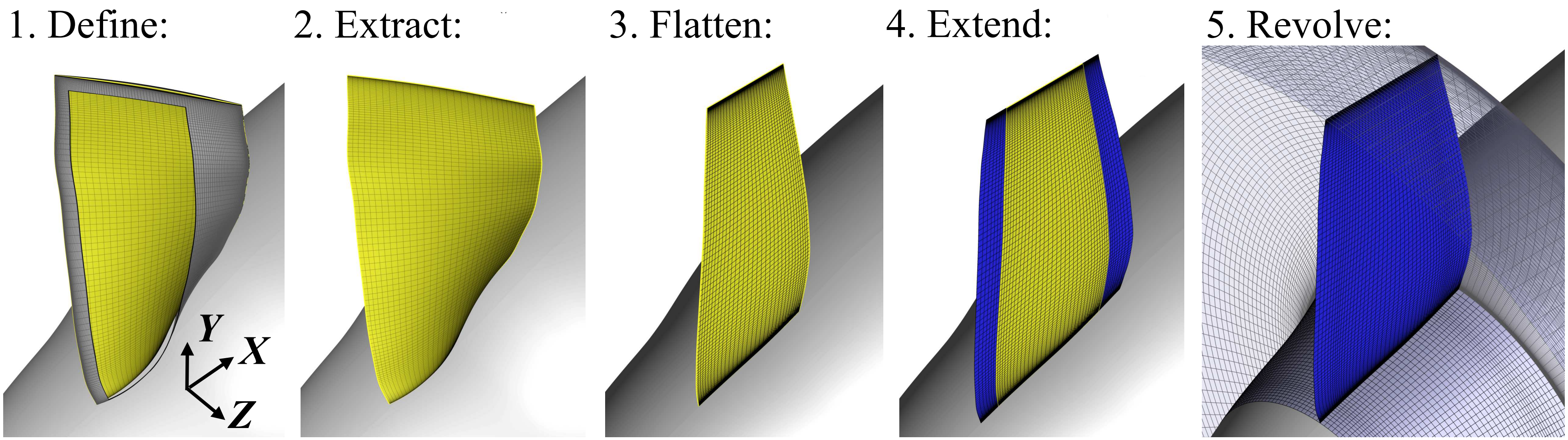
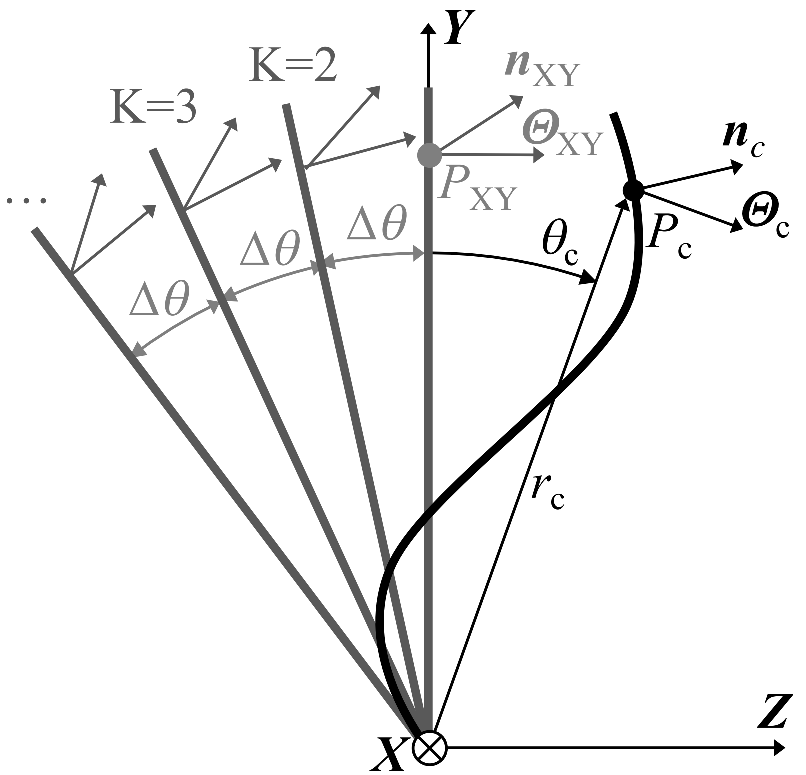
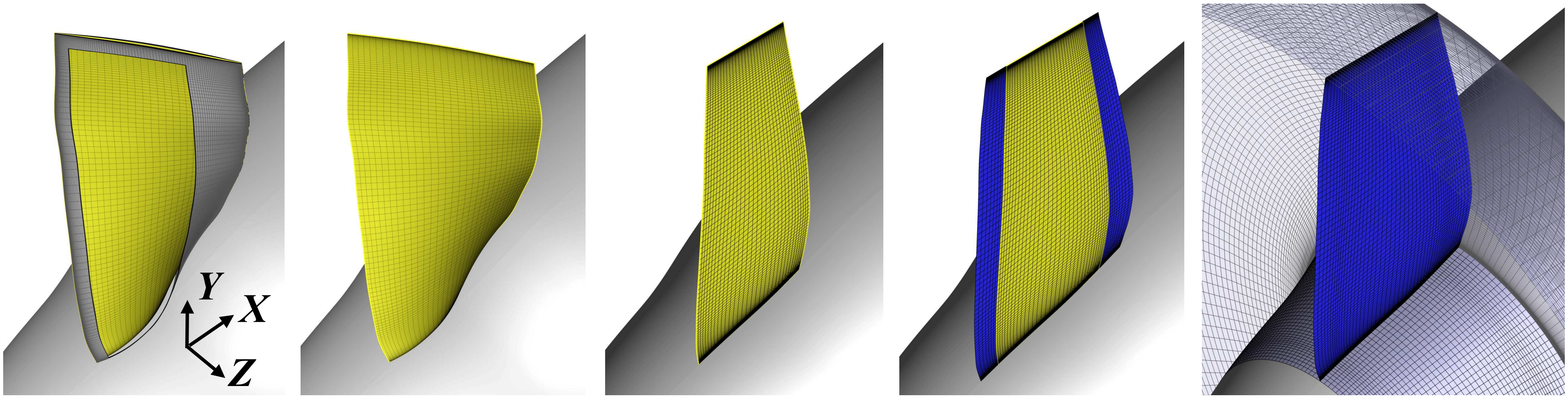


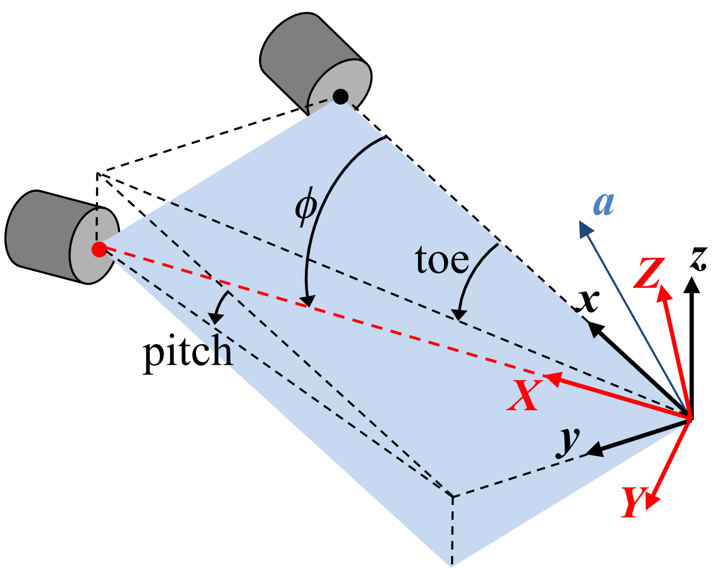


Implementation of the body force model

1. Define: 2. Extract: 3. Flatten: 4. Extend: 5. Revolve:



6. Rotate:



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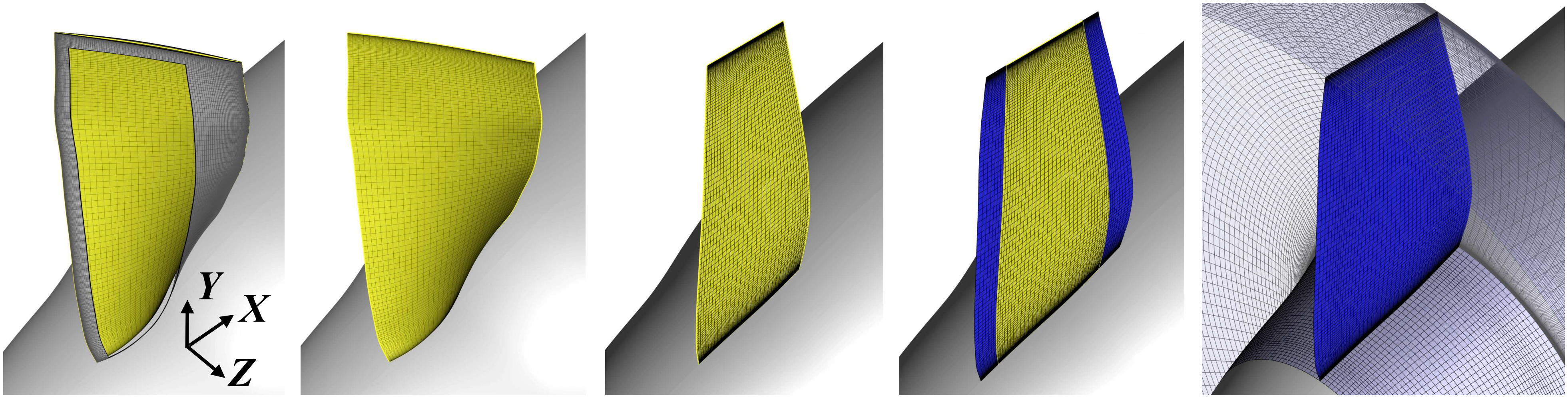

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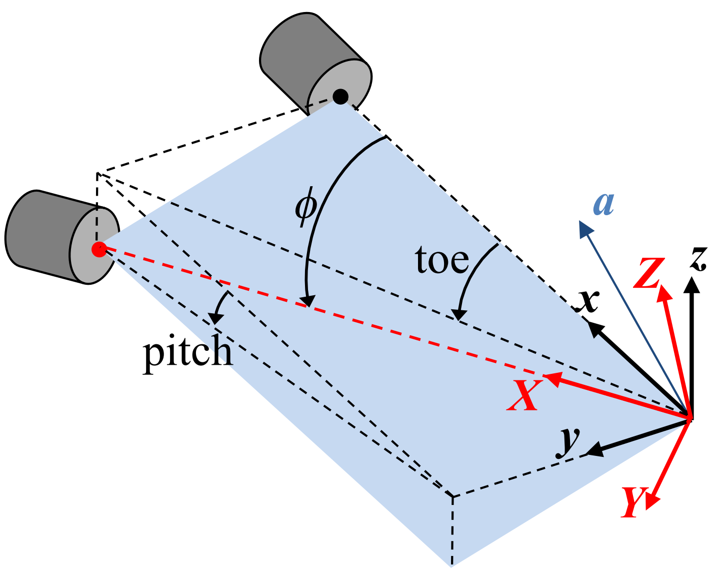

7. Save:

r

n_x

n_y

n_z

n_θ

Θ_x

Θ_y

Θ_z

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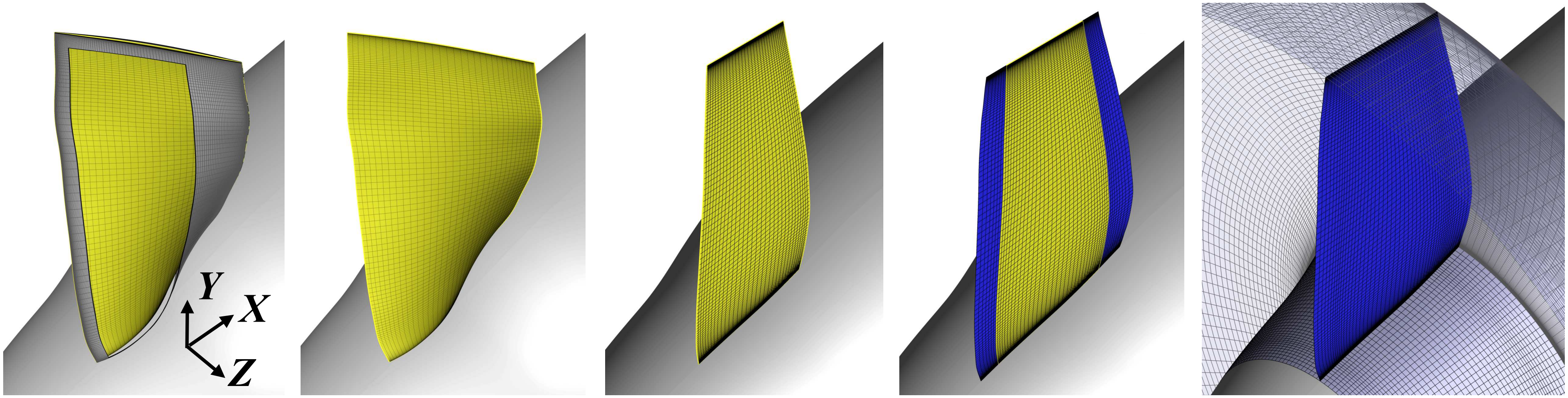

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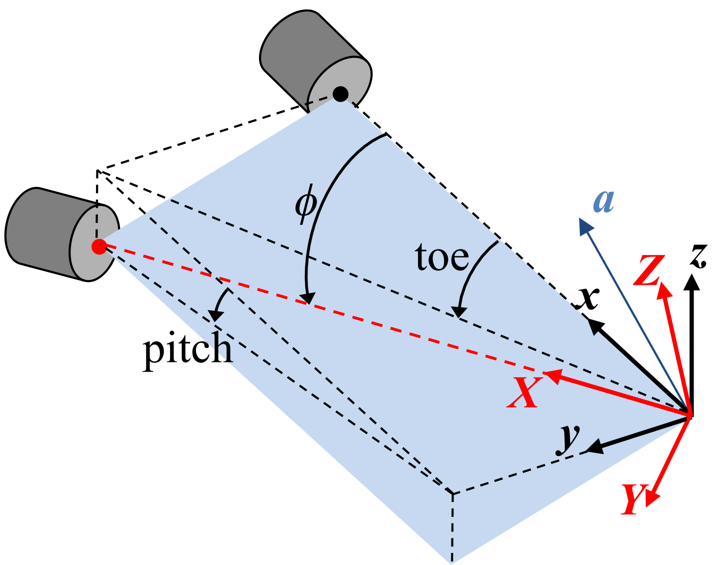

