AERODYNAMIC EFFECTS OF TURBULENCE INTENSITY ON A VARIABLE-SPEED POWER-TURBINE BLADE WITH LARGE INCIDENCE AND REYNOLDS NUMBER VARIATIONS

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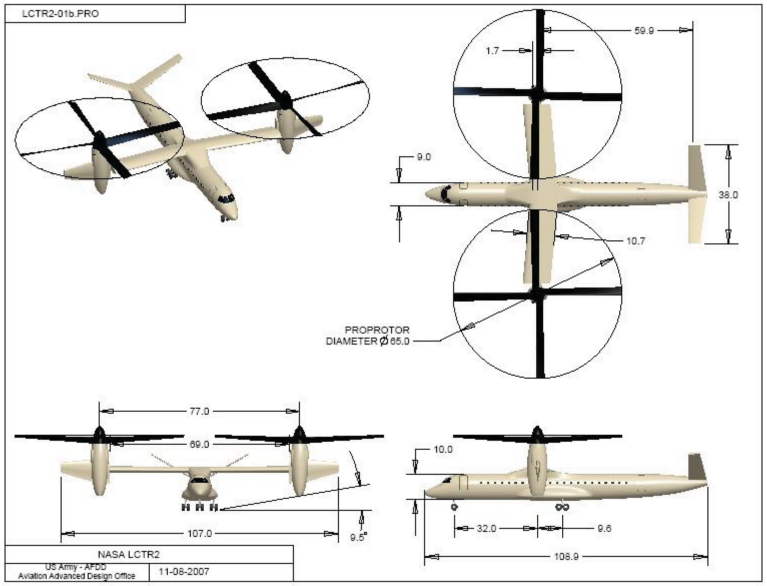
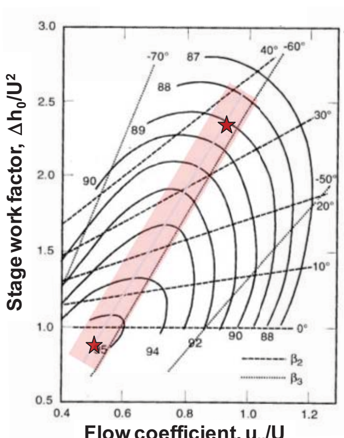
Ashlie B. Flegel, NASA Glenn Research Center
Paul W. Giel, Vantage Partners, LLC
Gerard E. Welch, NASA Glenn Research Center

Motivation for VSPT Technology



Acree, Hyeonsoo, and Sinsay, Int. Powered Lift Conf., 2008.



Smith chart

Large Civil Tilt-Rotor	
TOGW	108k lbm
Payload	90 PAX
Engines	4 x 7500 SHP
Range	> 1,000 nm
Cruise speed	> 300 kn
Cruise altitude	28 – 30 kft

Principal Challenge

Variability in main-rotor speed:
- 650 ft/s VTOL
- 350 ft/s at Mn 0.5 cruise

} ≈10 pts. in η_{prop}

Approaches

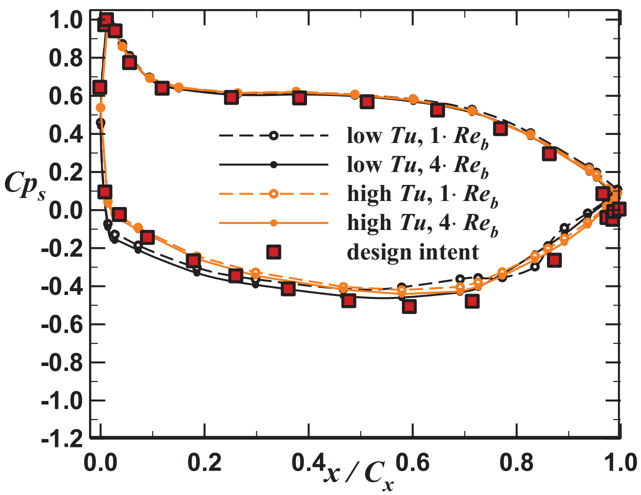
- Variable gear-ratio transmission
- Variable-speed power turbine **(VSPT)**
- or combination

VSPT Challenges

- Efficiency at high cruise work factor
  - $\Delta h_0 = D(u_q \cdot U) \approx$ const. at cruise and takeoff
  - $\Delta h_0/U^2$ cruise is 3.5 x takeoff
- 40^0 to 60^0 incidence angle variations in all blade row (and EGV) with 50% speed change
- Operation at low *Re* – transitional flow
  - 28 to 30 k-ft cruise leads to 60 k < $Re_{cx,2}$ < 100 k
  - Transitional flow

