



Computational Analysis of a Boundary Layer Ingesting Tailcone Thruster Configuration Using the LAVA Curvilinear Solver

Luís S. Fernandes

Aerosciences Branch, NASA Ames Research Center, Moffett Field, California

David T. Chan

Configuration Aerodynamics Branch, NASA Langley Research Center, Hampton, Virginia

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Boundary Layer Ingesting Tailcone System (BLITS)



- **Problem / Objective / Approach**

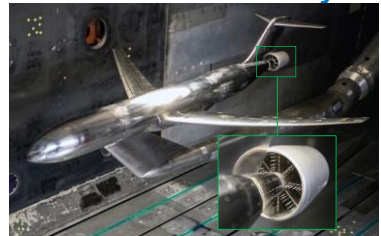
- Investigate potential benefit of Type-II BLI systems such as STARC-ABL
 - Ingestion of lower momentum flow → higher propulsive efficiency
 - Propulsion Airframe Integration (PAI) effects may overwhelm or negate benefit
- Develop integrated airframe-turbomachinery computational simulation capability
 - Enable system-level predictions for tightly-coupled PAI configurations
- Conduct ground experiments to provide comparison data for the computational tools



Single Aisle
Turboelectric Aircraft
Concept with Aft
Boundary Layer
Ingestion
(STARC-ABL)

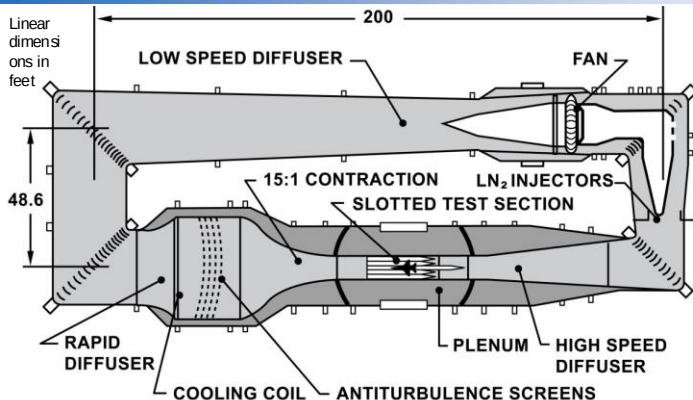
- **CRM-TCT high Reynolds number experiment in National Transonic Facility**

- Characterize and measure:
 - [Tailcone nacelle inlet pressure and flow angle profile](#)
 - Aftbody boundary layer heights and surface pressures
 - Overall airframe cruise performance
- Evaluate sensitivity of measured quantities to:
 - Mach number, Reynolds number, angle of attack
 - Mass flow rates through the nacelle
- Provide comparison dataset for computational tools



Common Research Model with Tail Cone
Thrustor

National Transonic Facility (NTF)



Photos :
NASA

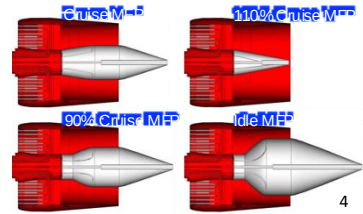
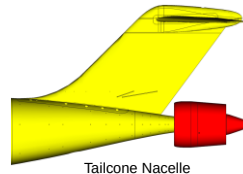
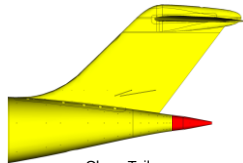
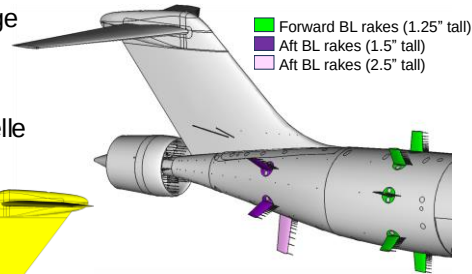
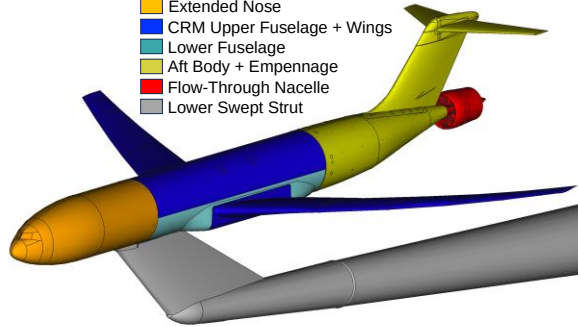
- Located at the NASA Langley Research Center
- Pressurized, cryogenic wind tunnel
- Operate in dry air or gaseous nitrogen
- Achieve very high Reynolds numbers
 - Flight or near-flight for many vehicles

Test Gas	Air	Nitrogen
Mach Number	0.1 – 1.10	0.1 – 1.20
Max Unit Reynolds Number	20x10 ⁶ / ft	145x10 ⁶ / ft
Total Pressure	1 – 8.3 atm	1 – 8.3 atm
Total Temperature	80°F to 130°F	-250°F to 80°F

- **Common Research Model with Tail Cone Thruster (CRM-TCT)**

- 2.7%-scale CRM model with new aftbody and empennage
- Underchin blade support system
- Clean tailcone or rotating tailcone nacelles (2)
- 4 mass flow plugs (MFP) to vary mass flow through nacelle
- Miniature boundary layer (BL) rakes on aftbody
- Surface static pressure orifices (>200)

- Extended Nose
- CRM Upper Fuselage + Wings
- Lower Fuselage
- Aft Body + Empennage
- Flow-Through Nacelle
- Lower Swept Strut



Flow-Through Nacelles

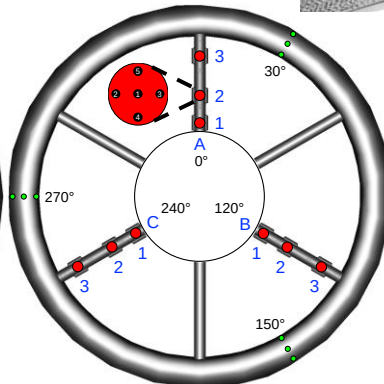
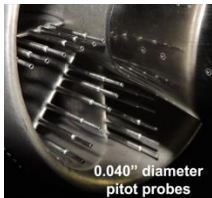
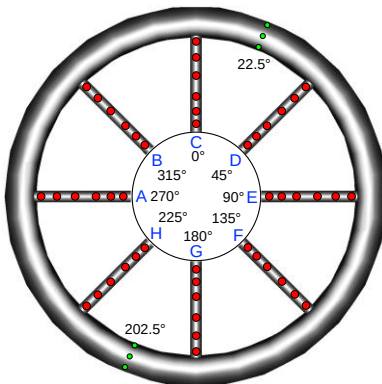


- **ARP1420 nacelle / 5-hole probe nacelle**

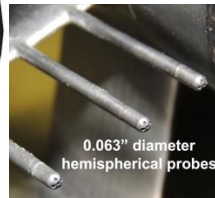
- 3.3" nacelle inlet diameter
- Measure total pressure and flow angle profile at nacelle highlight
- Controlled remotely with rotation range between -60° and 60°
- Operated at tunnel temperatures between -120°F and 120°F



ARP1420
Nacelle



5-hole probe
Nacelle



Experiment Setup

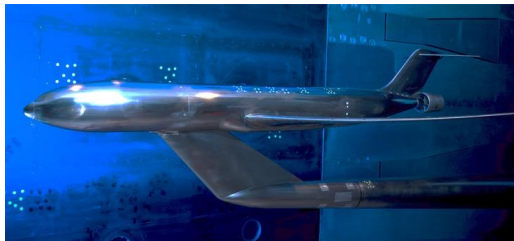


- **Test Conditions**

- $M_\infty = 0.75, 0.80, 0.85$
- $Re_{mac} = 5M, 10M, 15M$
- $T_0 = 120^\circ\text{F (Air)}, -50^\circ\text{F (N}_2\text{)}, -120^\circ\text{F (N}_2\text{)}$
- $\alpha = -3^\circ \text{ to } 3^\circ, \beta = 0^\circ$

- **Test Matrix**

- Model configurations
 - Clean tailcone, ARP1420 nacelle, or 5-hole probe nacelle
 - 4 mass flow plugs
 - Horizontal stabilizer on or off
 - Forward or aft BL rakes
- Data runs
 - Model angle-of-attack traverses at fixed nacelle roll angle
 - [Nacelle roll angle rotation at fixed model angle of attack](#)



CRM-TCT model in NTF (March – June 2023)

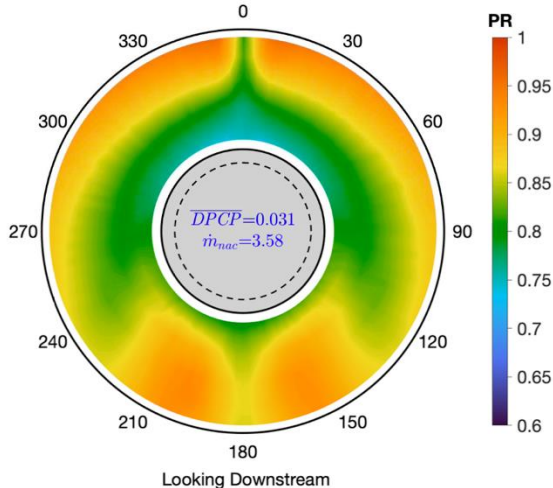
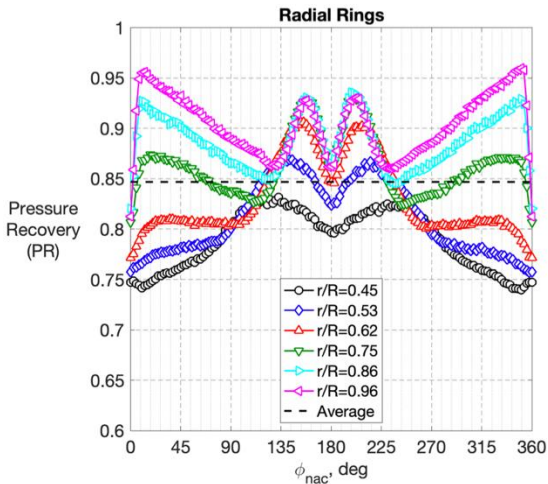
Inlet Flow Distortion (Total Pressure Recovery)



- Pressure recovery contour

ARP1420 nacelle with 110% cruise MFP ($M_\infty = 0.8$, $Re_{mac} = 10M$, $\alpha =$

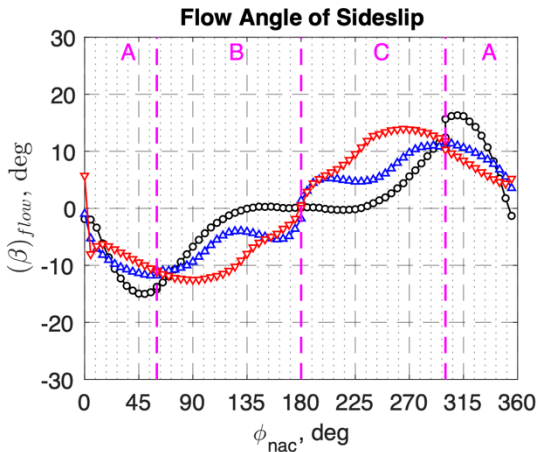
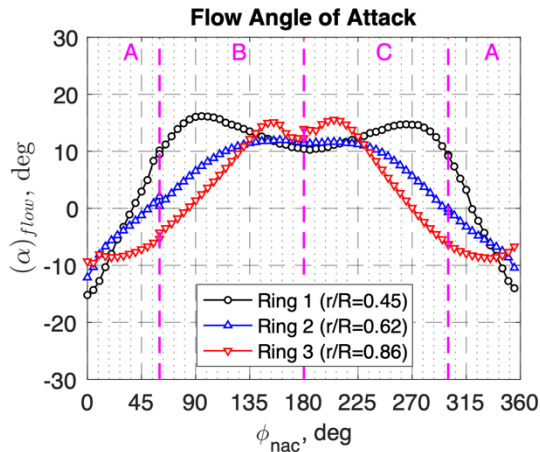
$$PR = \frac{(P_T)_{probe}}{P_0}$$