7. Save:

r

n_x

n_y

n_z

n_θ

Θ_x

Θ_y

Θ_z

8. Read in Overflow, compute the source terms each in iteration

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

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

$$\mathrm{V}\cdot\nabla\mathrm{V} + \frac{\nabla p}{\rho} = \mathbf{f}$$

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

Flow solution methods

Grid Generation: *Chimera Grid Tools (CGT)*
Steps 1 to 7 are automated by routines added to CGT codebase

Solver: *Overflow 2.2l*
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)

Nichols and Buning, *Users Manual for OVERFLOW 2.2*, https://overflow.larc.nasa.gov
Chan, Gomez, Rogers and Buning, *Best Practices in Overset Grid Generation*, 2002, AIAA-2002-3191

Test Cases

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

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A stand-alone TF8000 propulsor

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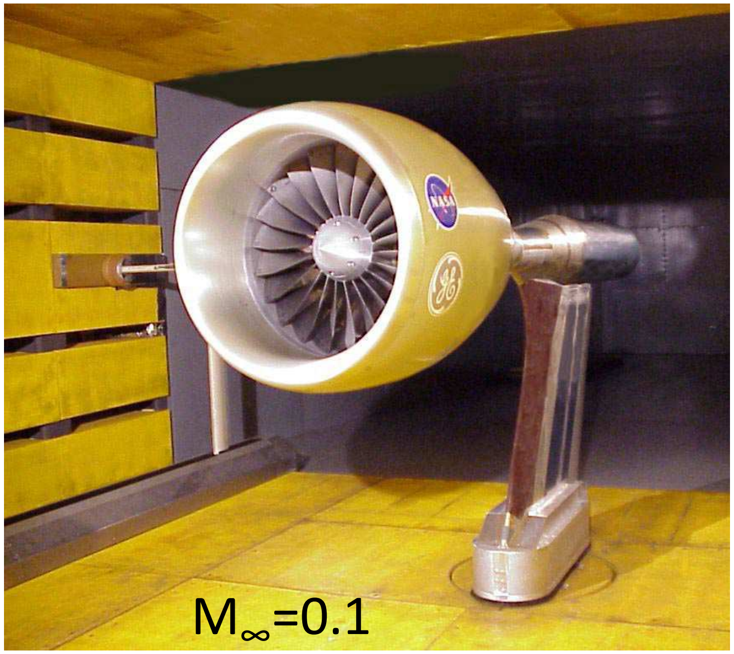
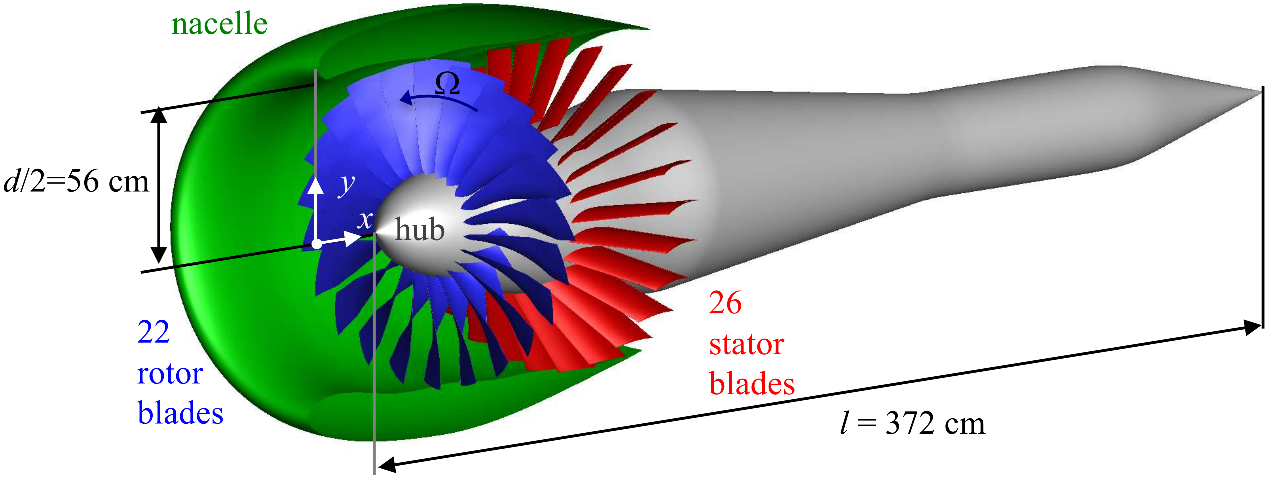
The D8 aircraft model in a wind tunnel

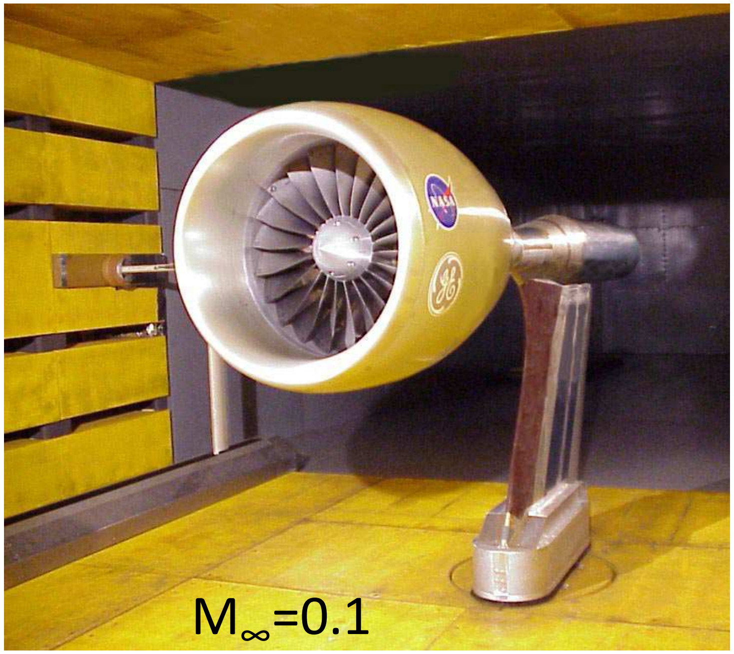
Source Diagnostics Test (SDT) fan with R4 Rotors



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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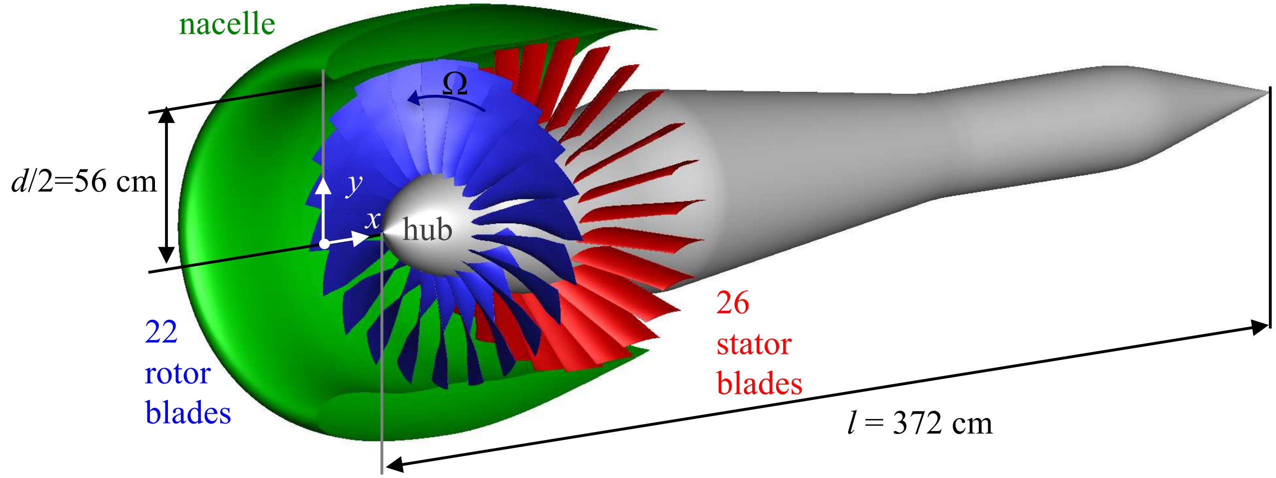
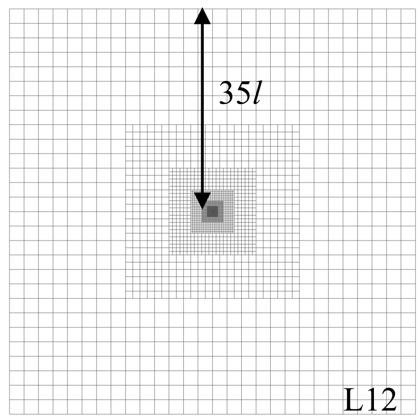
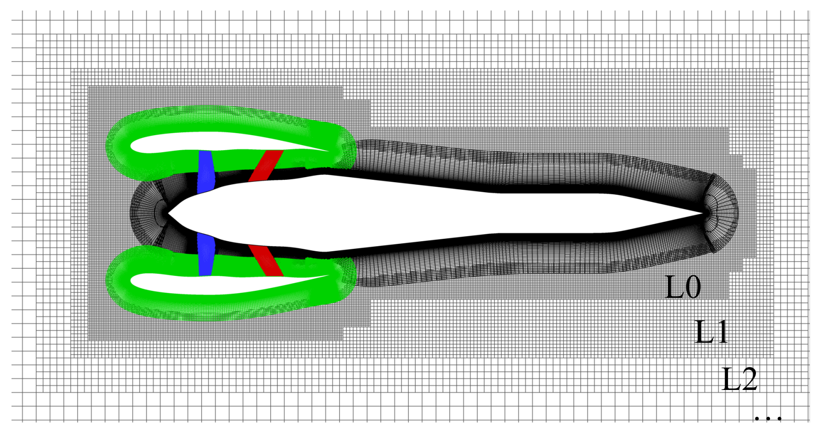
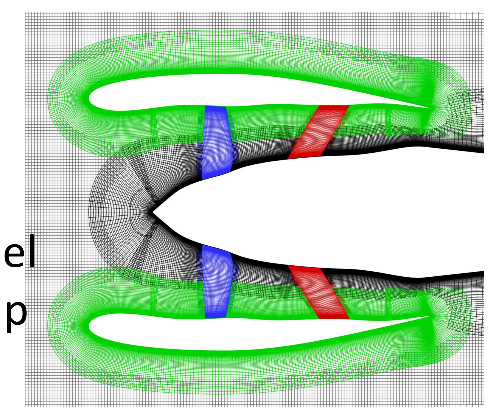


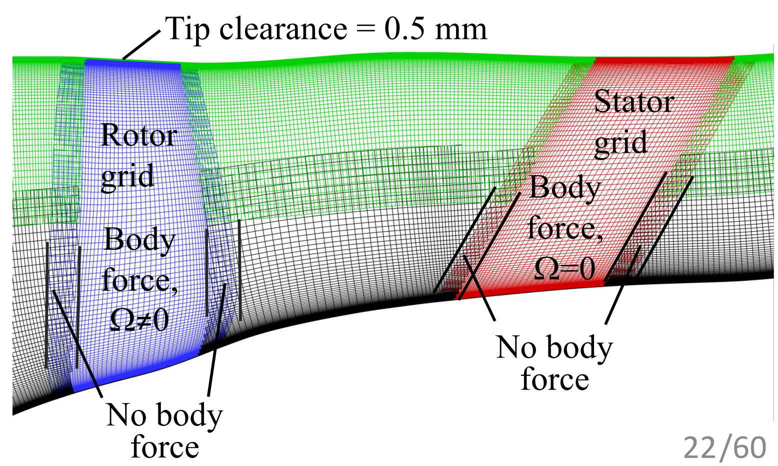




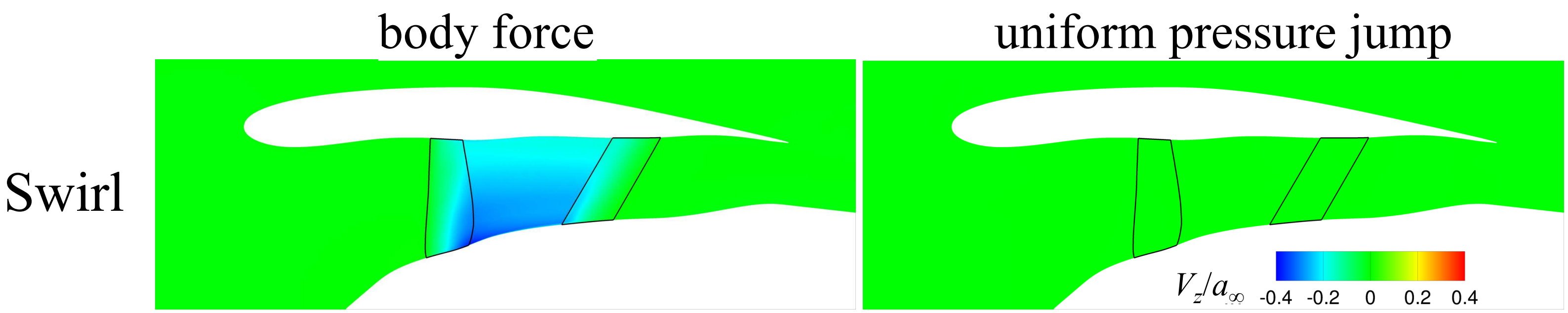
35 million vertices, $y^+ \approx 1$
4 to 8 hours on 128 Haswell cores