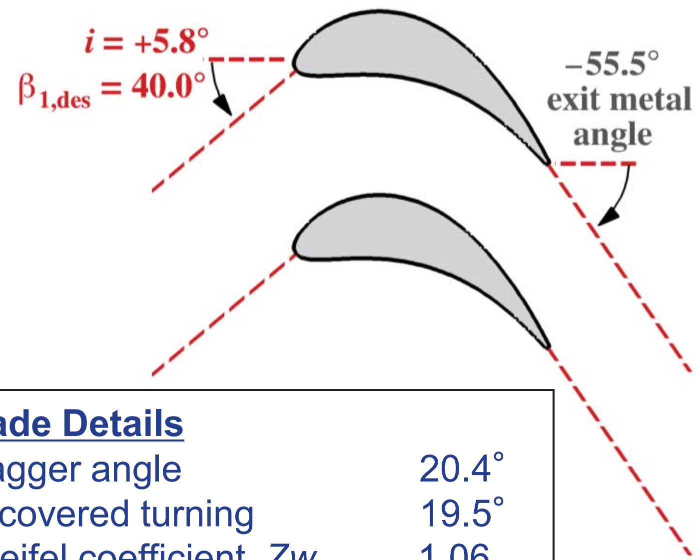
VSPT Approach and Objectives

- Document blade performance over wide incidence angle range, a wide Reynolds number range, and at mission-relevant Mach numbers.
  - Initial test conducted at low inlet turbulence in order to admit transitional flow on the blade surface.
  - Expand the dataset to include LPT-relevant turbulence levels and complement the existing dataset.



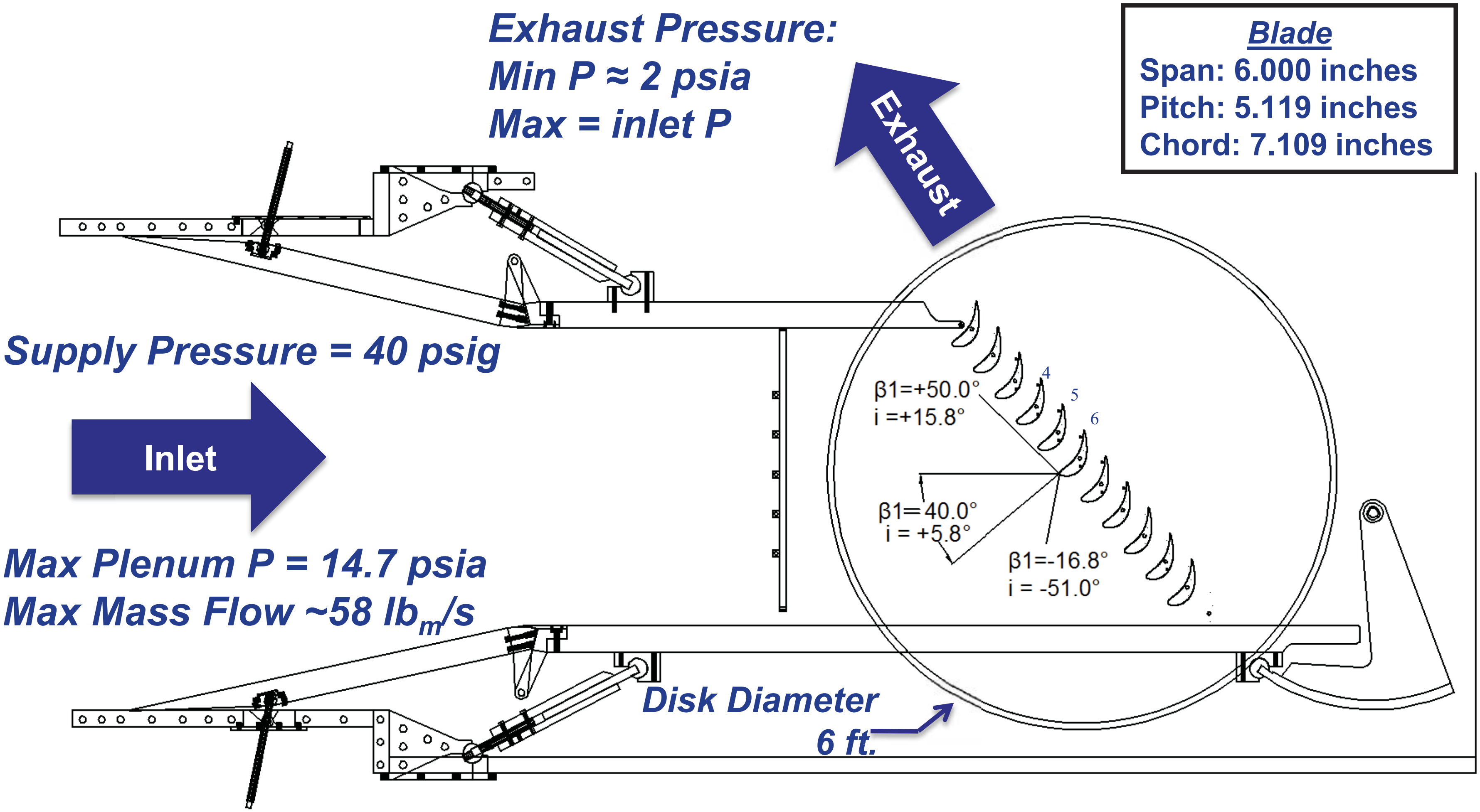
Design Intent Blade Loading and Exp. Data at $i = +5.8°$