Inlet Flow Distortion (Flow Angle)

- Data acquired with nacelle rotation in 5° increments over 120° range
 - Data mostly smooth and symmetric, but some discontinuities at overlap points

5-hole probe nacelle with cruise MFP ($M_\infty = 0.8$, $Re_{mac} = 5M$, $\alpha = 2^\circ$)



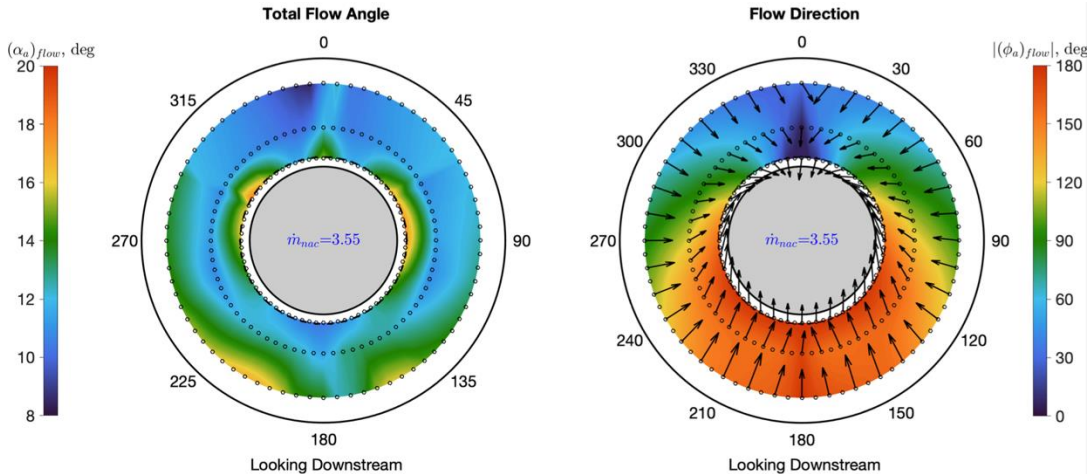
Inlet Flow Distortion (Flow Angle)



- Flow angle and flow direction contours

- Similar features to pressure profile, but also shows rollup around and onto top of hub

5-hole probe nacelle with cruise MFP ($M_\infty = 0.8$, $Re_{mac} = 5M$, $\alpha = 2^\circ$)



Characterization of TCT inlet pressure and swirl distortion at relevant cruise Mach and Reynolds numbers providing comparison data for PAI CFD capability

- **CRM-TCT test results documented in AIAA paper**
 - D. Chan, et al., “*Experimental Investigation of a Boundary Layer Ingesting Tailcone Thruster Configuration at the National Transonic Facility*”, [AIAA-2024-3515](#)
- **Test funded by NASA AATT Project**
 - BLITS team comprised of researchers from LaRC, GRC, ARC
 - Thanks to NTF facility team!



The goals of this work are to

- Develop best-practices to simulate BLI flows within the LAVA Curvilinear solver framework using steady RANS
 - ▶ Grid refinement study
 - ▶ Turbulence model sensitivity study
- Assess the ability of steady RANS to predict the aftbody flow ingested by the TCT
 - ▶ Under a variety of conditions
 - ▶ Using the experimental data collected for validation

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Modeling the problem

LAVA Launch, Ascent, and Vehicle Aerodynamics

- Several grid paradigms: **curvilinear** **overset**, unstructured, cartesian
- Conservative finite-difference formulation of the RANS equations

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- Turbulence closure: SA w/ RC and QCR corrections (SA-RC-QCR2000)

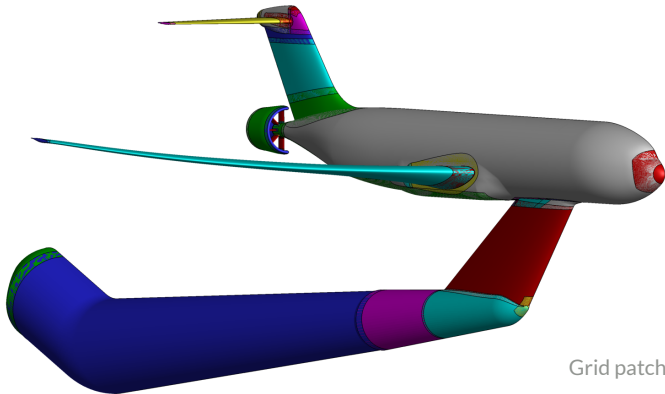
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- Conservative finite-difference formulation of the RANS equations
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- Convective fluxes
 - ▶ Modified Roe scheme w/ third-order left/right state reconstruction
 - ▶ Koren limiter

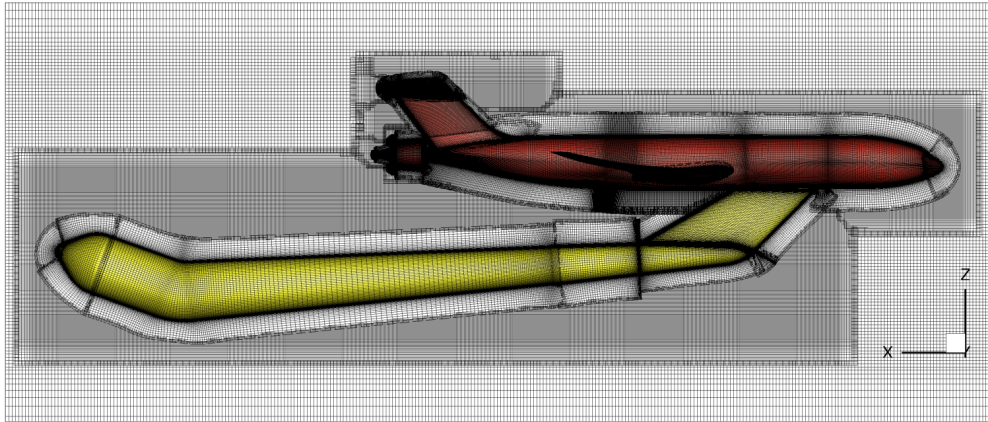
Computational setup

- Half-span model with symmetry BC at $Y = 0[\text{m}]$
- Viscous wall BC applied at model surfaces



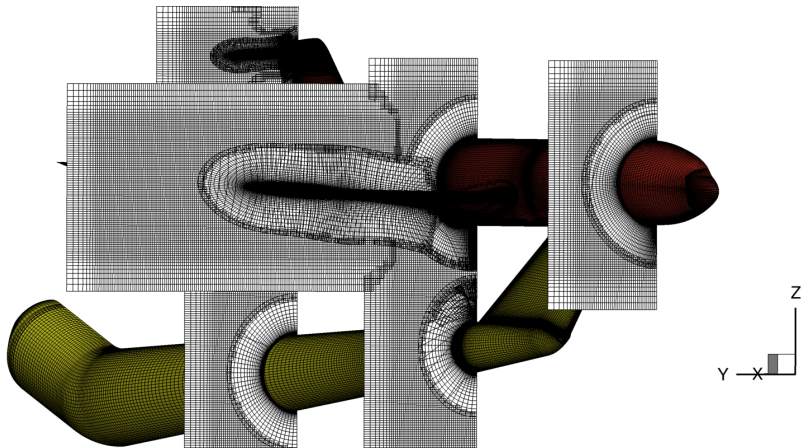
Grid patches overview

Overview of the grid system



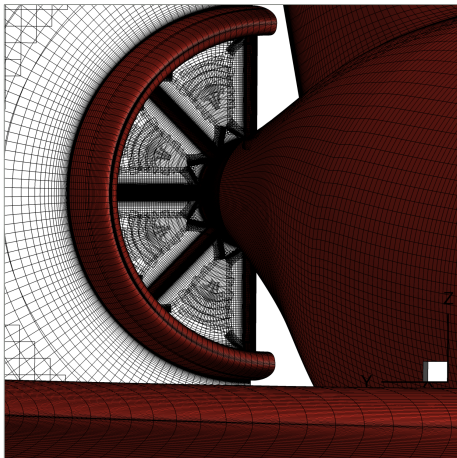
Grid slice side view. Configuration: *Flow-through w/ Cruise MFP (w/ sting)*

Overview of the grid system

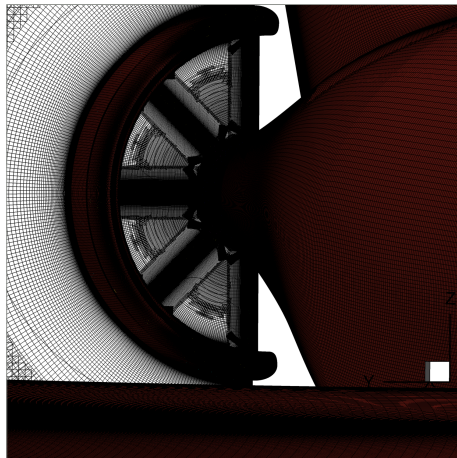


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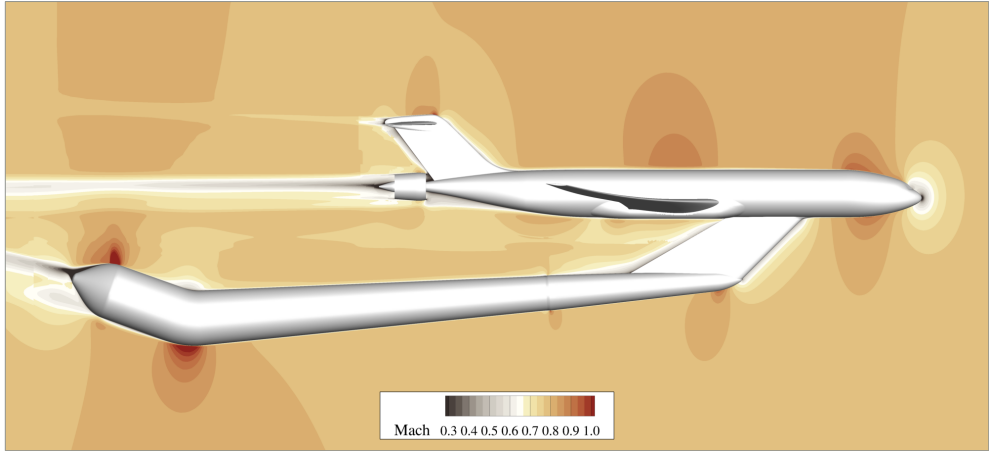


Coarse grid



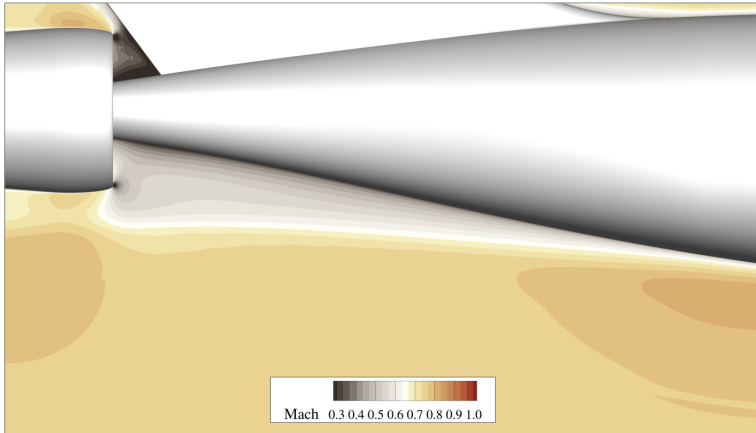
Extra fine grid

Flow-field overview



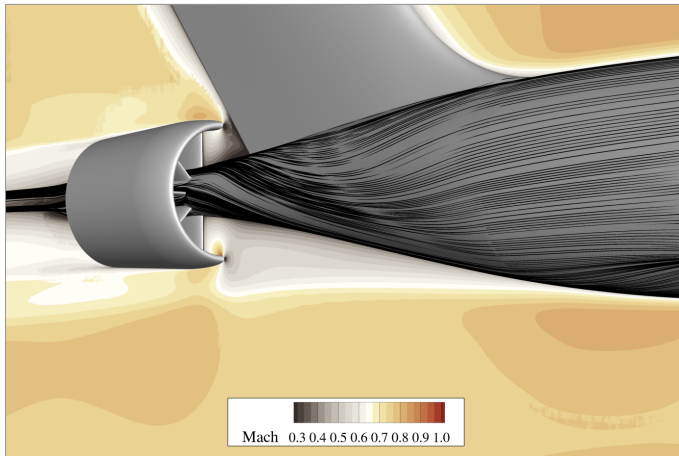
Flow-field side-view showing Mach number contours.