Full convergence with body force model
Partial convergence with pressure jump





SDT fan results



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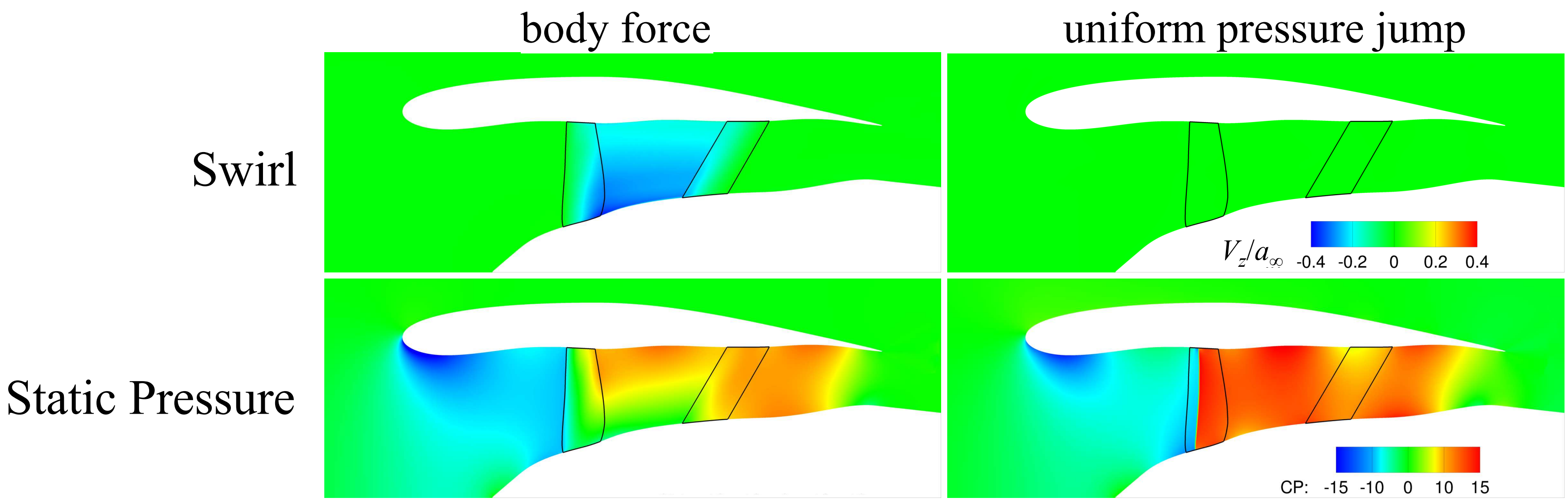

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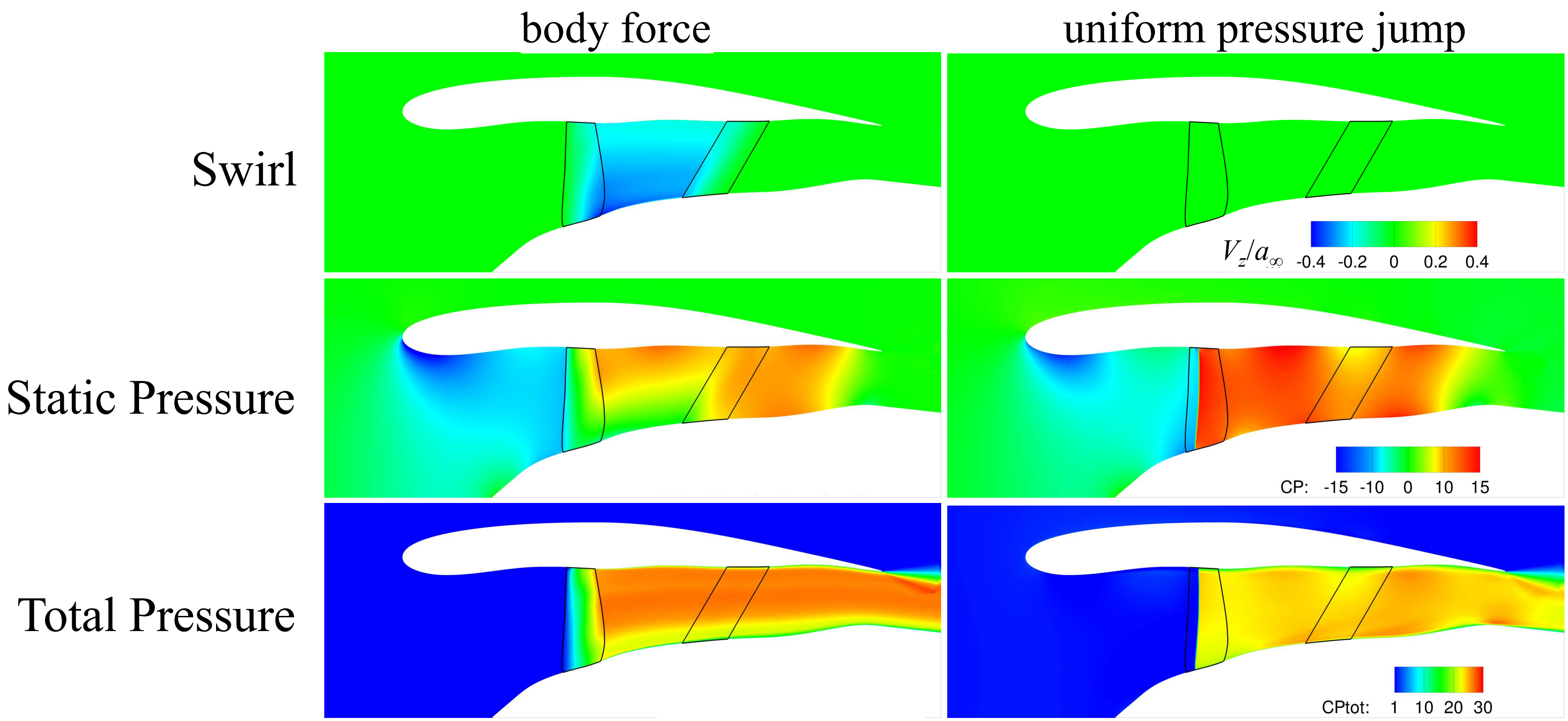

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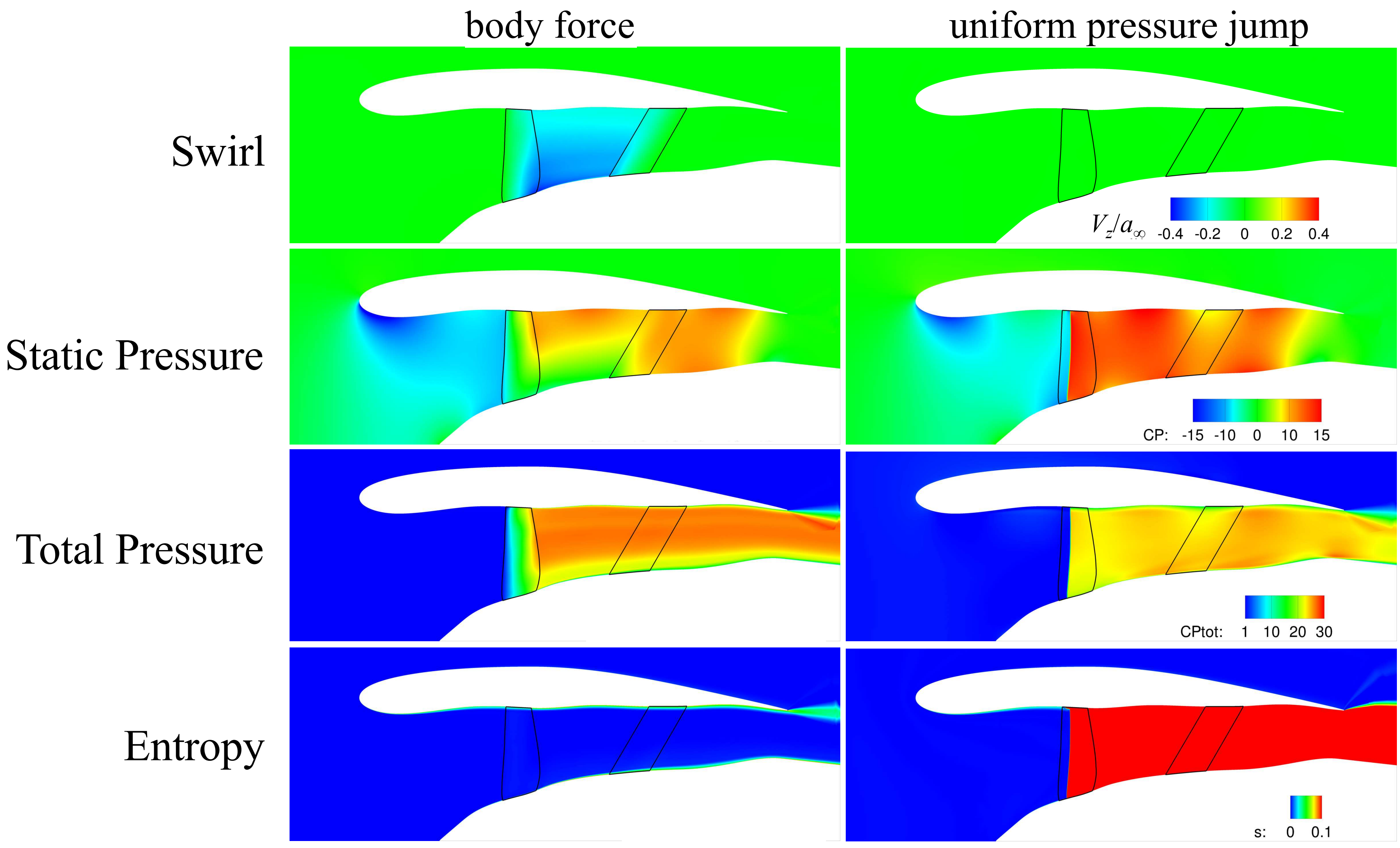

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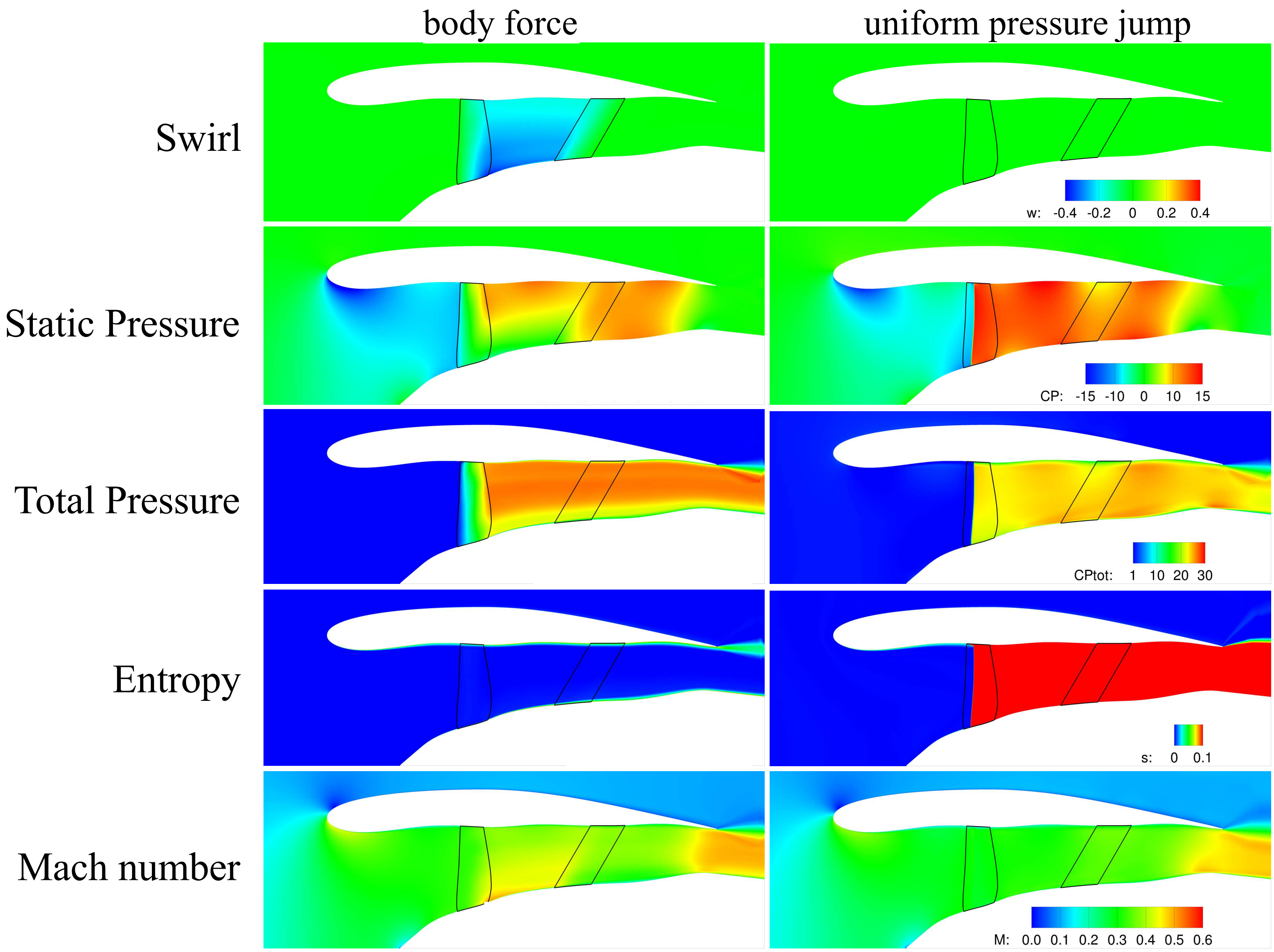
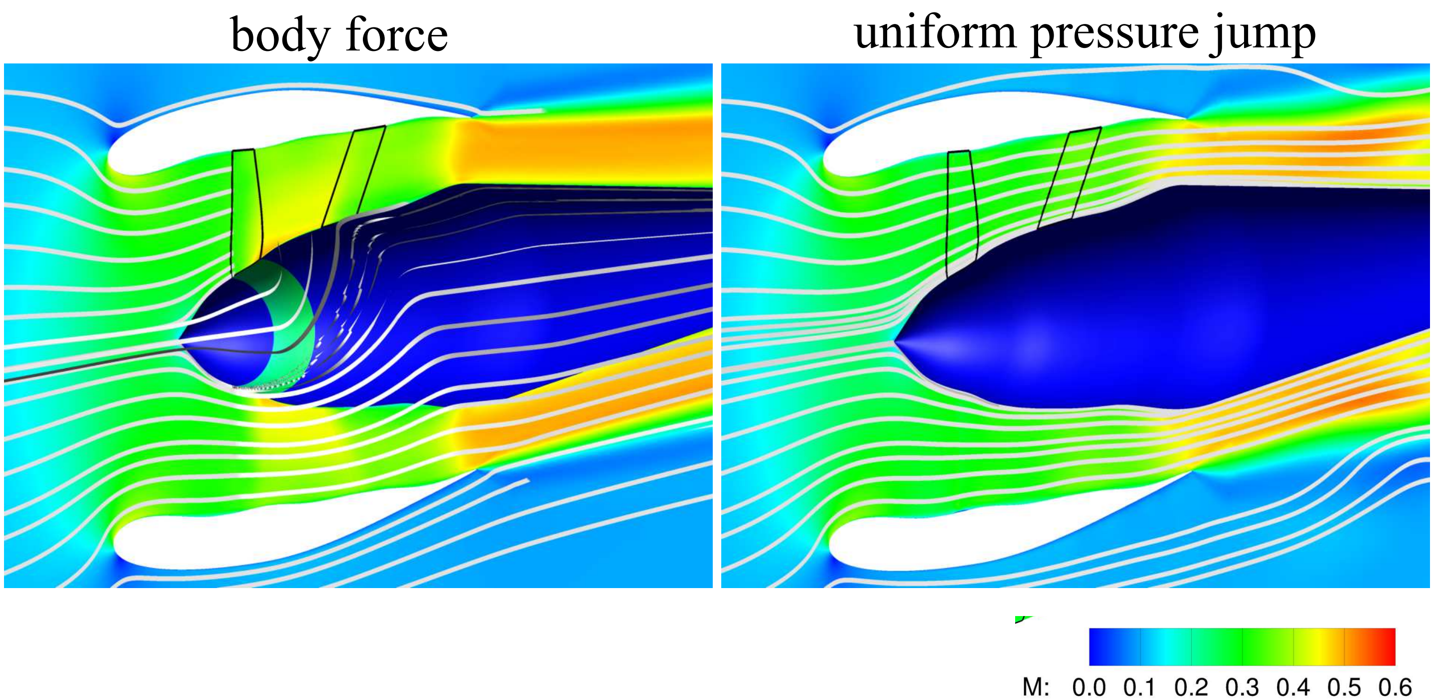