$$Cp_s = \frac{(P - \overline{P_2})}{(P_{t,1} - \overline{P_2})}$$



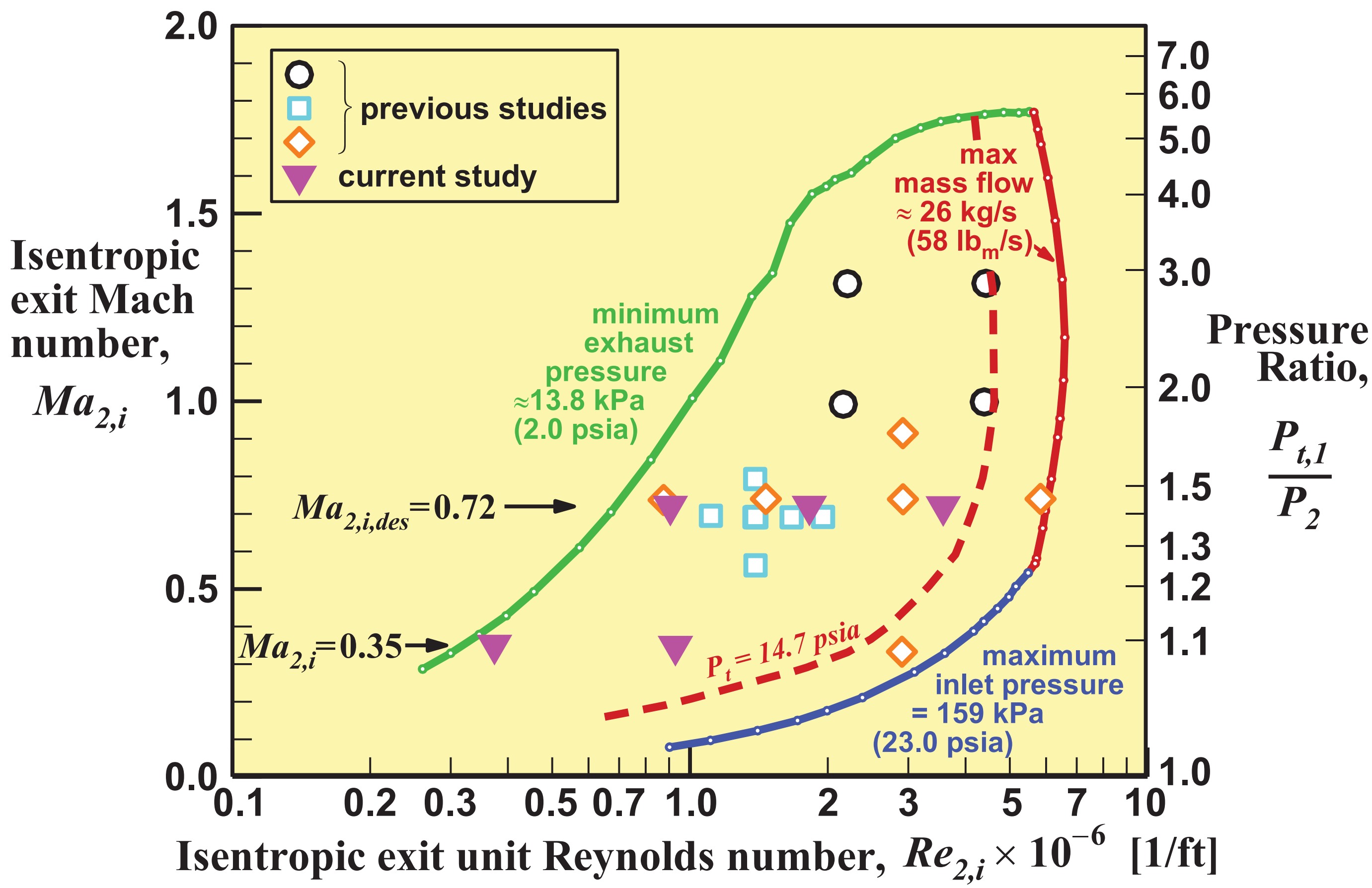
Blade Details	
Stagger angle	20.4°
Uncovered turning	19.5°
Zweifel coefficient, Zw_{des}	1.06
Solidity, Φ	1.39
Aspect Ratio	0.84