Flow-field overview



Flow-field side-view showing Mach number contours.

Flow-field overview



Flow-field side-view showing Mach number contours.

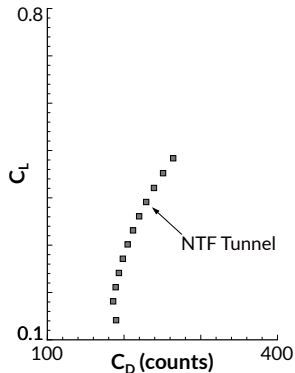
Grid refinement study results

	Coarse	Medium	Fine	Extra Fine
# Grid Points (millions)	49.6	116.9	276.4	685.3

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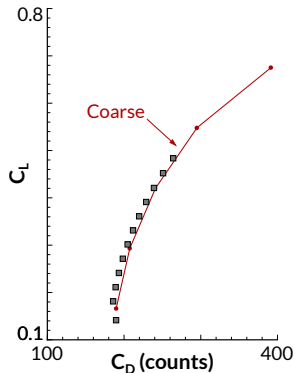
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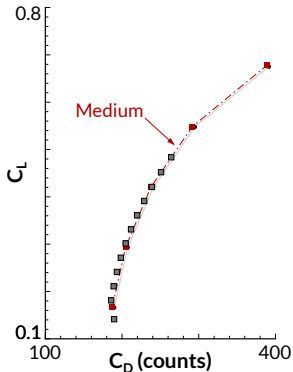
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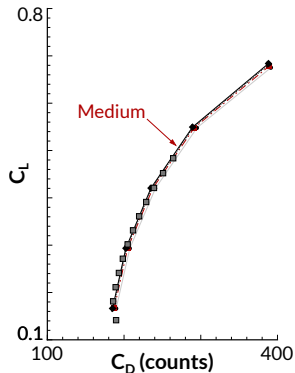
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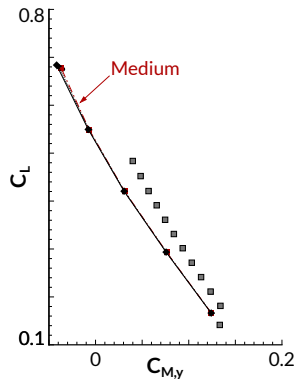
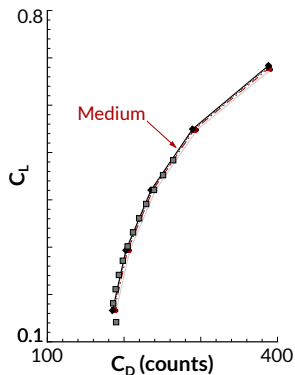
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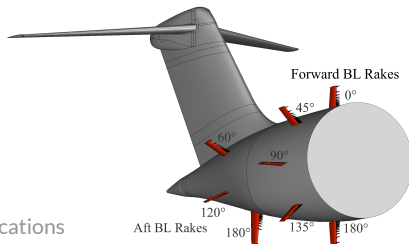
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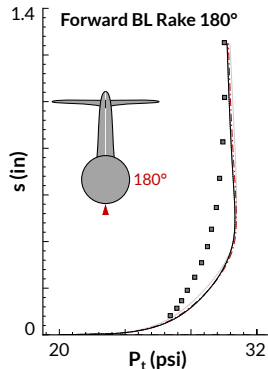
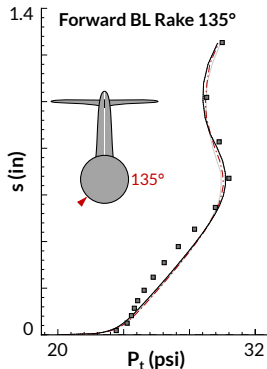
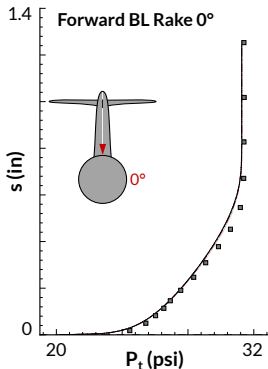


Grid refinement study results

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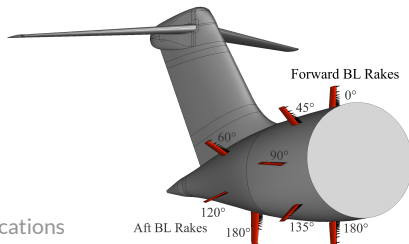


Boundary layer rakes locations

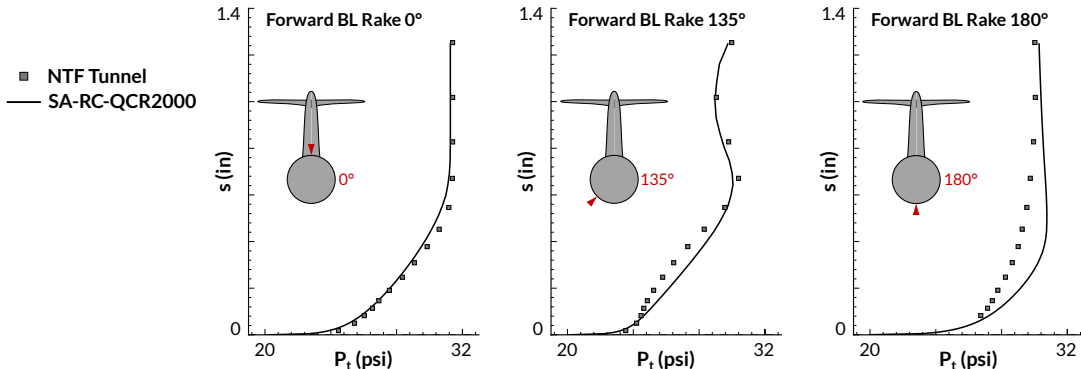


Turbulence model sensitivity

$Re = 5\text{-million}$, $Ma = 0.80$, $\alpha = 2^\circ$

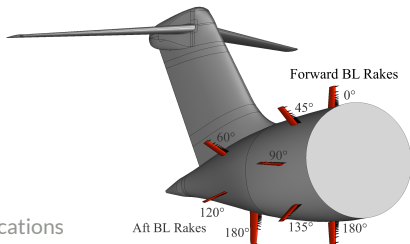


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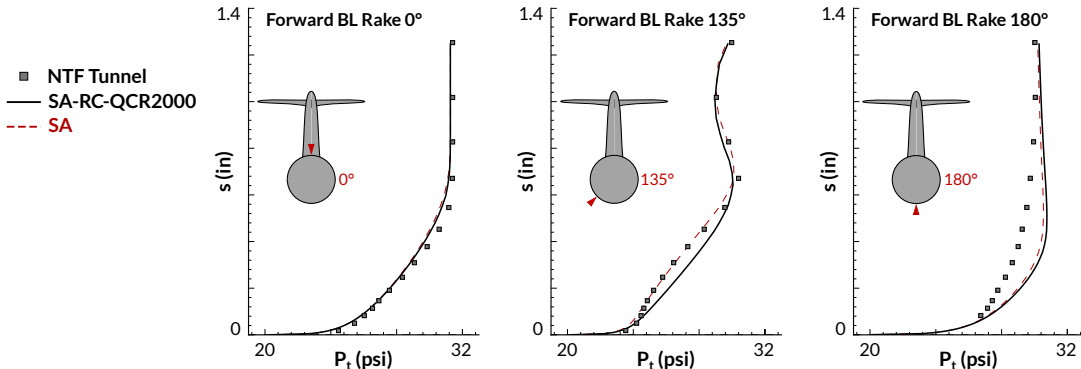


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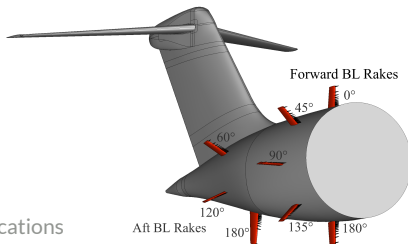


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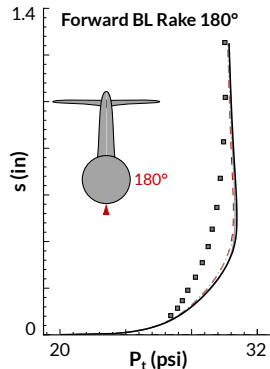
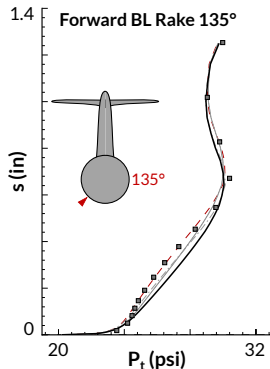
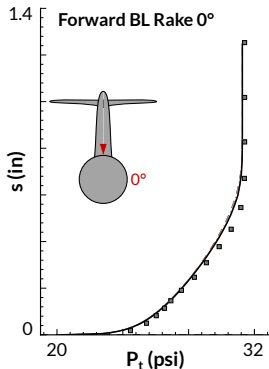
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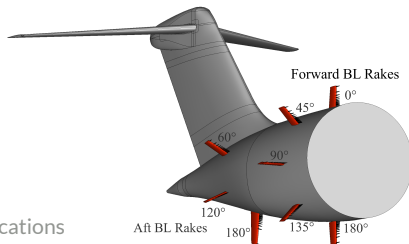
Boundary layer rakes locations