SDT fan results

Streamlines



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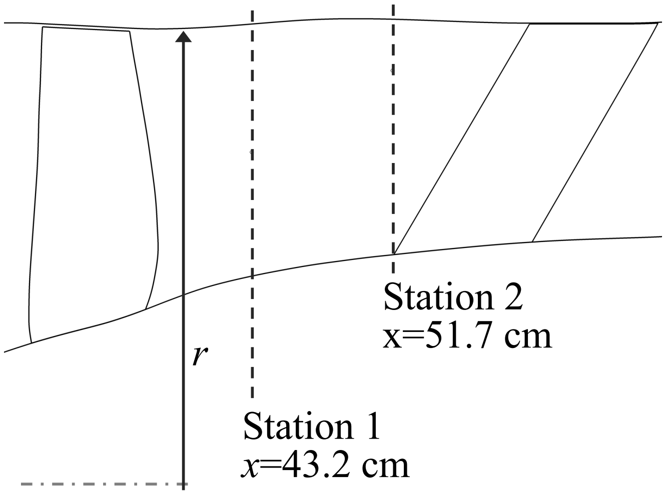

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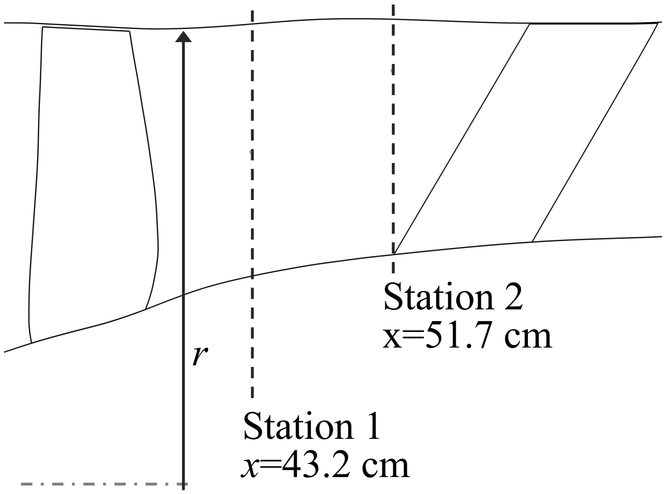
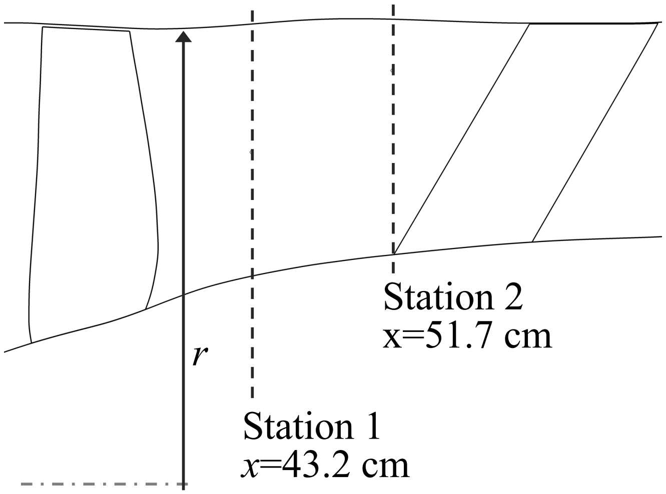
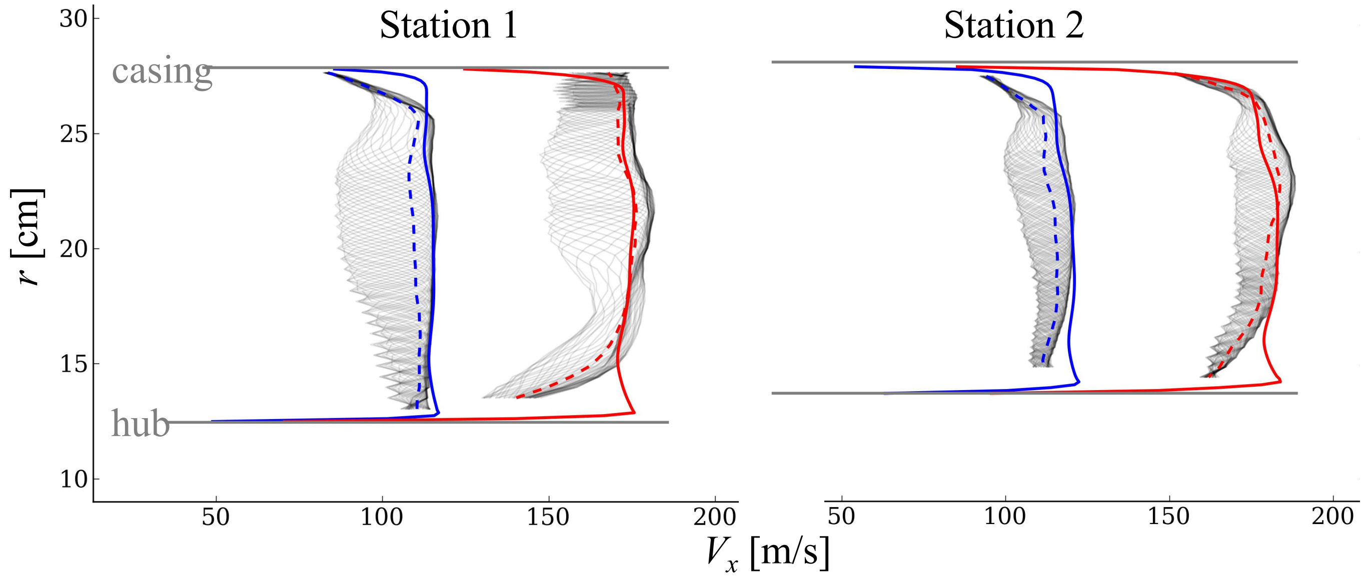


7,808 rpm 12,657 rpm

7,808 rpm	12,657 rpm		
—— (black solid)	—— (black solid)	Experiment (phase-avg.)	SDT campaign at NASA Glenn Research Center POC: Dr. Ed Envia
- - - (blue dashed)	- - - (red dashed)	Experiment (mean of phase-avg.)	
—— (blue solid)	—— (red solid)	Simulation (body force model)	

SDT fan results





7,808 rpm 12,657 rpm

Experiment (phase-avg.)

Experiment (mean of phase-avg.)

Simulation (body force model)

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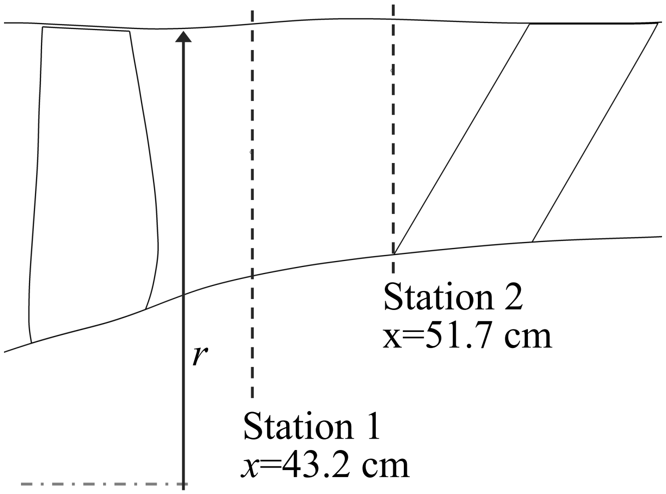