Transonic Turbine Blade Cascade Facility



Facility Inlet Angle Range: $-17° \le \beta_1 \le +78.8°$

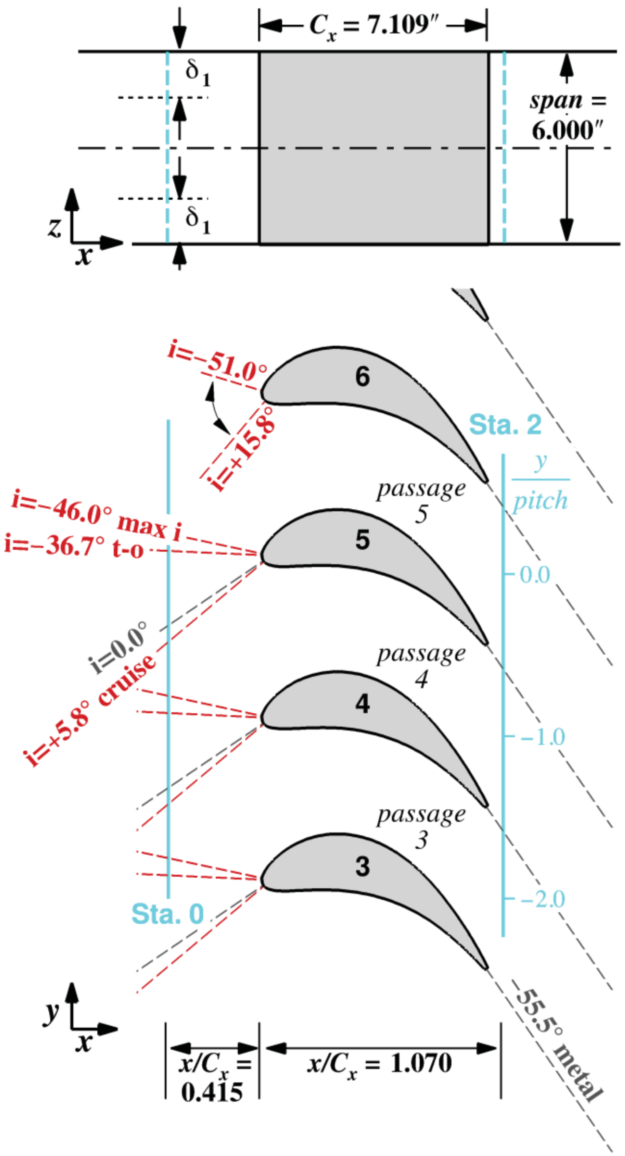
Facility Operating Envelope



Nominal Test Conditions

Re_{inlet}	PR	$M_{2,is}$
2.12 x 10^6	1.412	0.72
1.06 x 10^6	1.412	0.72
5.30 x 10^5 (Baseline)	1.412	0.72
5.30 x 10^5 (Baseline)	1.087	0.35
2.12 x 10^5	1.087	0.35

Test Configuration



- VSPT midspan section blade, $\beta_{1,des}$= 34.2°
- Ten incidence angles tested: +15.8° to −51.0°
- 5 flow conditions each