- NTF Tunnel
- SA-RC-QCR2000
- - - SA
- SA-RC
- · - · SA-QCR2000



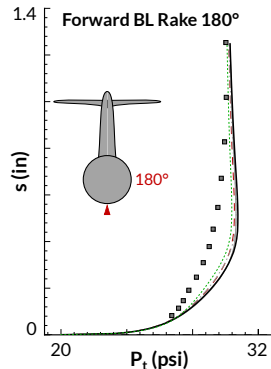
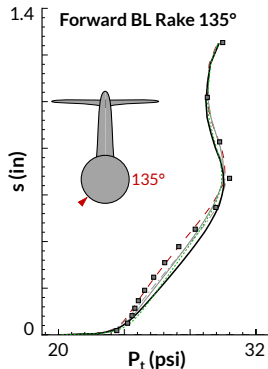
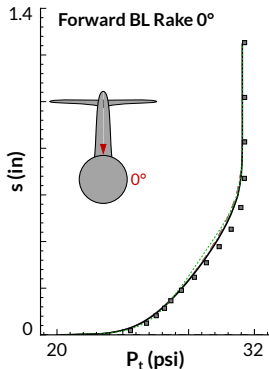
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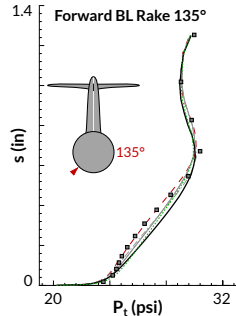
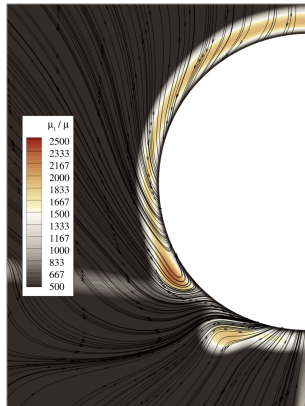
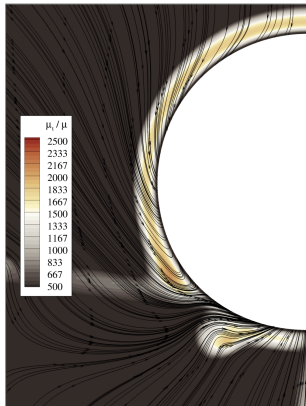
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- . . . k-w BSL



Turbulence model sensitivity

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SA-RC-QCR2000

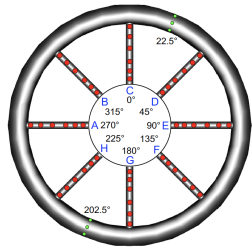


SA

Turbulence model sensitivity

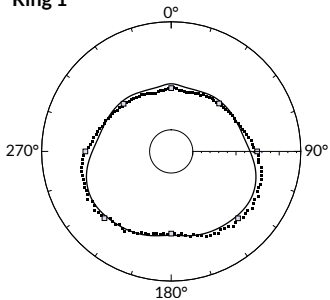
$Re = 10\text{-million}$, $Ma = 0.80$, $\alpha = 2^\circ$

ARP1420 probe locations
(Credit: Chan, D., 2024)

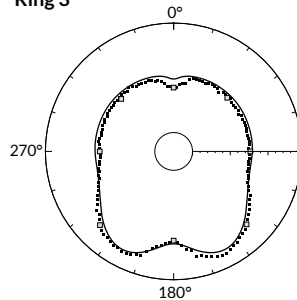


■ NTF Tunnel
— SA-RC-QCR2000

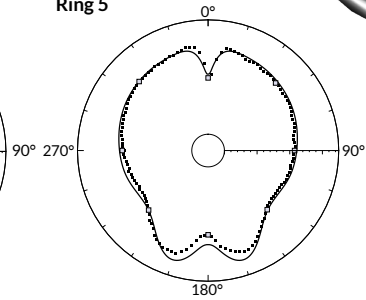
Ring 1



Ring 3



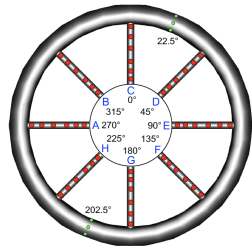
Ring 5



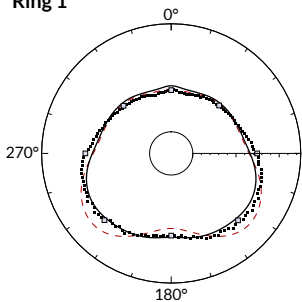
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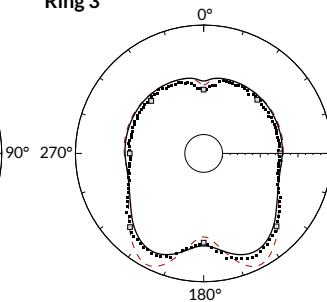
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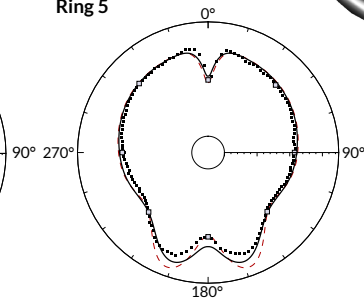
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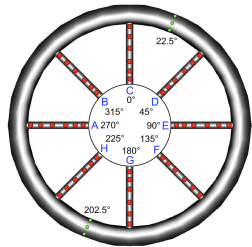


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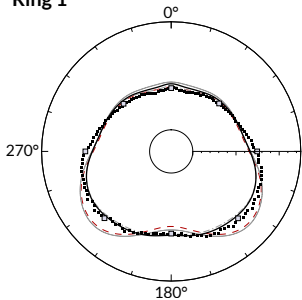
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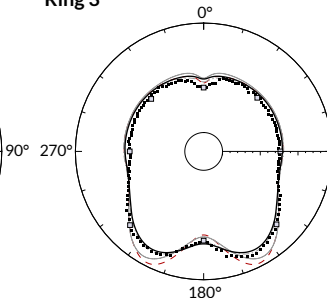
ARP1420 probe locations
(Credit: Chan, D., 2024)



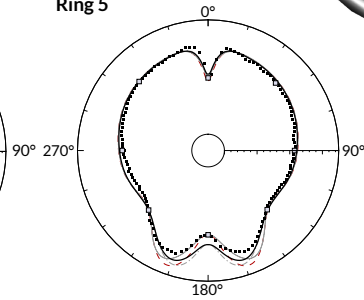
Ring 1



Ring 3



Ring 5

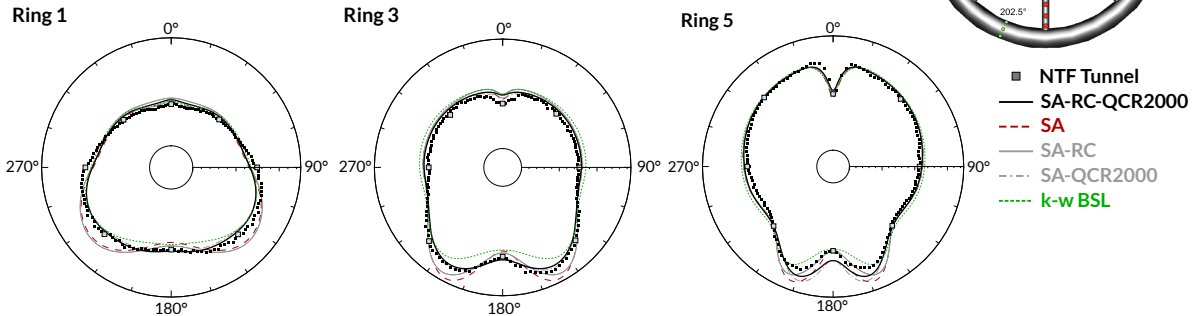
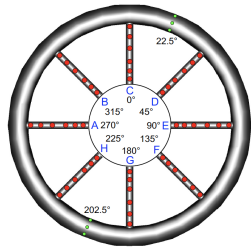


- NTF Tunnel
- SA-RC-QCR2000
- - - SA
- SA-RC
- - - SA-QCR2000

Turbulence model sensitivity

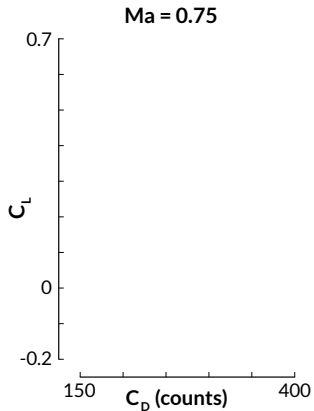
$Re = 10\text{-million}$, $Ma = 0.80$, $\alpha = 2^\circ$

ARP1420 probe locations
(Credit: Chan, D., 2024)



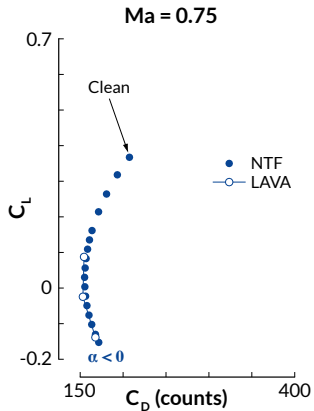
Results - Load coefficients

Re = 5-million



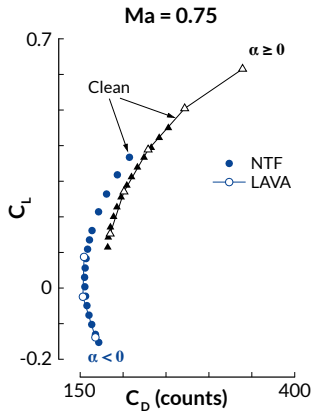
Results - Load coefficients

Re = 5-million



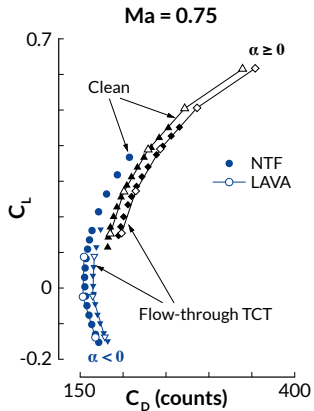
Results - Load coefficients

Re = 5-million



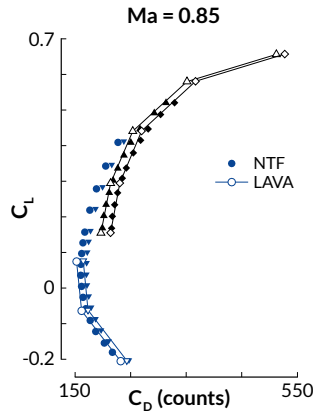
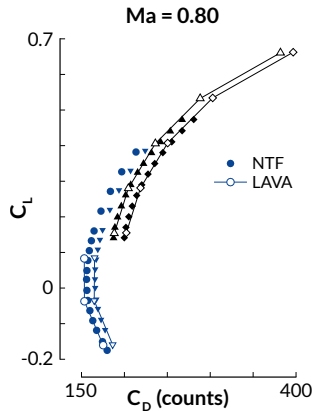
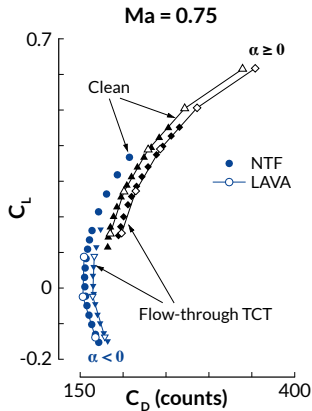
Results - Load coefficients