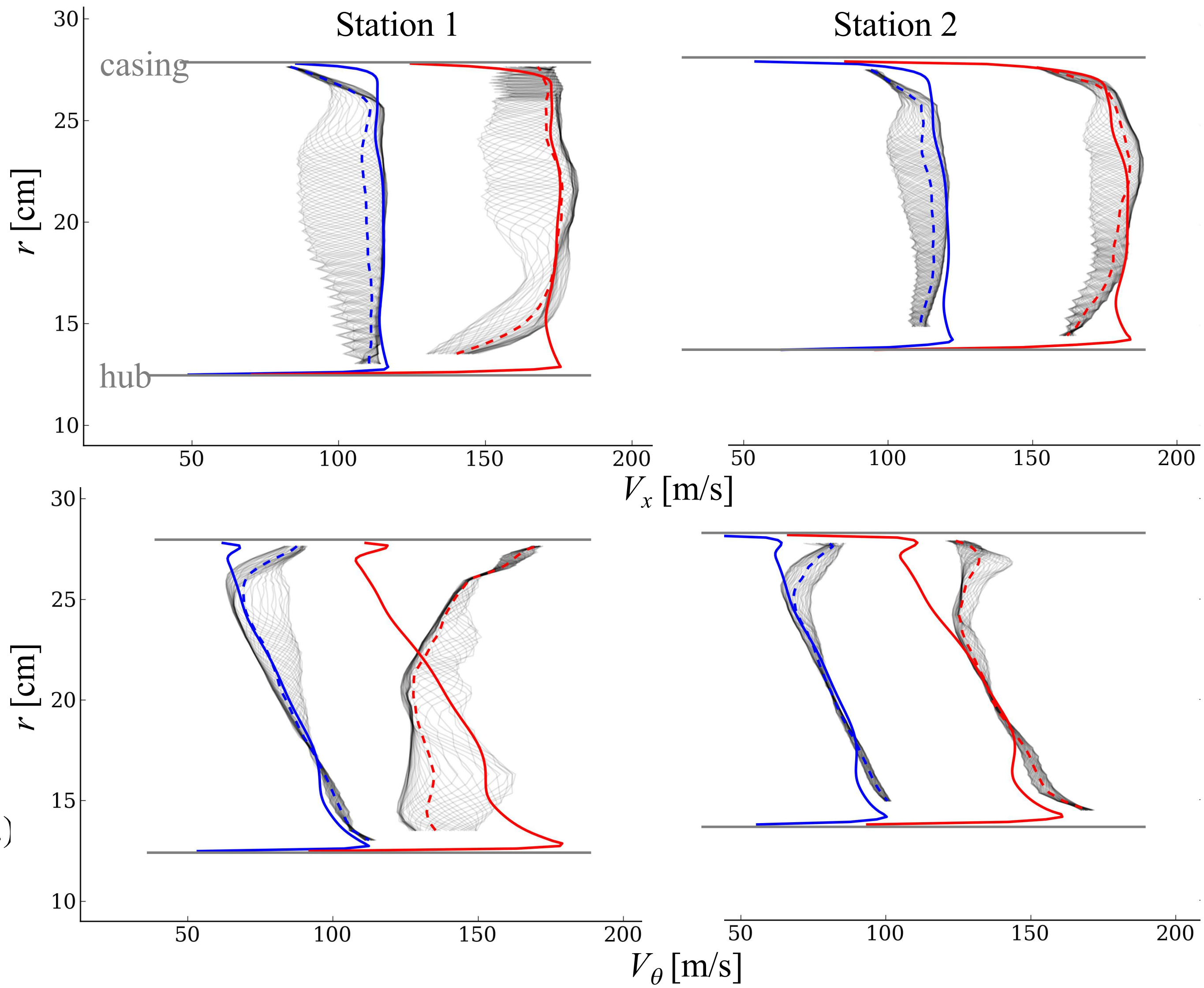

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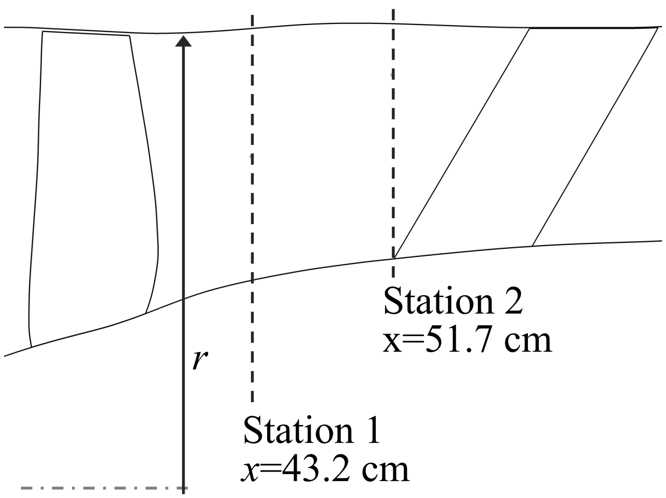
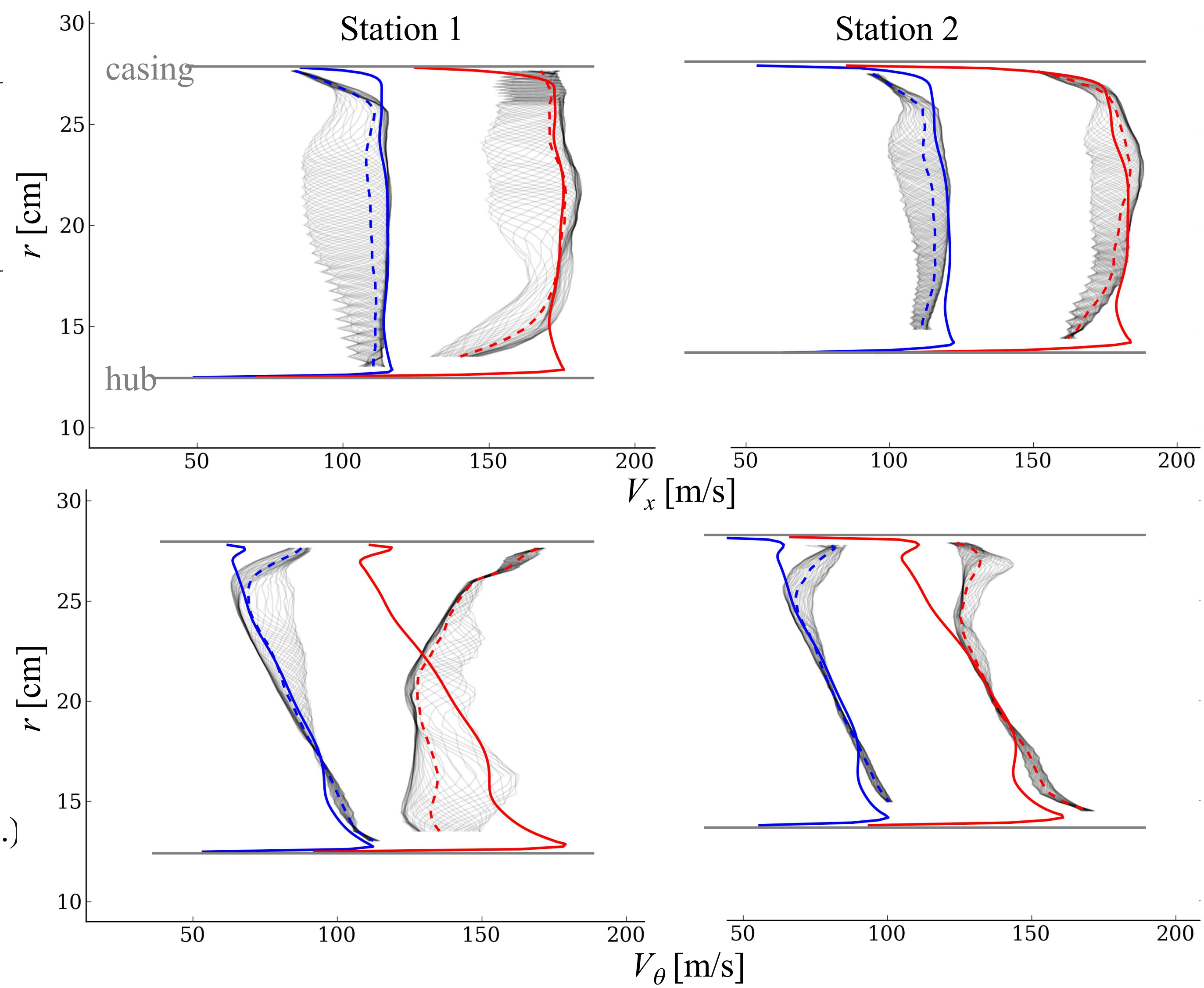




7,808 rpm 12,657 rpm

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

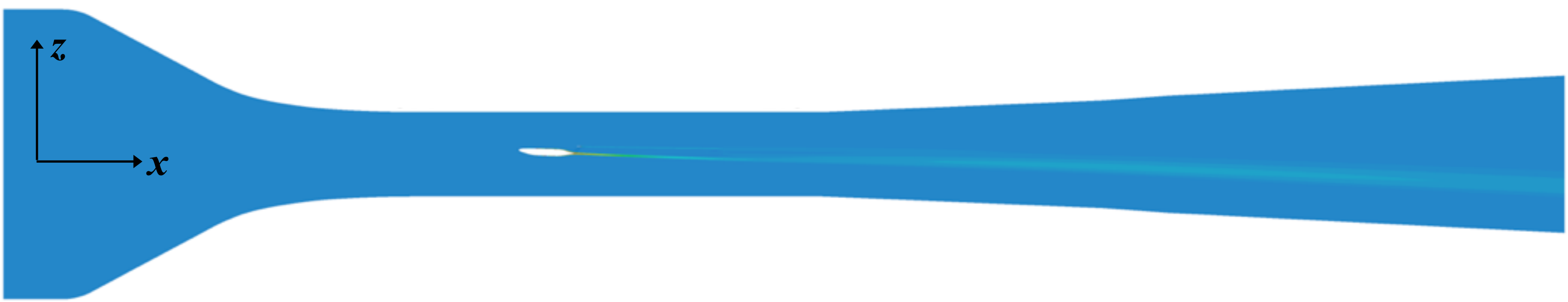
Hughes et al., 2005

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

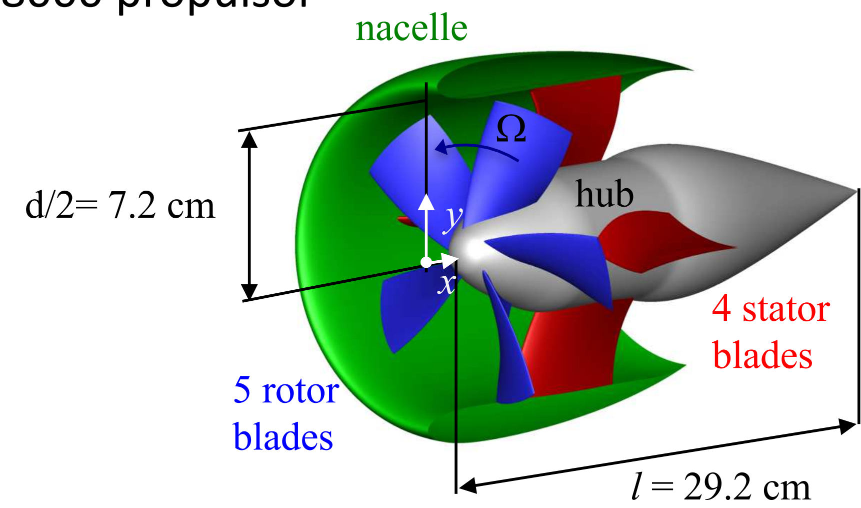
CFD: Simulation of the model in the wind tunnel including the contraction and diffuser sections



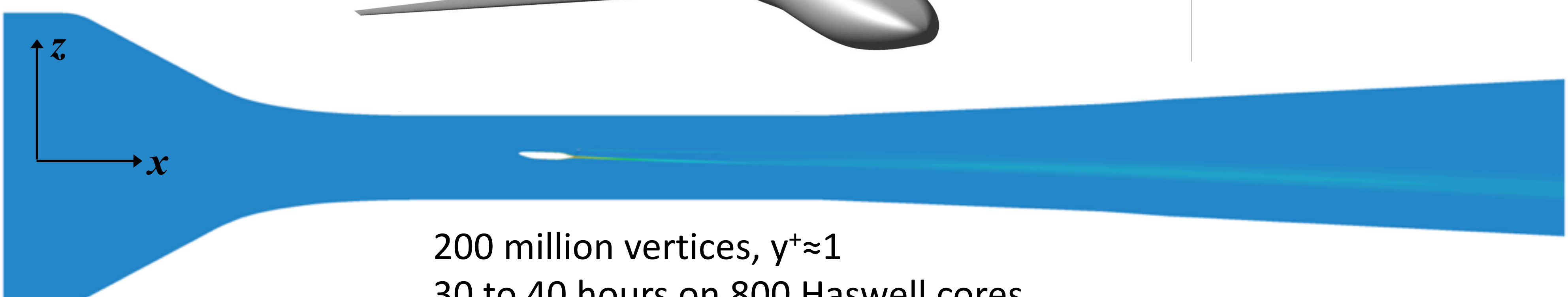
Pandya, *External Aerodynamics Simulations for the MIT D8 "Double-Bubble" Aircraft Design*, 2012, ICCFD7-4304

TF8000 propulsor on D8

TF8000 propulsor

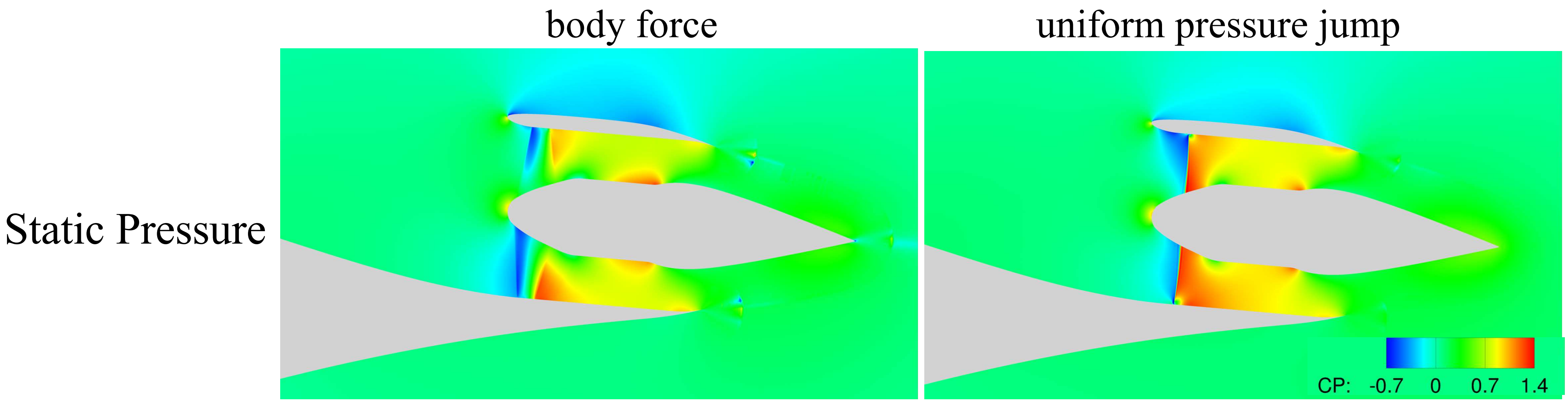


D8 aircraft in wind tunnel



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

TF8000 propulsor on D8 -- Results



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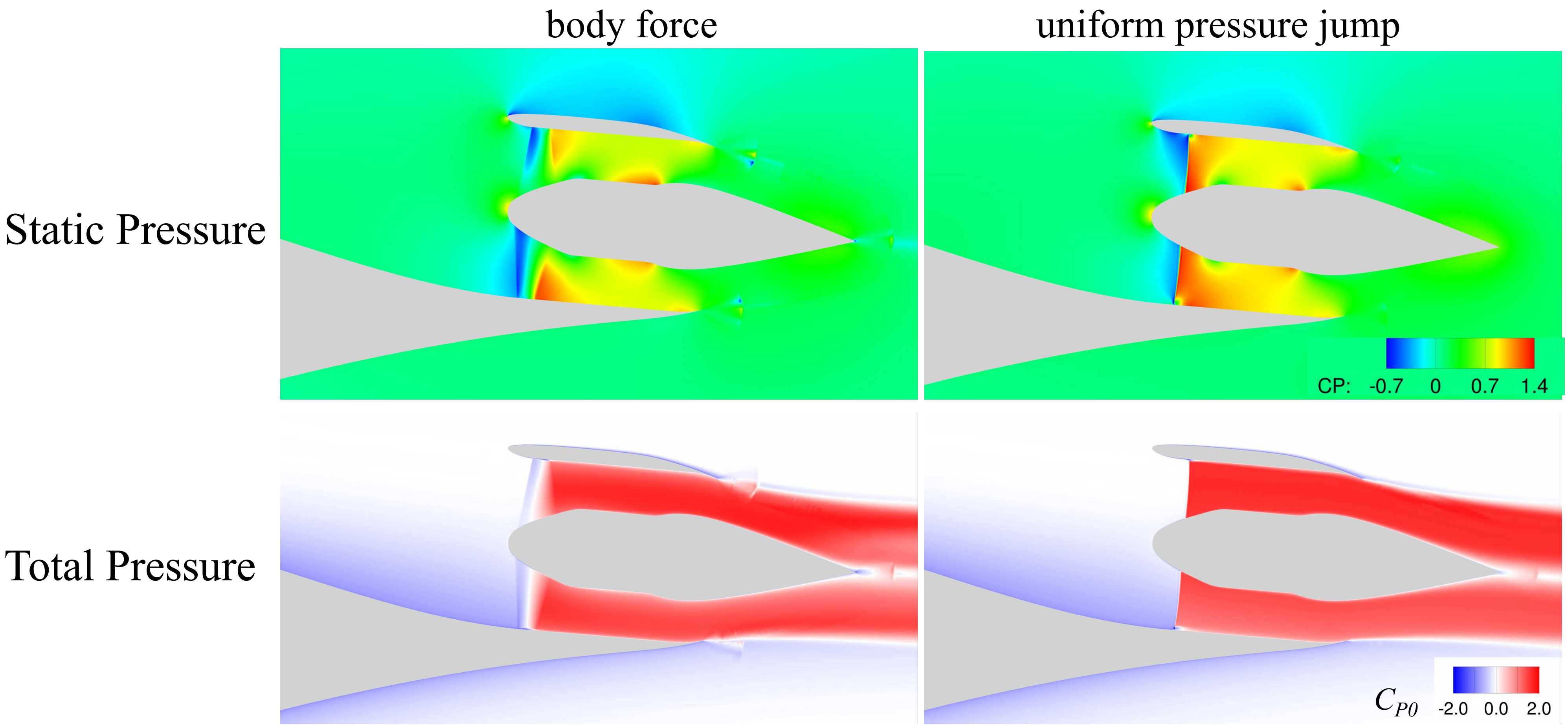