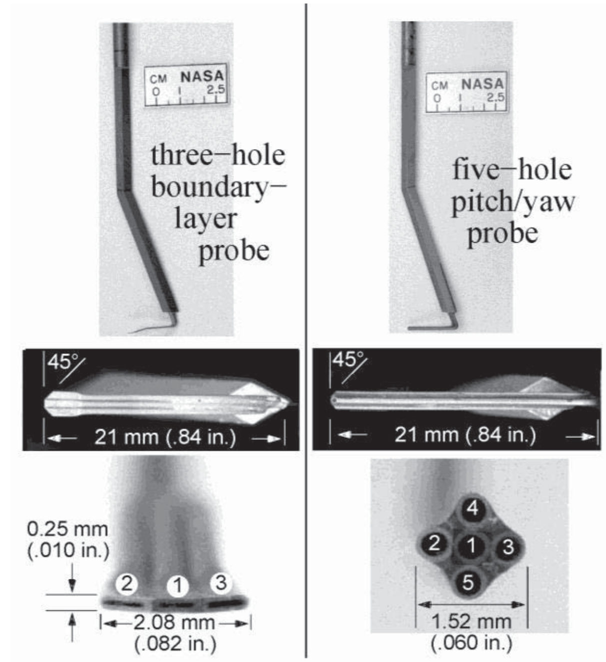
	Low Tu	High Tu
Inlet Turbulence Intensity	0.24% - 0.40%	8% - 15%
B-L Thickness [portion of half-span]	39% - 56%	19% - 29%

Inlet Flow Angles

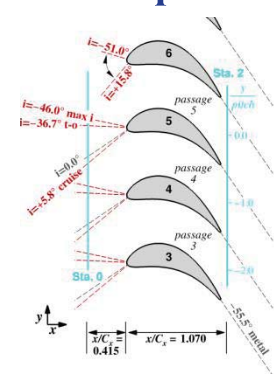
Inlet Angle, β_1	Incidence Angle, i	Zw
50.0°	15.8°	1.22
45.0°	10.8°	1.13
40.0° (Cruise)	**5.8°**	**1.06**
34.2°	0.0°	0.99
28.0°	−6.2°	0.92
18.1°	−16.1°	0.82
8.2°	−26.0°	0.74
−2.5° (Takeoff)	**−36.7°**	**0.65**
−11.8° (Mission Max-*i*)	−46.0°	0.58
−16.8°	−51.0°	0.53

Measurements

- Total pressure and exit flow angles measured 7% C_x downstream of trailing edge
- Blade and endwall static pressure measurements
- 12 exit static taps located 3 axial chords downstream
- Inlet P_t, P_s, and T_t measured at Station 0.
- Inlet boundary layer and turbulence documented.