Re = 5-million



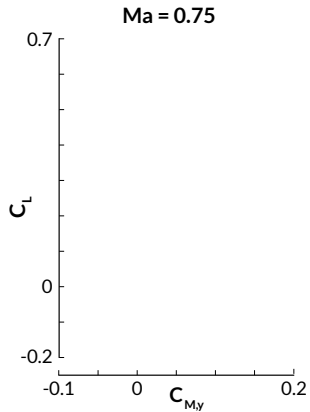
Results - Load coefficients

Re = 5-million



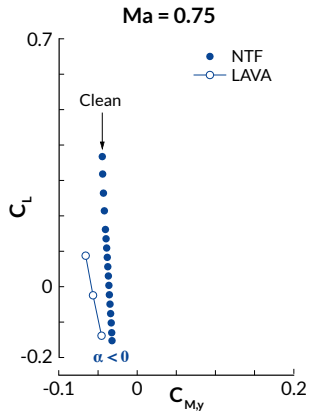
Results - Load coefficients

Re = 5-million



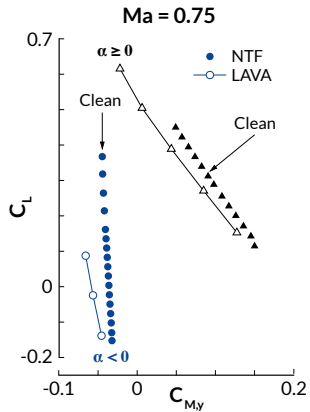
Results - Load coefficients

Re = 5-million



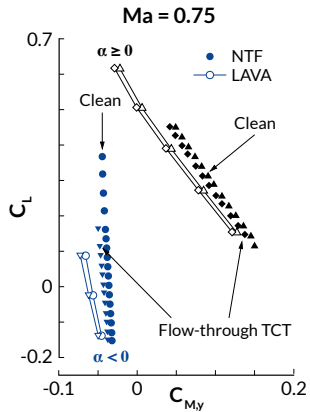
Results - Load coefficients

Re = 5-million



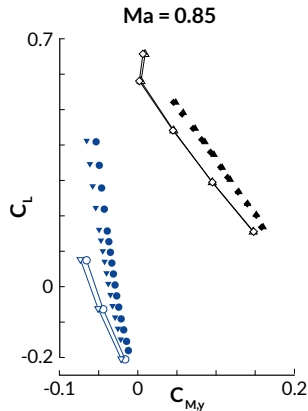
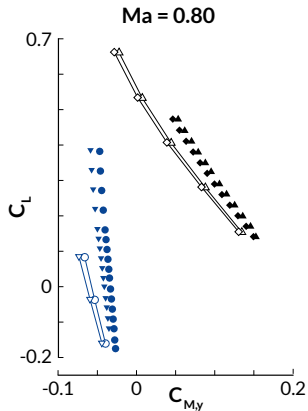
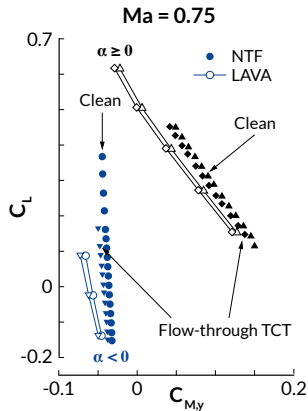
Results - Load coefficients

Re = 5-million



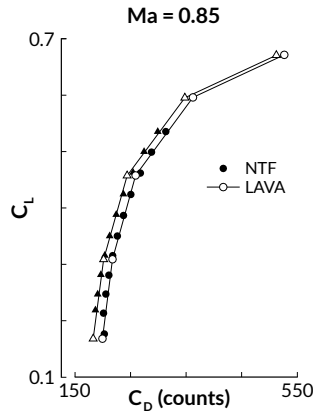
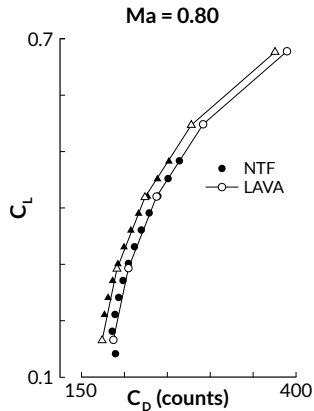
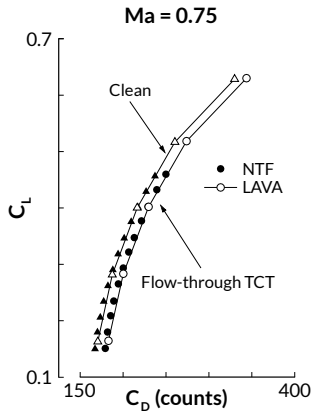
Results - Load coefficients

Re = 5-million



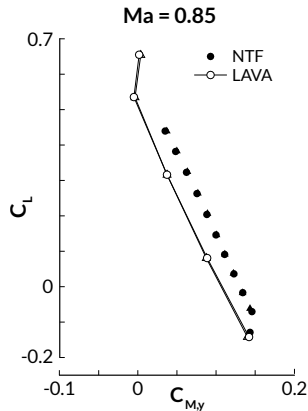
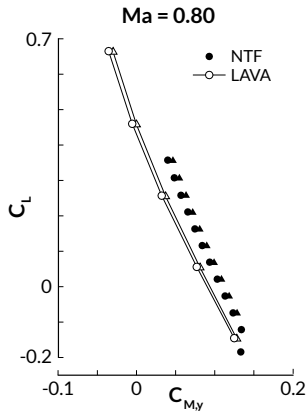
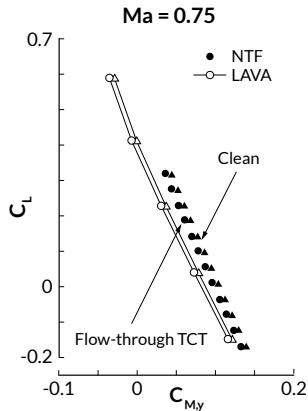
Results - Load coefficients

Re = 10-million



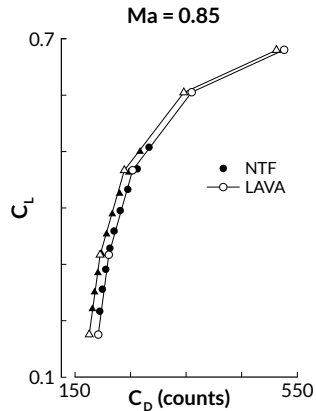
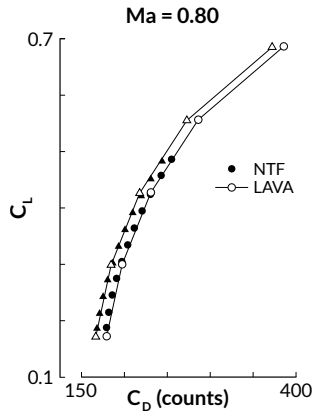
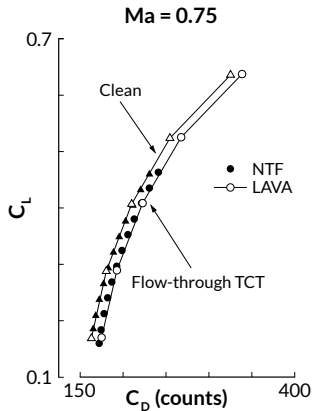
Results - Load coefficients

Re = 10-million



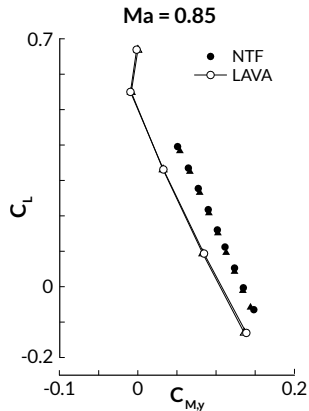
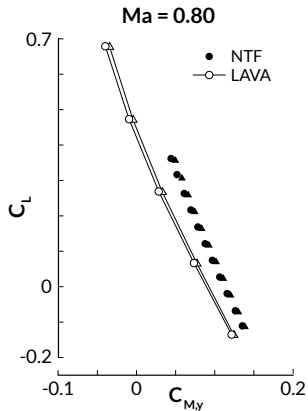
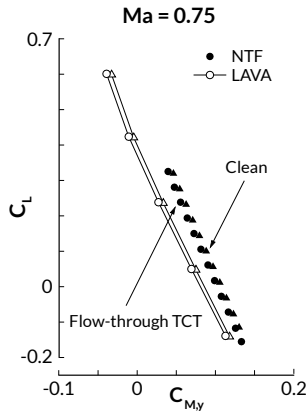
Results - Load coefficients

Re = 15-million



Results - Load coefficients

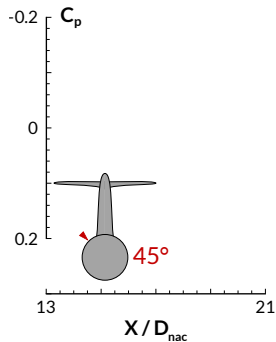
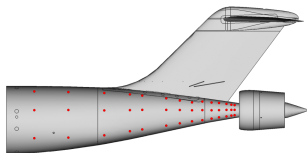
Re = 15-million



Results - Aftbody surface pressures

$Re = 5\text{-million}$, $Ma = 0.80$, $\alpha = 2^\circ$

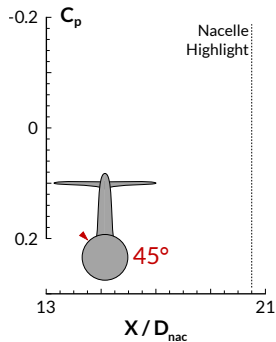
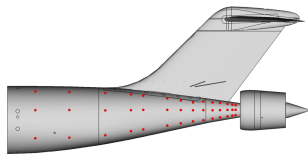
5-hole probe locations
(Credit: Chan, D., 2024)



Results - Aftbody surface pressures

$Re = 5\text{-million}$, $Ma = 0.80$, $\alpha = 2^\circ$

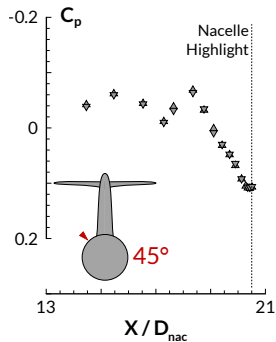
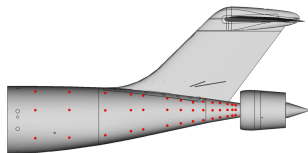
5-hole probe locations
(Credit: Chan, D., 2024)



Results - Aftbody surface pressures

$Re = 5\text{-million}$, $Ma = 0.80$, $\alpha = 2^\circ$

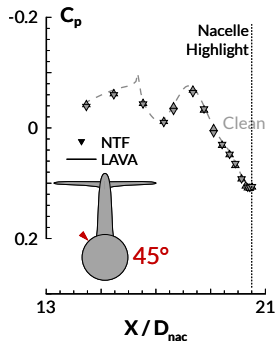
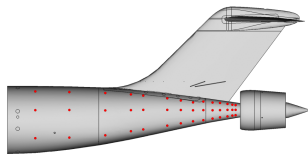
5-hole probe locations
(Credit: Chan, D., 2024)



Results - Aftbody surface pressures

$Re = 5\text{-million}$, $Ma = 0.80$, $\alpha = 2^\circ$

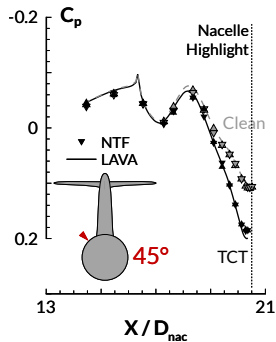
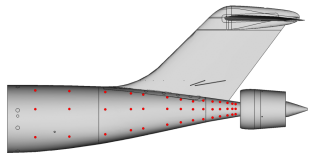
5-hole probe locations
(Credit: Chan, D., 2024)