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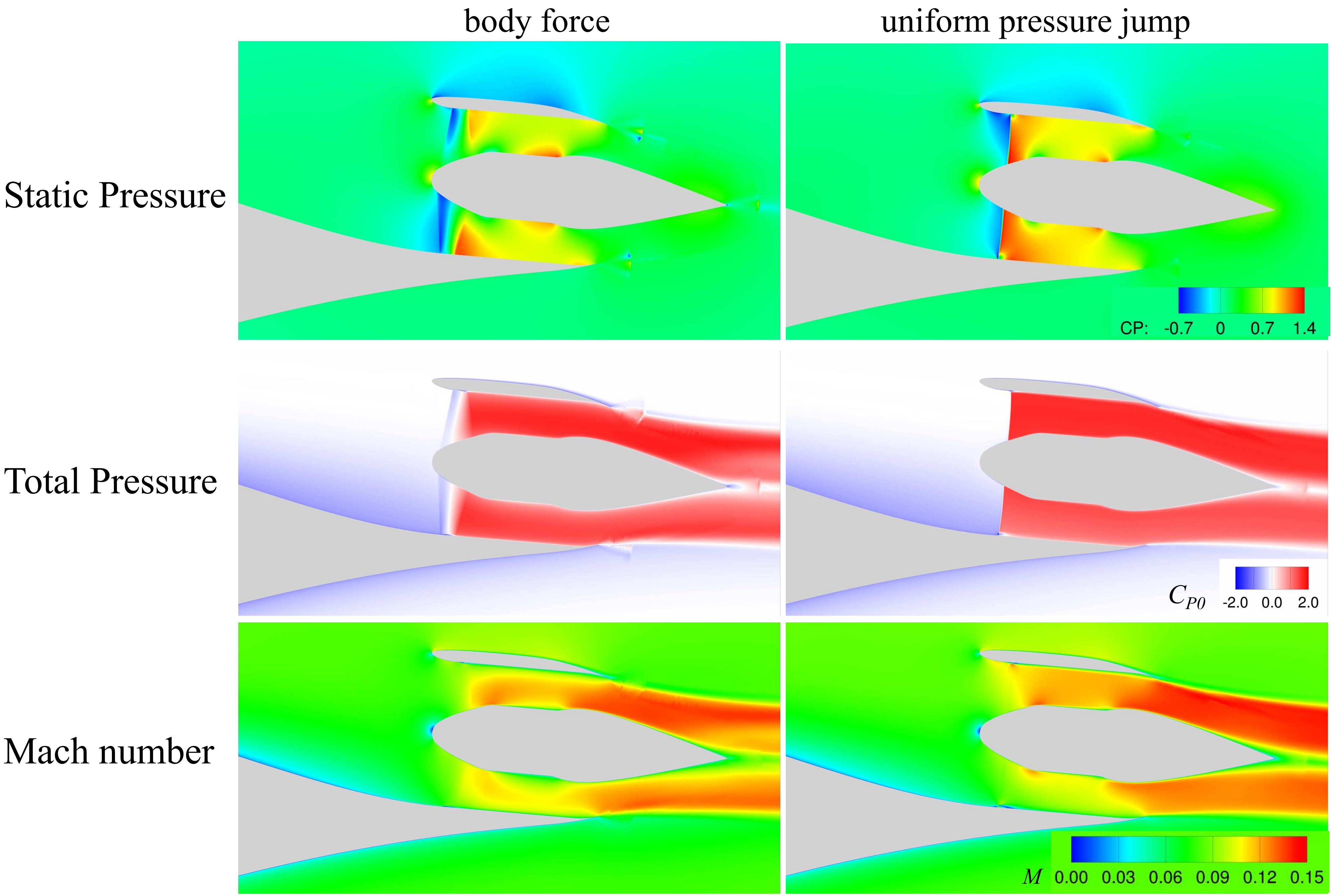
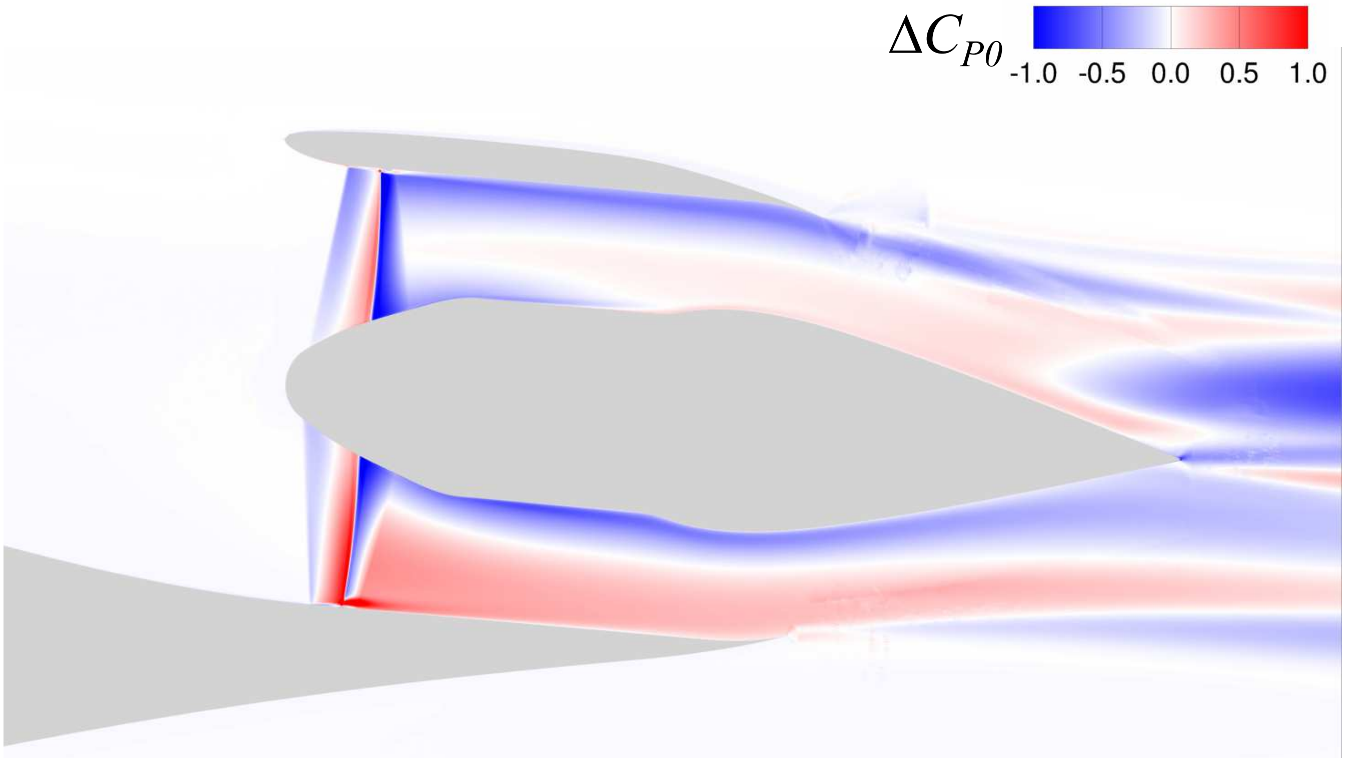


TF8000 propulsor on D8 -- Results

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



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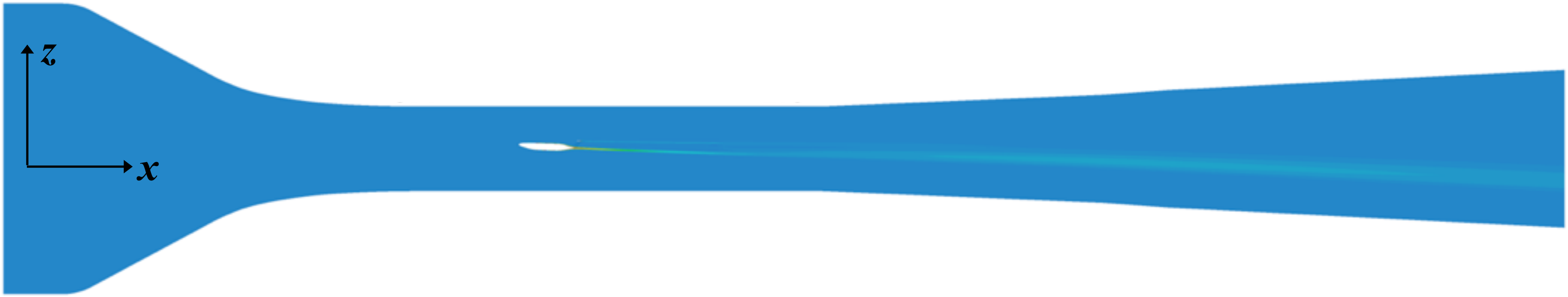
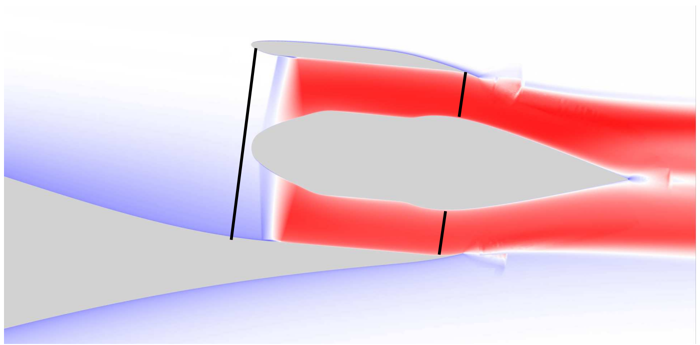
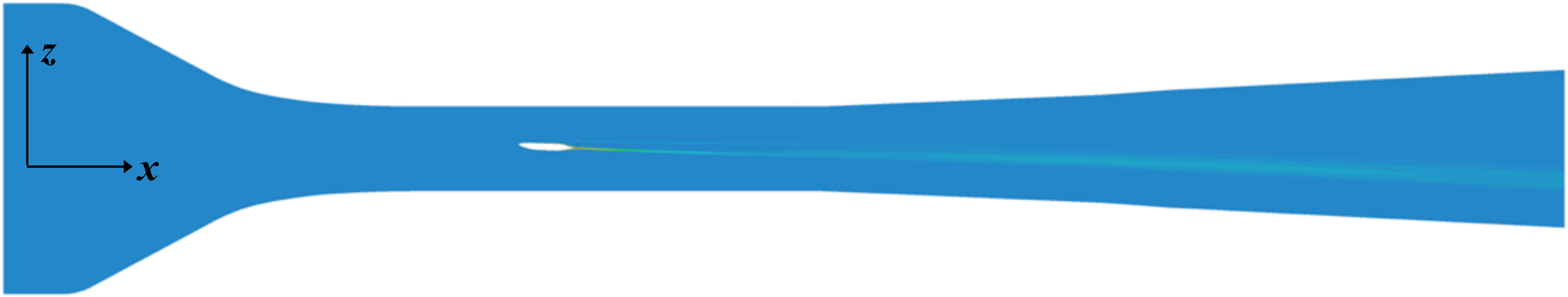
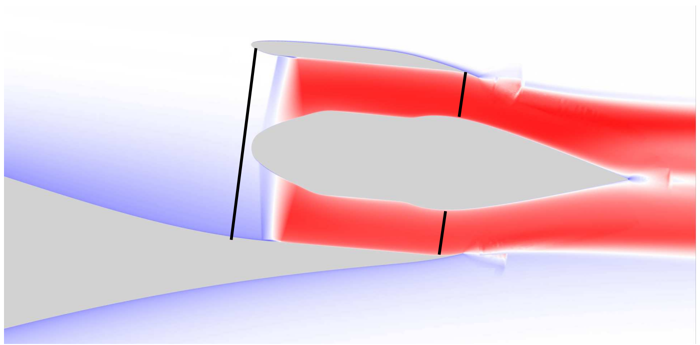




$$C_{\mathrm{PK}} = \frac{\int_{fan} (p_{t,\infty} - p_t)(\mathbf{V} \cdot \mathbf{n})\, dA}{q_\infty V_\infty S_{ref}}$$