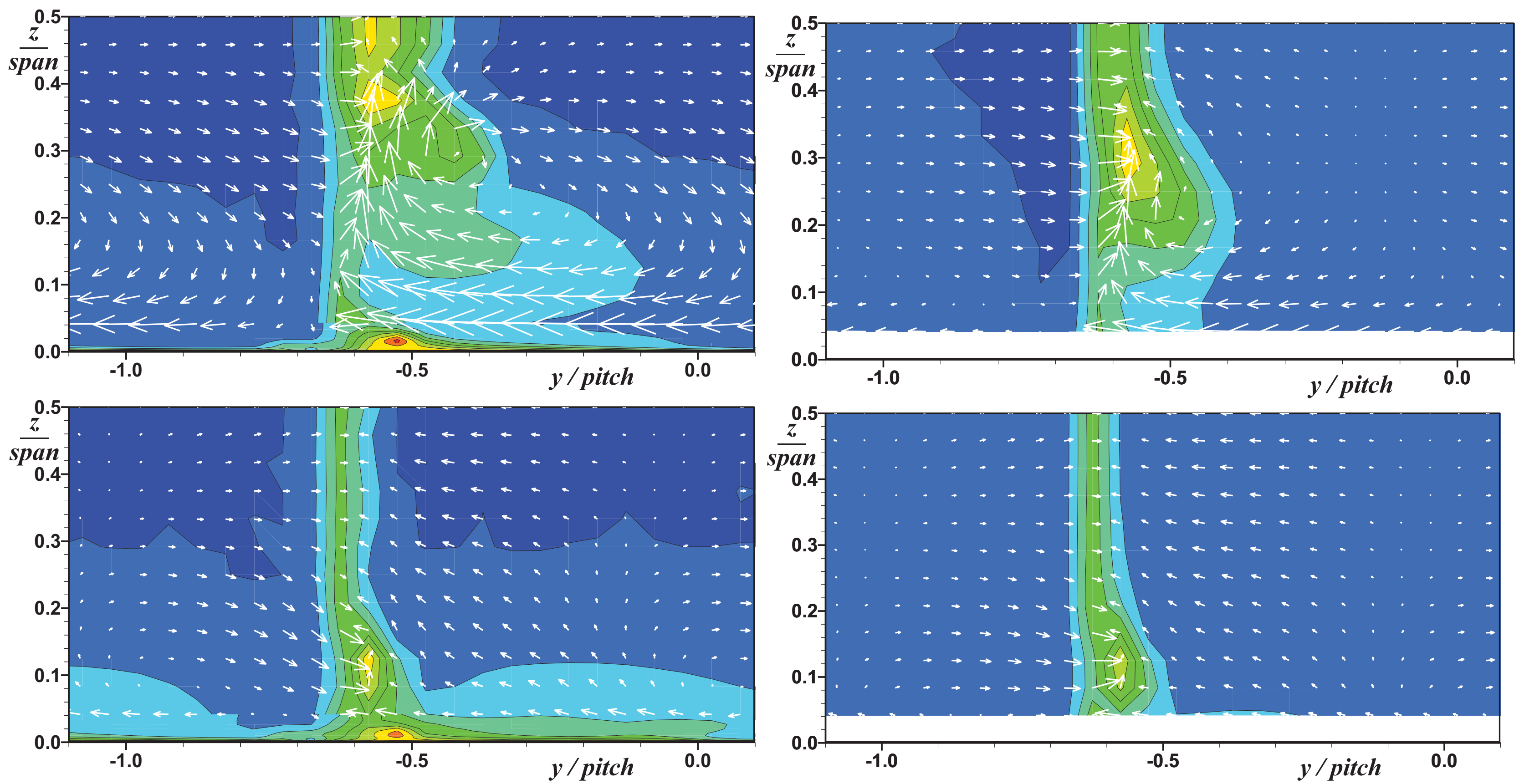
3-hole and 5-hole Probe Description



3-D FLOWFIELD RESULTS

Total Pressure Coefficient Contours and Secondary Flow Vectors