Results - Aftbody surface pressures

$Re = 5\text{-million}$, $Ma = 0.80$, $\alpha = 2^\circ$

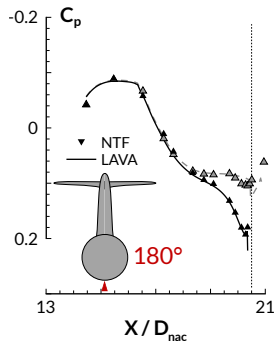
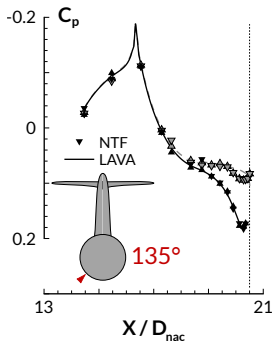
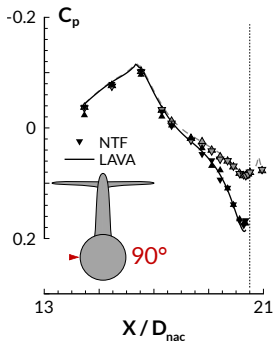
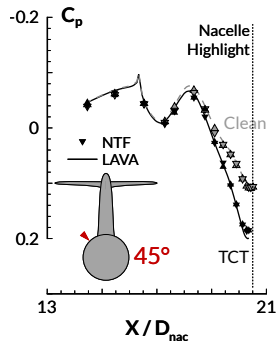
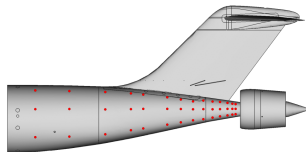
5-hole probe locations
(Credit: Chan, D., 2024)



Results - Aftbody surface pressures

$Re = 5\text{-million}$, $Ma = 0.80$, $\alpha = 2^\circ$

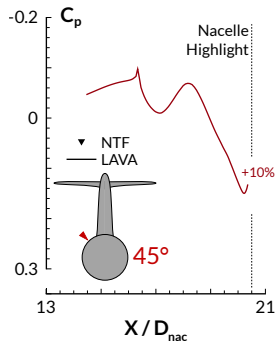
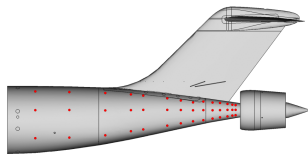
5-hole probe locations
(Credit: Chan, D., 2024)



Results - Aftbody surface pressures

$Re = 5\text{-million}$, $Ma = 0.80$, $\alpha = 2^\circ$

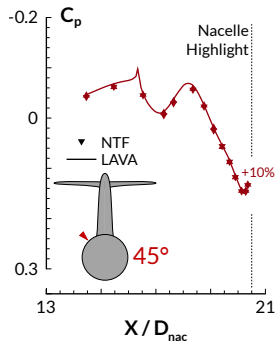
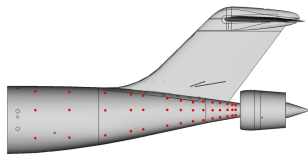
5-hole probe locations
(Credit: Chan, D., 2024)



Results - Aftbody surface pressures

$Re = 5\text{-million}$, $Ma = 0.80$, $\alpha = 2^\circ$

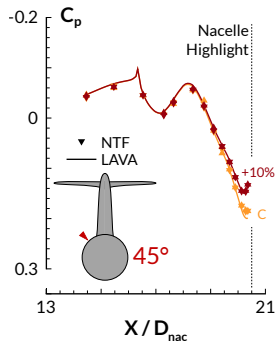
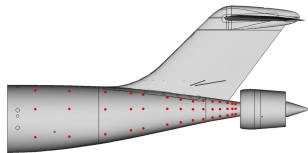
5-hole probe locations
(Credit: Chan, D., 2024)



Results - Aftbody surface pressures

$Re = 5\text{-million}$, $Ma = 0.80$, $\alpha = 2^\circ$

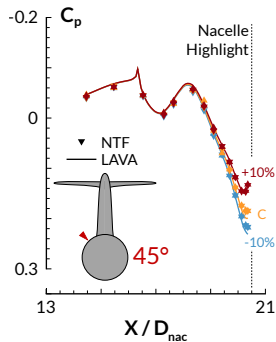
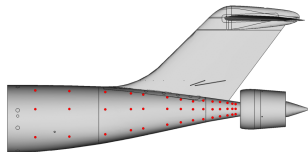
5-hole probe locations
(Credit: Chan, D., 2024)



Results - Aftbody surface pressures

$Re = 5\text{-million}$, $Ma = 0.80$, $\alpha = 2^\circ$

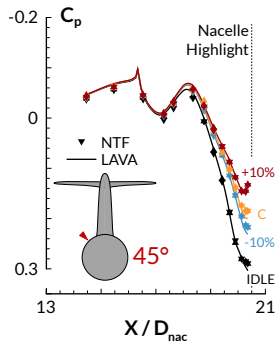
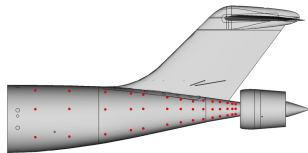
5-hole probe locations
(Credit: Chan, D., 2024)



Results - Aftbody surface pressures

$Re = 5\text{-million}$, $Ma = 0.80$, $\alpha = 2^\circ$

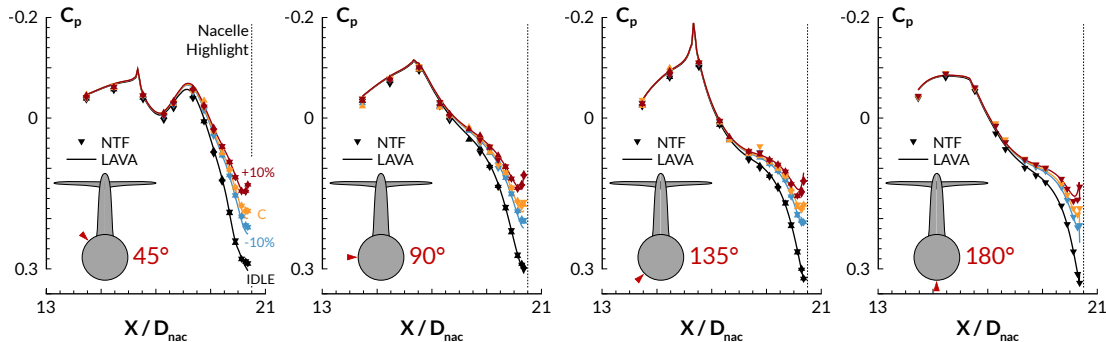
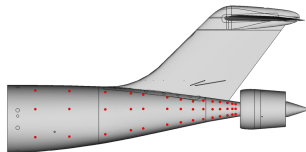
5-hole probe locations
(Credit: Chan, D., 2024)



Results - Aftbody surface pressures

$Re = 5\text{-million}$, $Ma = 0.80$, $\alpha = 2^\circ$

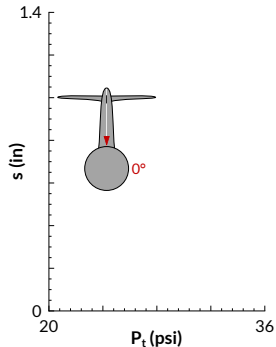
5-hole probe locations
(Credit: Chan, D., 2024)



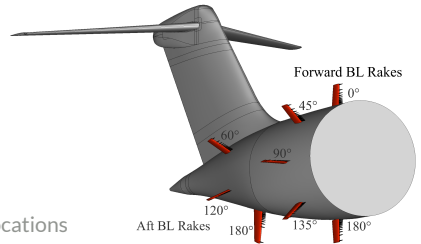
Results - Boundary layer rakes

$Re = 5\text{-million}$, $Ma = 0.85$

Front rakes



Boundary layer rakes locations

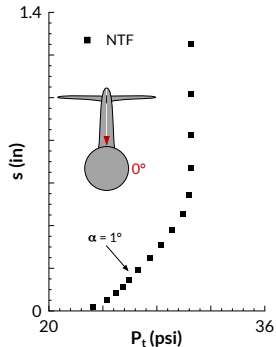
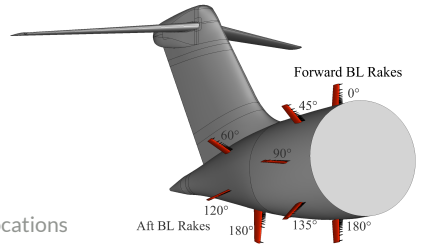


Results - Boundary layer rakes

$Re = 5\text{-million}$, $Ma = 0.85$, $\alpha = 1^\circ$

Front rakes

Boundary layer rakes locations

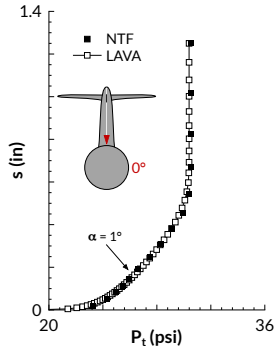
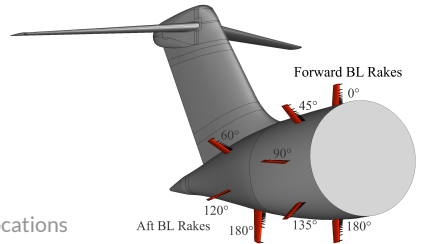


Results - Boundary layer rakes

$Re = 5\text{-million}$, $Ma = 0.85$, $\alpha = 1^\circ$

Front rakes

Boundary layer rakes locations

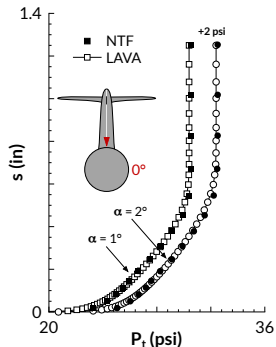
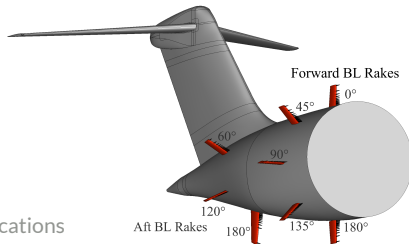


Results - Boundary layer rakes

$Re = 5\text{-million}$, $Ma = 0.85$, $\alpha = 1^\circ, 2^\circ$

Front rakes

Boundary layer rakes locations

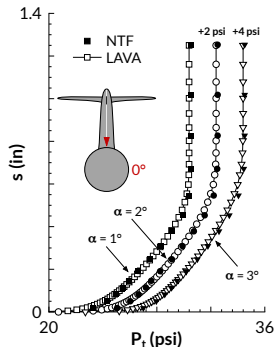
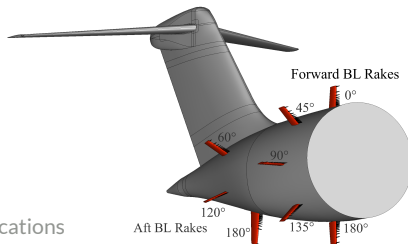