TF8000 propulsor on D8 -- Results



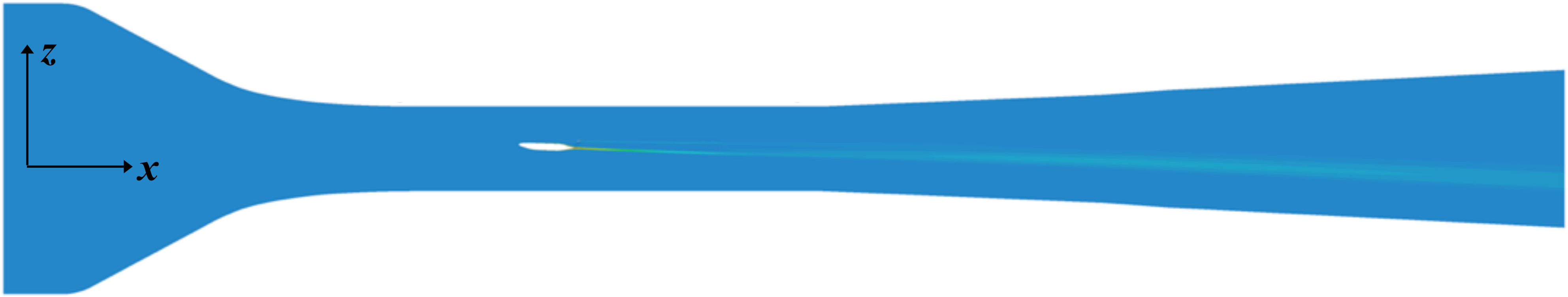


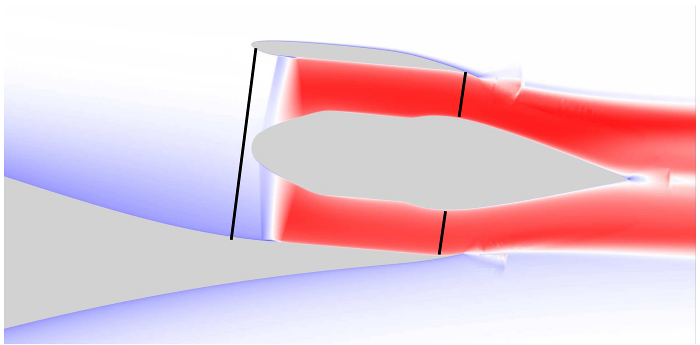
$$C_{\text{PK}} = \frac{\int_{fan} (p_{t,\infty} - p_t)(\mathbf{V} \cdot \mathbf{n})\, dA}{q_\infty V_\infty S_{ref}}$$

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

Experimental data inferred from Uranga et al., 2014

TF8000 propulsor on D8 -- Results





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

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

Experimental data inferred from Uranga et al., 2014

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.

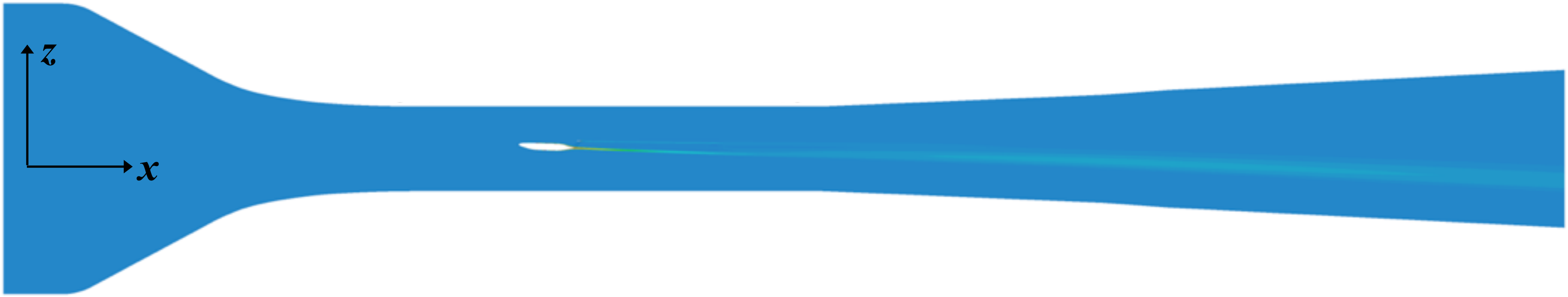
- Dr. Edmane Envia of NASA Glenn Research Center provided the SDT aerodynamic data and geometry definition files.

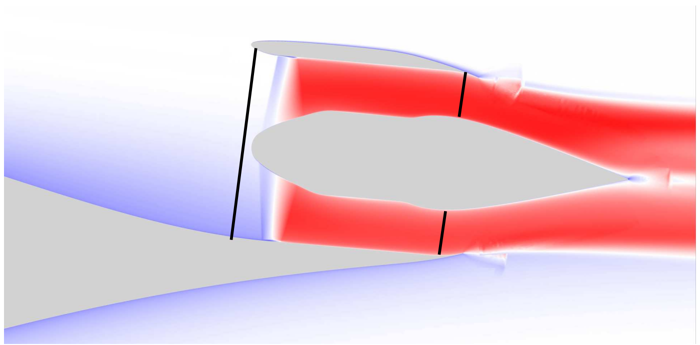
- NASA Advanced Air Transport Technology (AATT) project provided the funding for this work.

- NASA Advanced Supercomputing (NAS) Division at NASA Ames Research Center provided computing resources.

Backup Slides

TF8000 propulsor on D8 -- Results



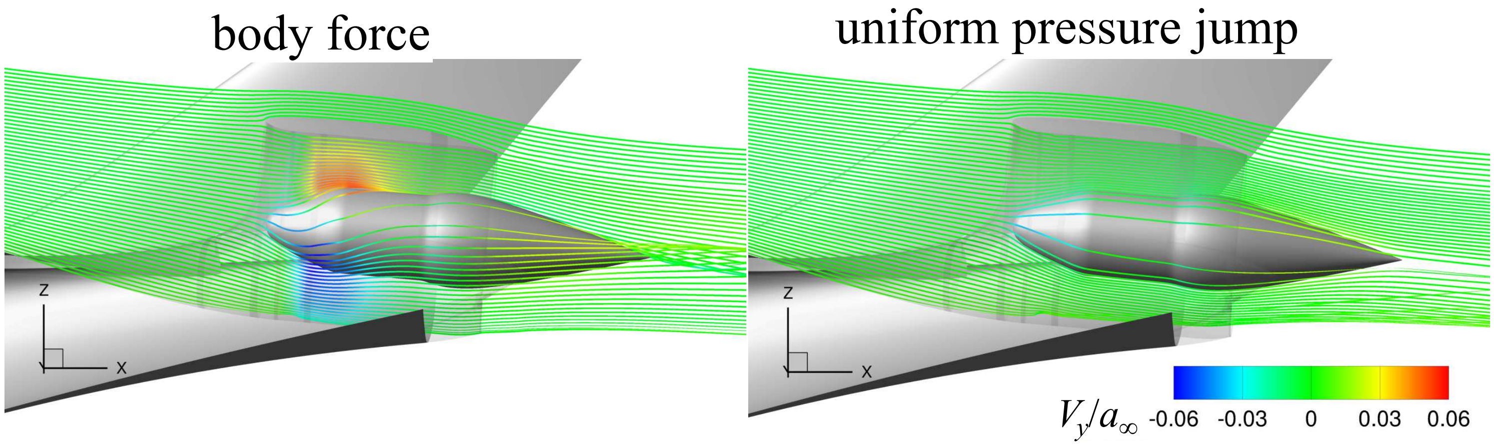


$$C_{\text{PK}} = \frac{\int_{fan} (p_{t,\infty} - p_t)(\mathbf{V} \cdot \mathbf{n})\, dA}{q_\infty V_\infty S_{ref}}$$

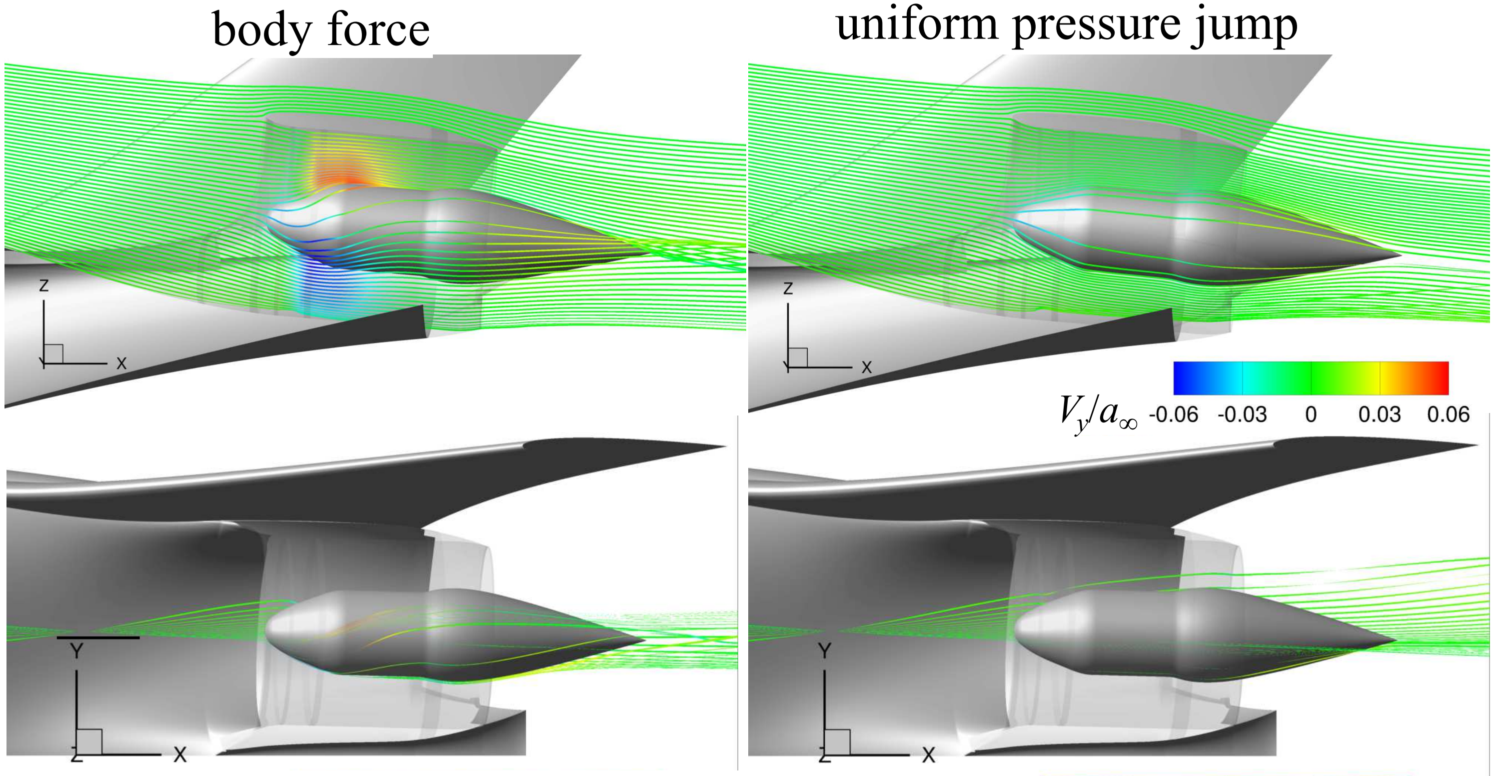
Method	C_x	C_z	C_{PK}	$C_{\dot{m}}$
Experiment	0.0000 ± 0.0006	0.644 ± 0.001	0.045 ± 0.001	0.0267 ± 0.0006
Uniform Pressure Jump	0.0002	0.651	0.045	0.0282
Body Force, 11,450 rpm	0.0005	0.678	0.043	0.0281
Body Force, 11,100 rpm	0.0028	0.672	0.039	0.0275