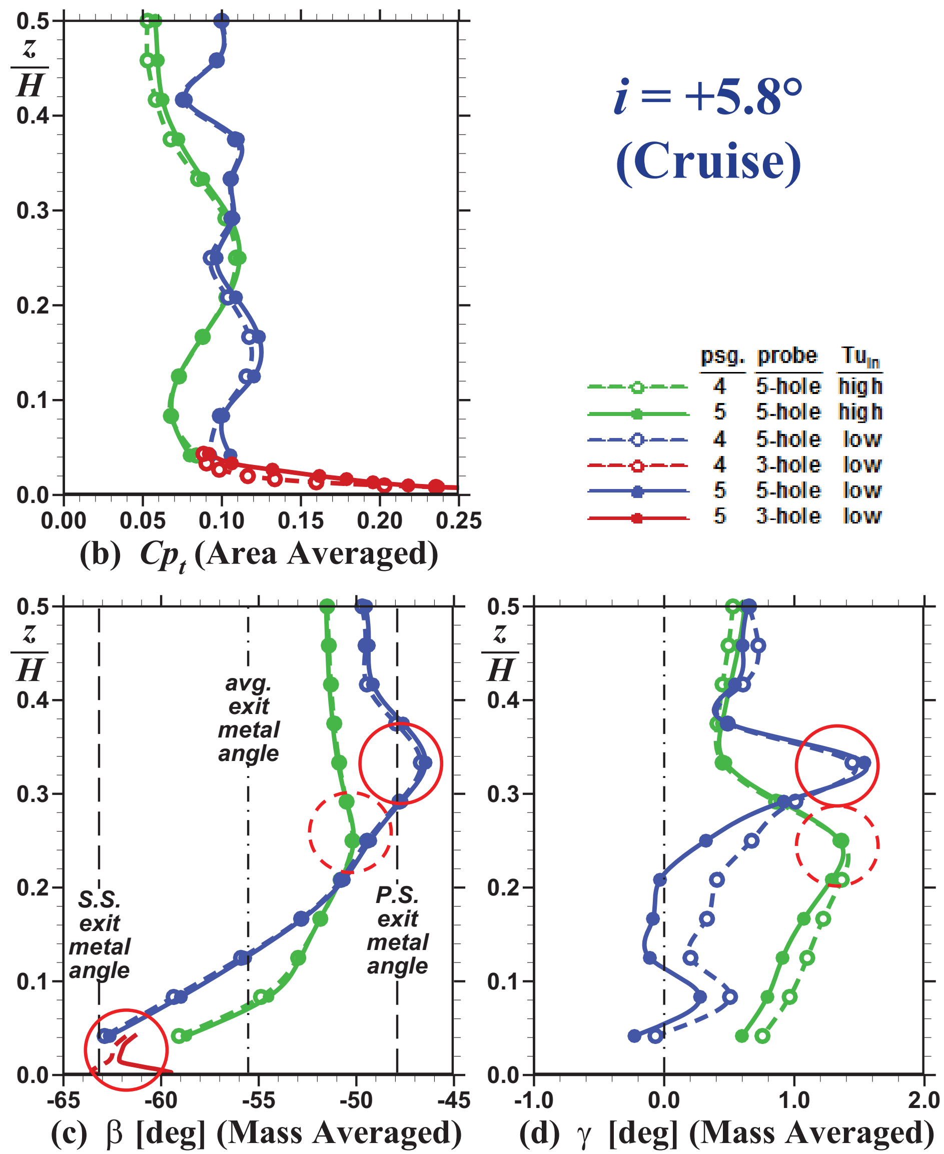
Low *Tu* **High *Tu***

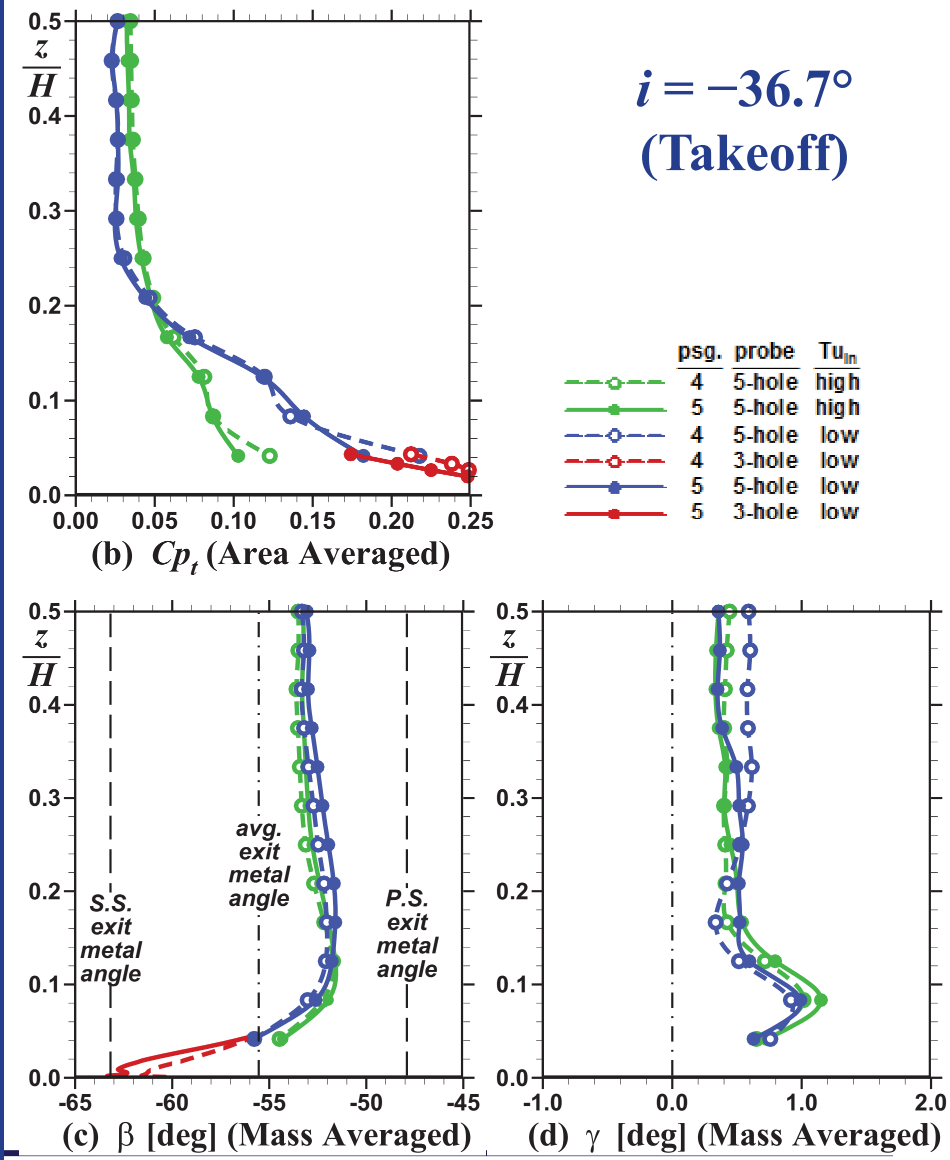


$i = +5.8°$
(Cruise)
$Re_{Cx,2} = Re_b$
$M_{2,i} = 0.72$

$i = -36.7°$