Results - Boundary layer rakes

$Re = 5\text{-million}$, $Ma = 0.85$, $\alpha = 1^\circ, 2^\circ, 3^\circ$

Front rakes

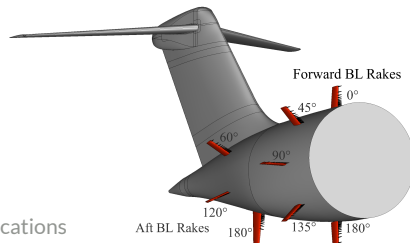
Boundary layer rakes locations



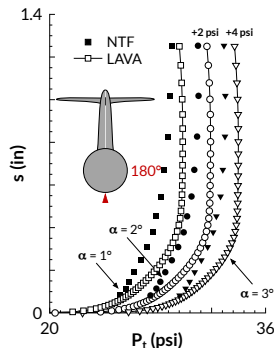
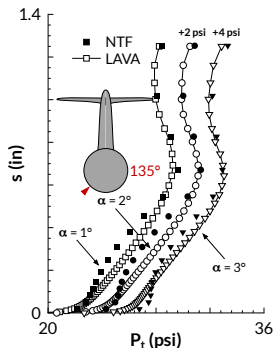
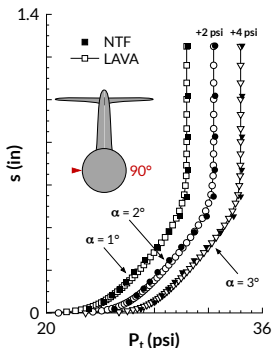
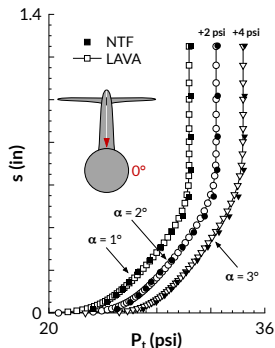
Results - Boundary layer rakes

$Re = 5\text{-million}$, $Ma = 0.85$, $\alpha = 1^\circ, 2^\circ, 3^\circ$

Front rakes



Boundary layer rakes locations

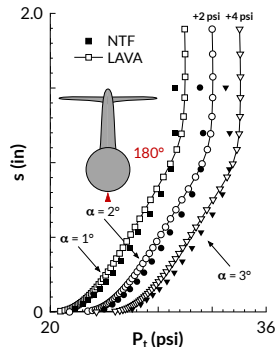
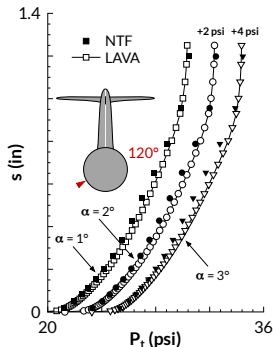
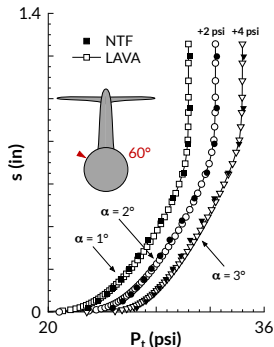
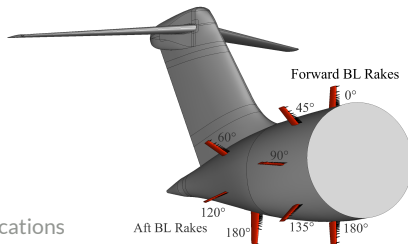


Results - Boundary layer rakes

$Re = 5\text{-million}$, $Ma = 0.85$, $\alpha = 1^\circ, 2^\circ, 3^\circ$

Aft rakes

Boundary layer rakes locations

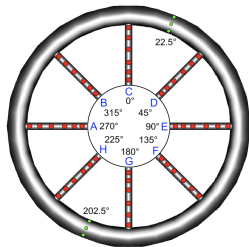


Results - Nacelle highlight total pressure distortion

$Re = 5\text{-million}, Ma = 0.75, \alpha = 2^\circ$

Pressure Recovery = $\frac{P_t}{P_{t,\infty}}$

ARP1420 probe locations
(Credit: Chan, D., 2024)

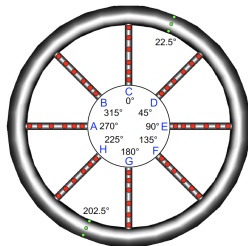
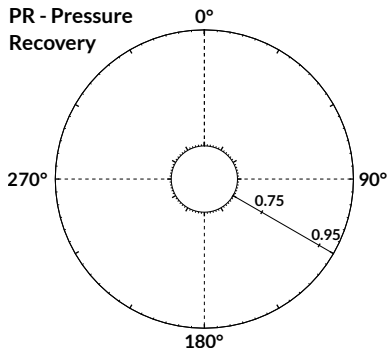


Results - Nacelle highlight total pressure distortion

$Re = 5\text{-million}, Ma = 0.75, \alpha = 2^\circ$

$$\text{Pressure Recovery} = \frac{P_t}{P_{t,\infty}}$$

ARP1420 probe locations
(Credit: Chan, D., 2024)

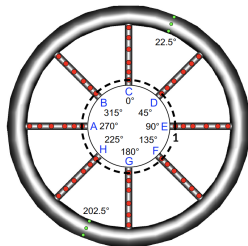
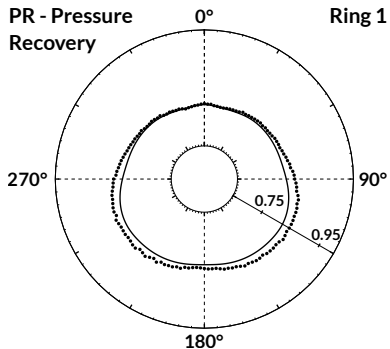


Results - Nacelle highlight total pressure distortion

$Re = 5\text{-million}, Ma = 0.75, \alpha = 2^\circ$

$$\text{Pressure Recovery} = \frac{P_t}{P_{t,\infty}}$$

ARP1420 probe locations
(Credit: Chan, D., 2024)

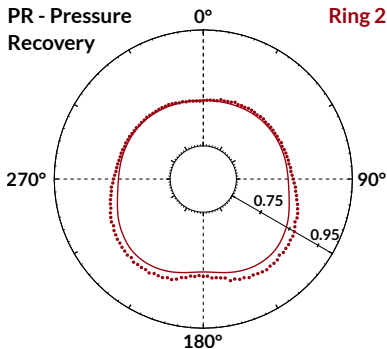
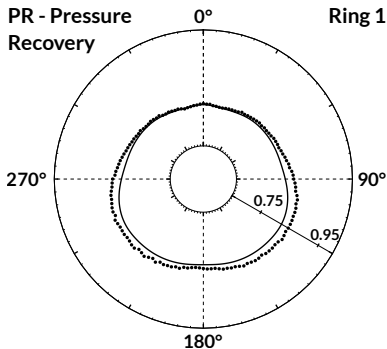
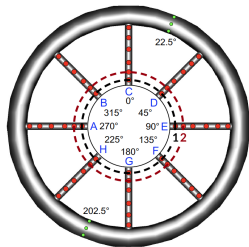


Results - Nacelle highlight total pressure distortion

$Re = 5\text{-million}, Ma = 0.75, \alpha = 2^\circ$

$$\text{Pressure Recovery} = \frac{P_t}{P_{t,\infty}}$$

ARP1420 probe locations
(Credit: Chan, D., 2024)

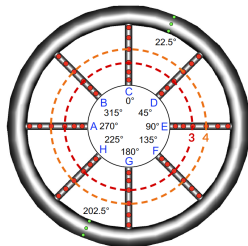


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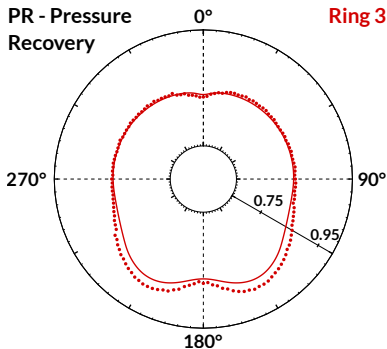
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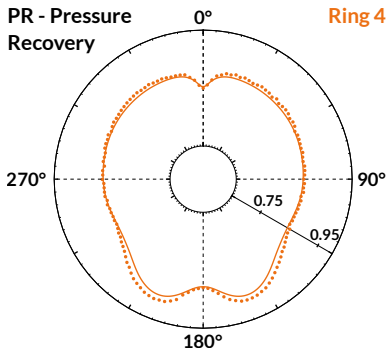
ARP1420 probe locations
(Credit: Chan, D., 2024)



PR - Pressure
Recovery



PR - Pressure
Recovery

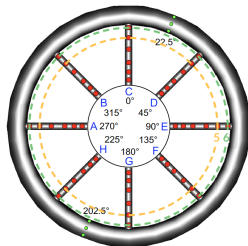


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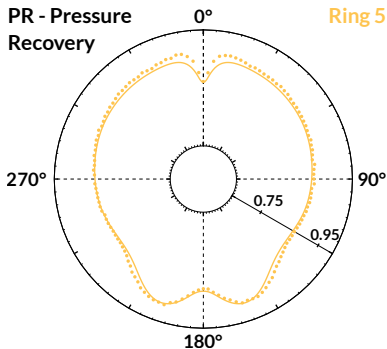
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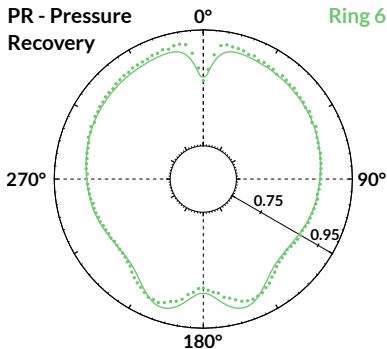
ARP1420 probe locations
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PR - Pressure
Recovery



PR - Pressure
Recovery



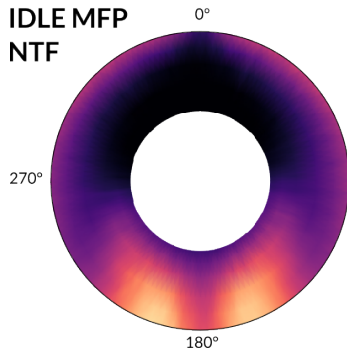
Results - Nacelle highlight total pressure distortion

$Re = 5\text{-million}$, $Ma = 0.85$, $\alpha = 2^\circ$

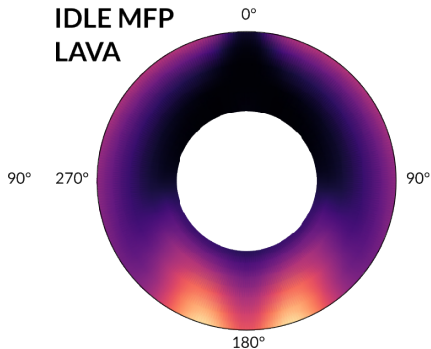
Mass flow plug (MFP) effects

ARP1420 probe locations
(Credit: Chan, D., 2024)

IDLE MFP
NTF



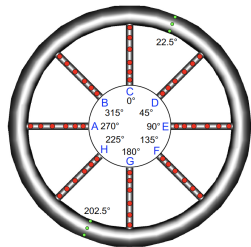
IDLE MFP
LAVA



PR

0.950

0.725



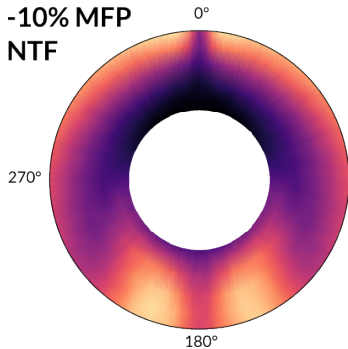
Results - Nacelle highlight total pressure distortion

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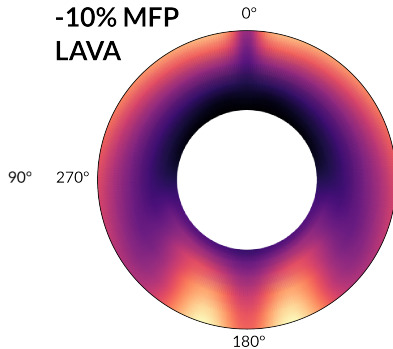
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-10% MFP
NTF