Experimental data inferred from Uranga et al., 2014

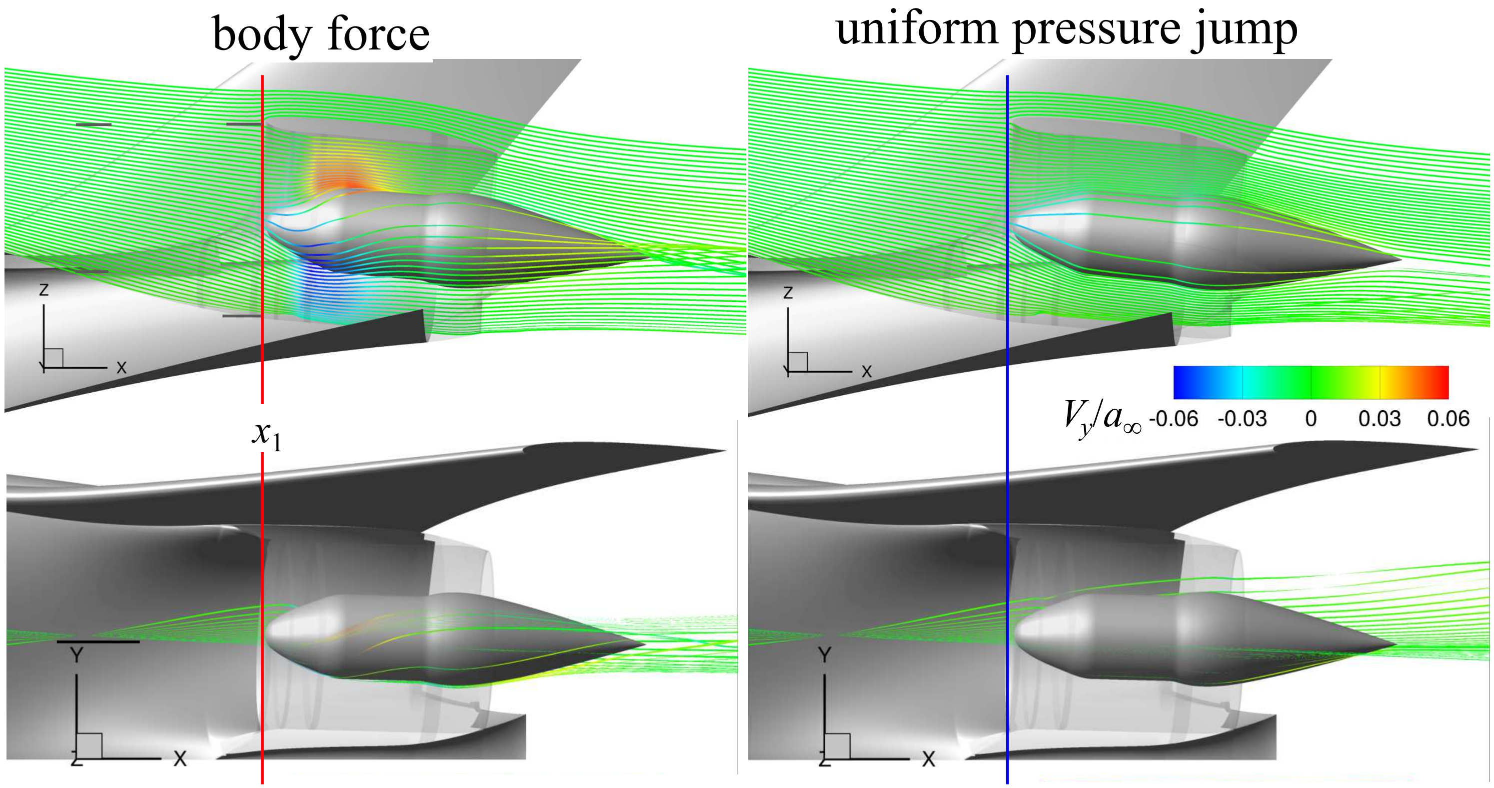
TF8000 propulsor on D8 -- Results

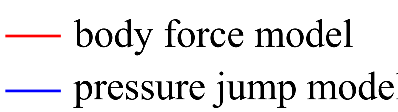


TF8000 propulsor on D8 -- Results

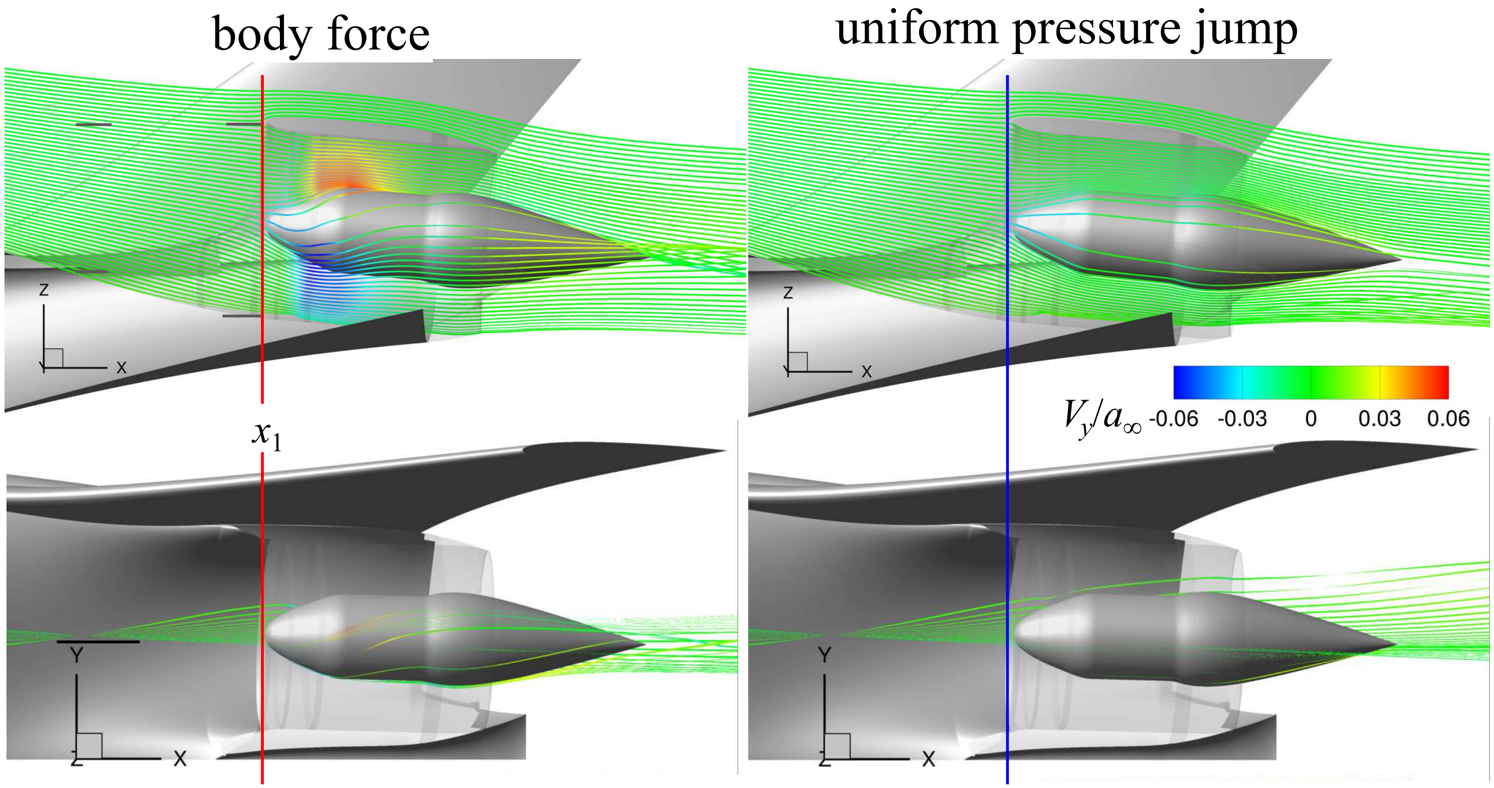


TF8000 propulsor on D8 -- Results

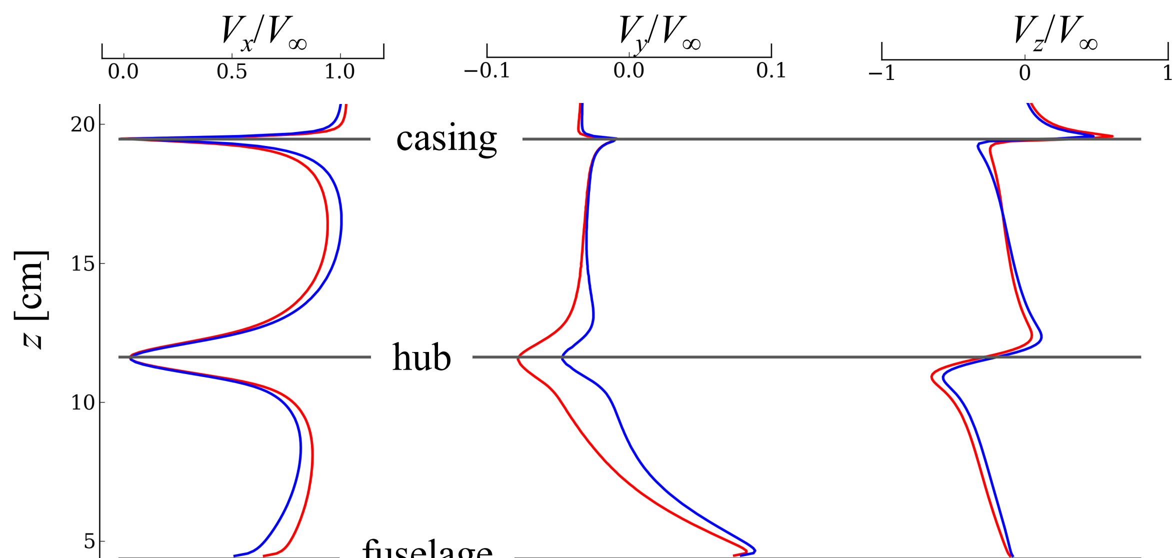




TF8000 propulsor on D8 -- Results

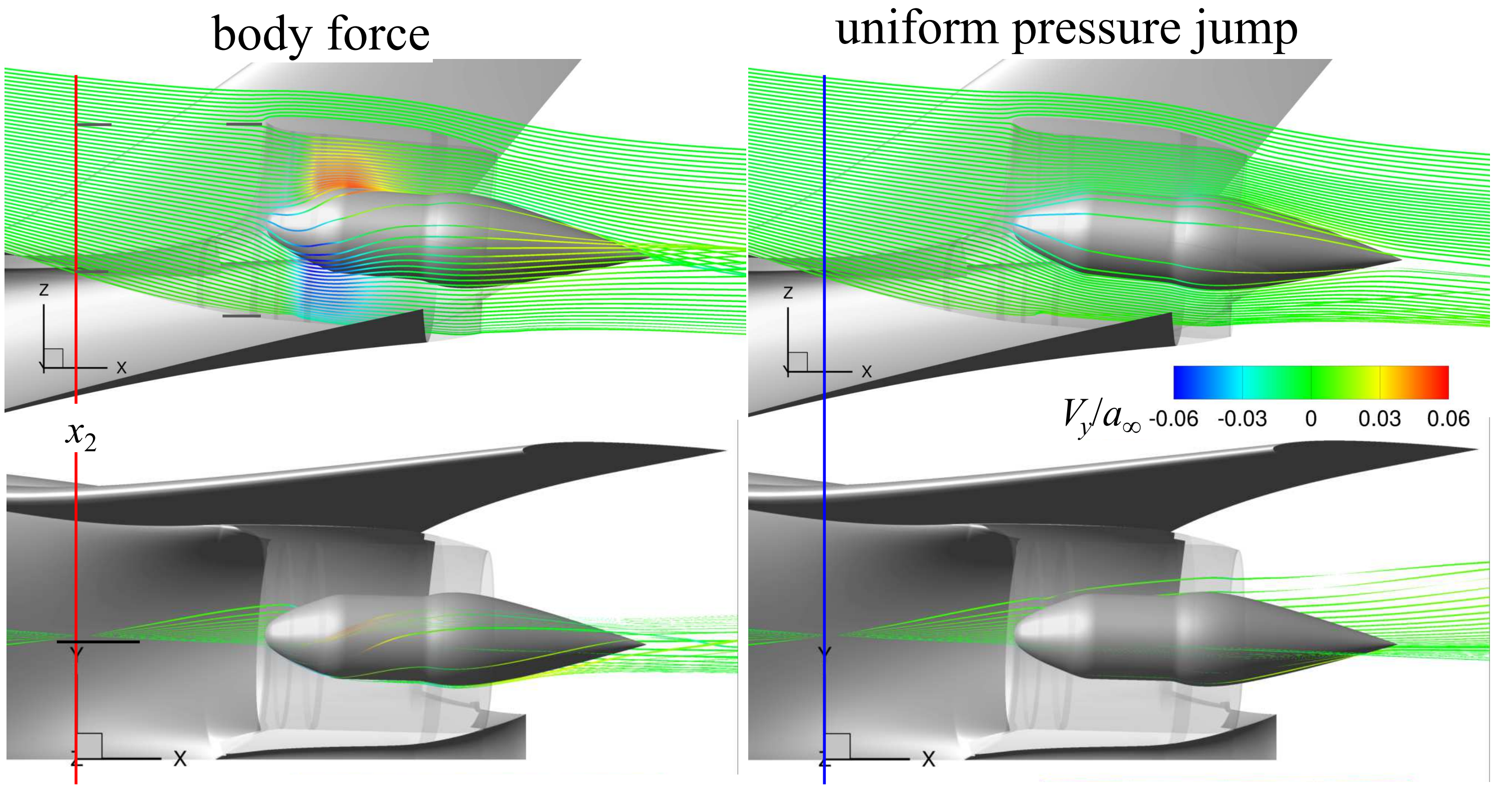


x_1=2.79 m:
(fan face)

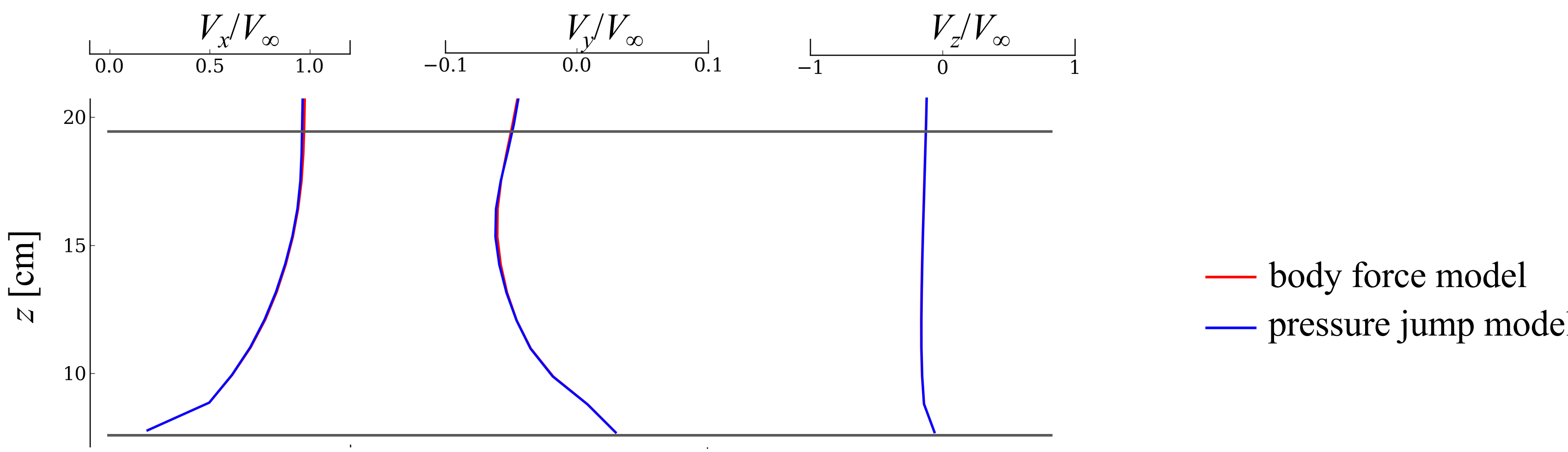


body force model
pressure jump model

TF8000 propulsor on D8 -- Results



x_2=2.67 m:
(0.88d upstream)



TF8000 propulsor, standalone

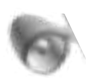
D8

D8, podded variant (non-BLI)

TF8000 propulsor, standalone

D8, podded variant (non-BLI)

TF8000 propulsor, standalone



Standalone TF8000 propulsor