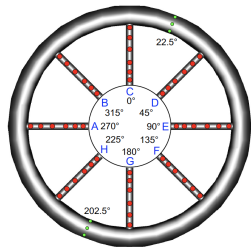
-10% MFP
LAVA



PR

0.950

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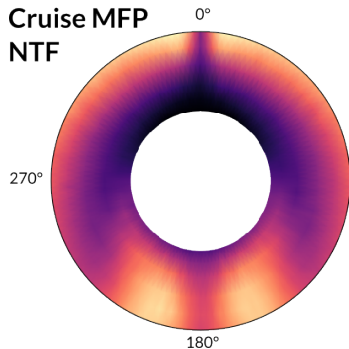
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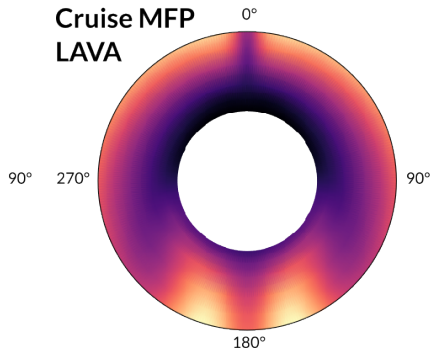
Mass flow plug (MFP) effects

ARP1420 probe locations
(Credit: Chan, D., 2024)

Cruise MFP
NTF



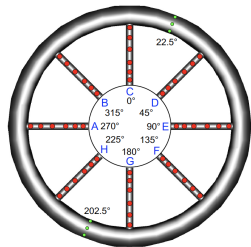
Cruise MFP
LAVA



PR

0.950

0.725



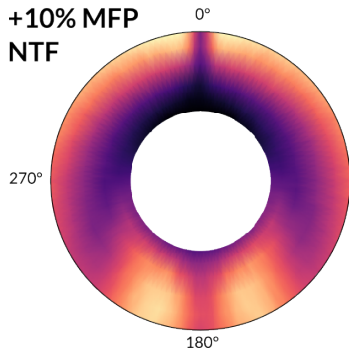
Results - Nacelle highlight total pressure distortion

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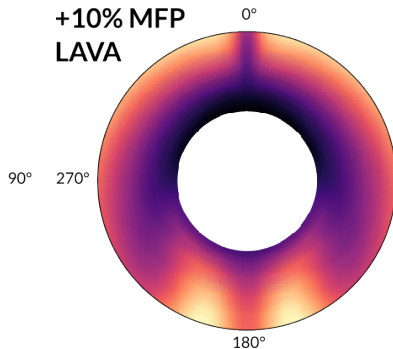
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ARP1420 probe locations
(Credit: Chan, D., 2024)

+10% MFP
NTF



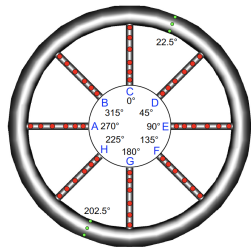
+10% MFP
LAVA



PR

0.950

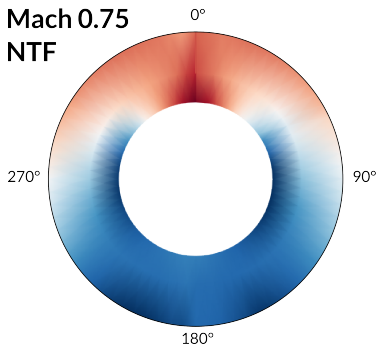
0.725



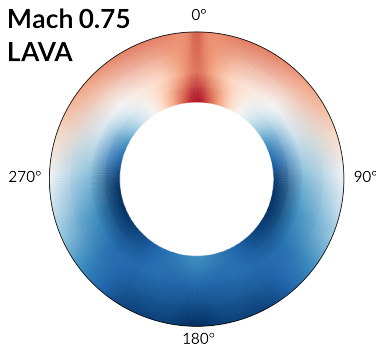
Results - Nacelle highlight flow angularity distortion

Re = 5-million, $\alpha = 2^\circ$
Mach number effects

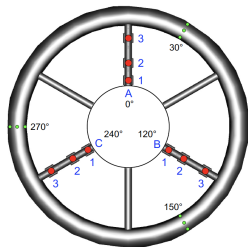
Mach 0.75
NTF



Mach 0.75
LAVA



5-hole probe locations
(Credit: Chan, D., 2024)

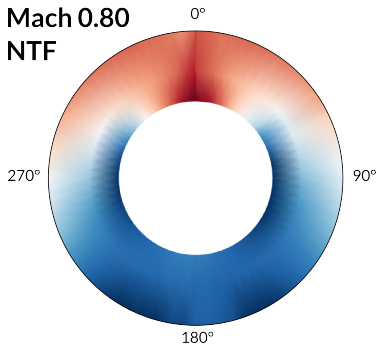


$$\alpha_{\text{flow}} = \text{atan} \frac{V_z}{V_x}$$

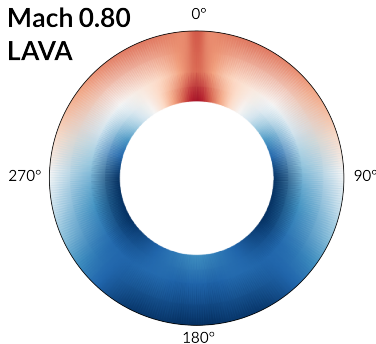
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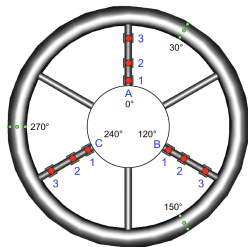
Mach 0.80
NTF



Mach 0.80
LAVA



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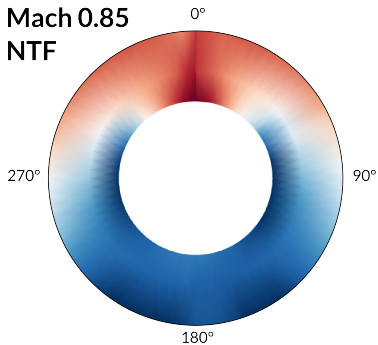
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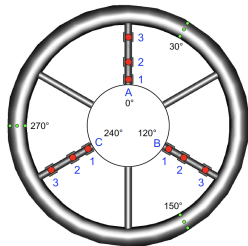
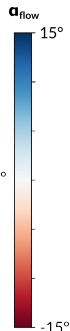
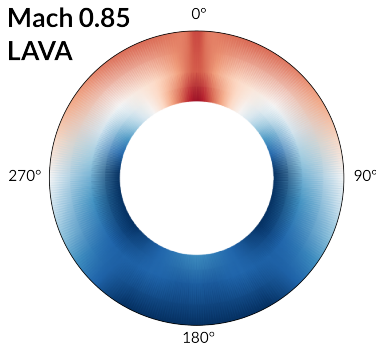
Re = 5-million, $\alpha = 2^\circ$
Mach number effects

5-hole probe locations
(Credit: Chan, D., 2024)

Mach 0.85
NTF



Mach 0.85
LAVA

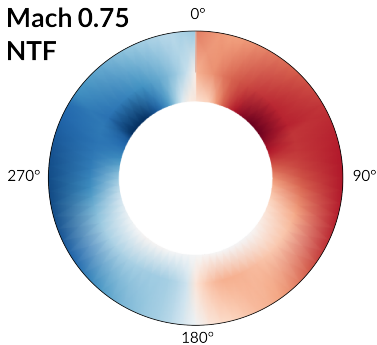


$$\alpha_{\text{flow}} = \text{atan} \frac{V_z}{V_x}$$

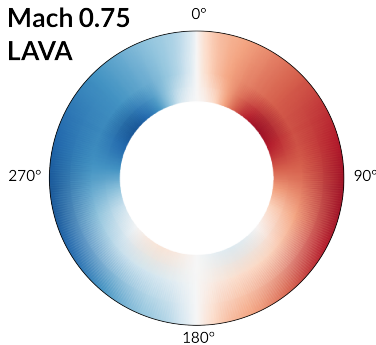
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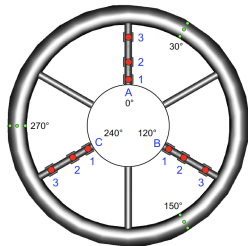
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NTF



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LAVA



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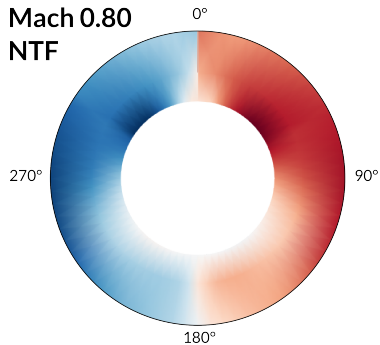


$$\beta_{\text{flow}} = \text{atan} \frac{V_y}{V_x}$$

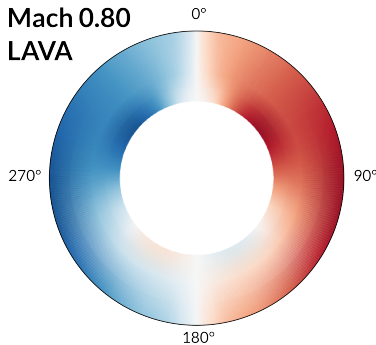
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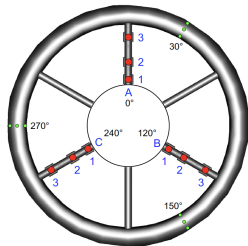
Mach 0.80
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LAVA



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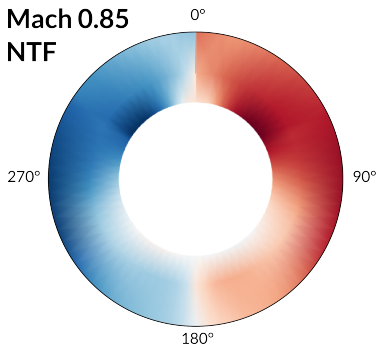


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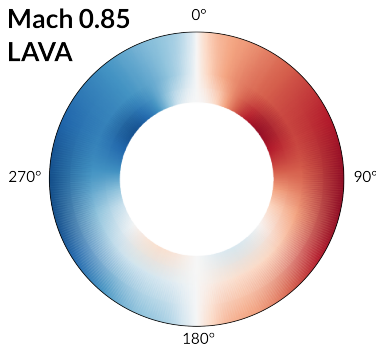
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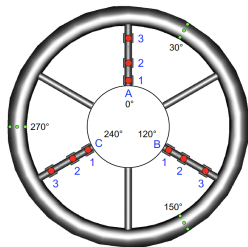
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- Demonstrated that RANS-based flow analysis can be used to accurately model TCT configurations using the LAVA curvilinear flow solver

Acknowledgements



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- Special thanks to Leonardo Machado, Jeffrey Housman and Jared Duensing for their contributions to this work
- Thanks to Dr. Shishir Pandya for the valuable technical guidance, Dr. Michael Bozeman for the discussions surrounding the comparisons between LAVA and the USM3D code

If you are interested in more details about this research

- **Luis S. Fernandes et al., AIAA 2024-3766**
Computational Analysis of a Boundary-Layer Ingesting Tailcone Thruster Configuration Within the National Transonic Facility Using the LAVA Solver
- **David T. Chan et al., AIAA-2024-3515**
Experimental Investigation of a Boundary Layer Ingesting Tailcone Thruster Configuration at the National Transonic Facility
- **Michael D. Bozeman, AIAA 2024-4022**
USM3D-ME Analyses Performed in Support of a Wind Tunnel Test of a Boundary-Layer Ingestion Configuration