(Takeoff)
$Re_{Cx,2} = Re_b$
$M_{2,i} = 0.67$

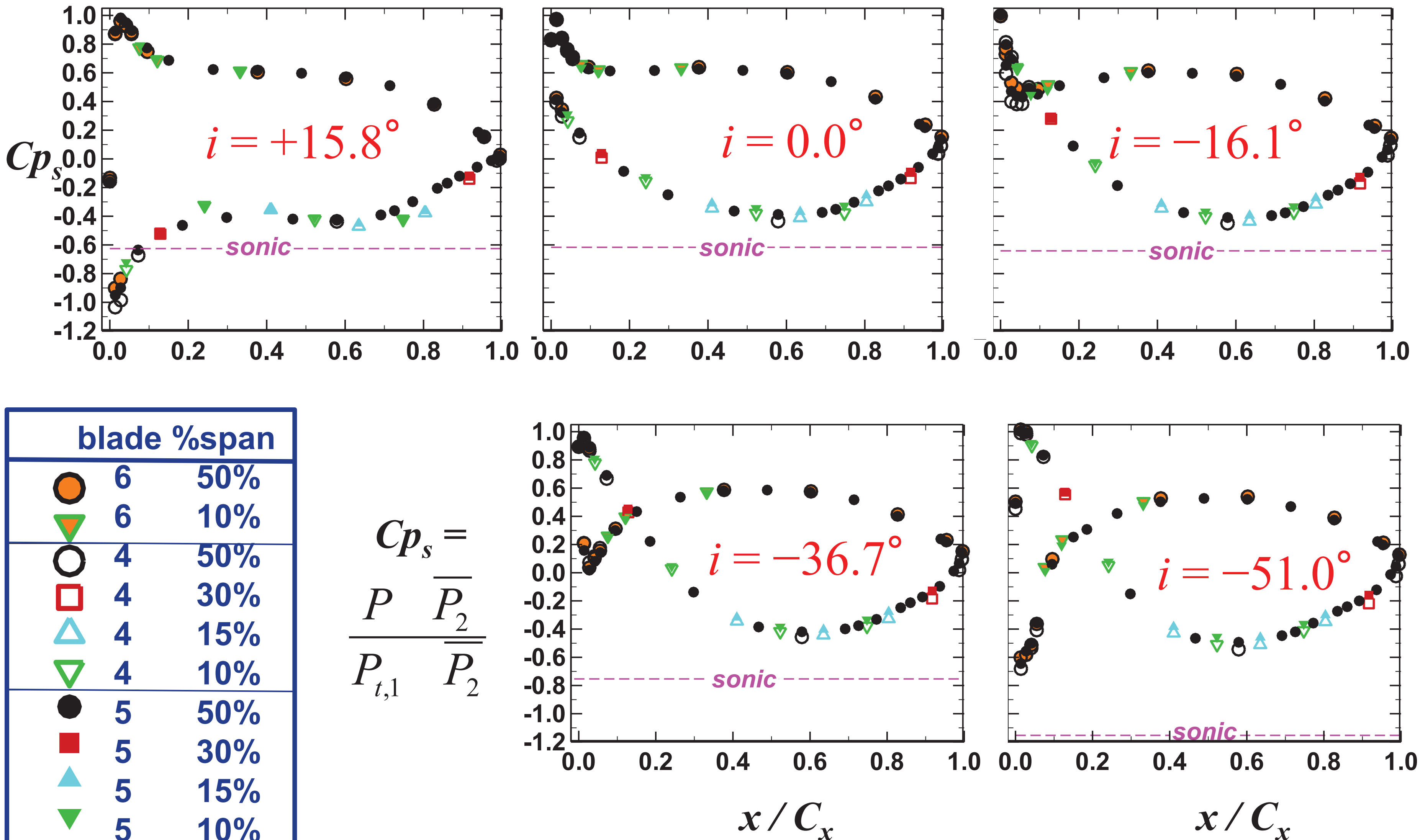
Pitchwise Integrated Data





EFFECT OF INCIDENCE AND TURBULENCE ON BLADE LOADING

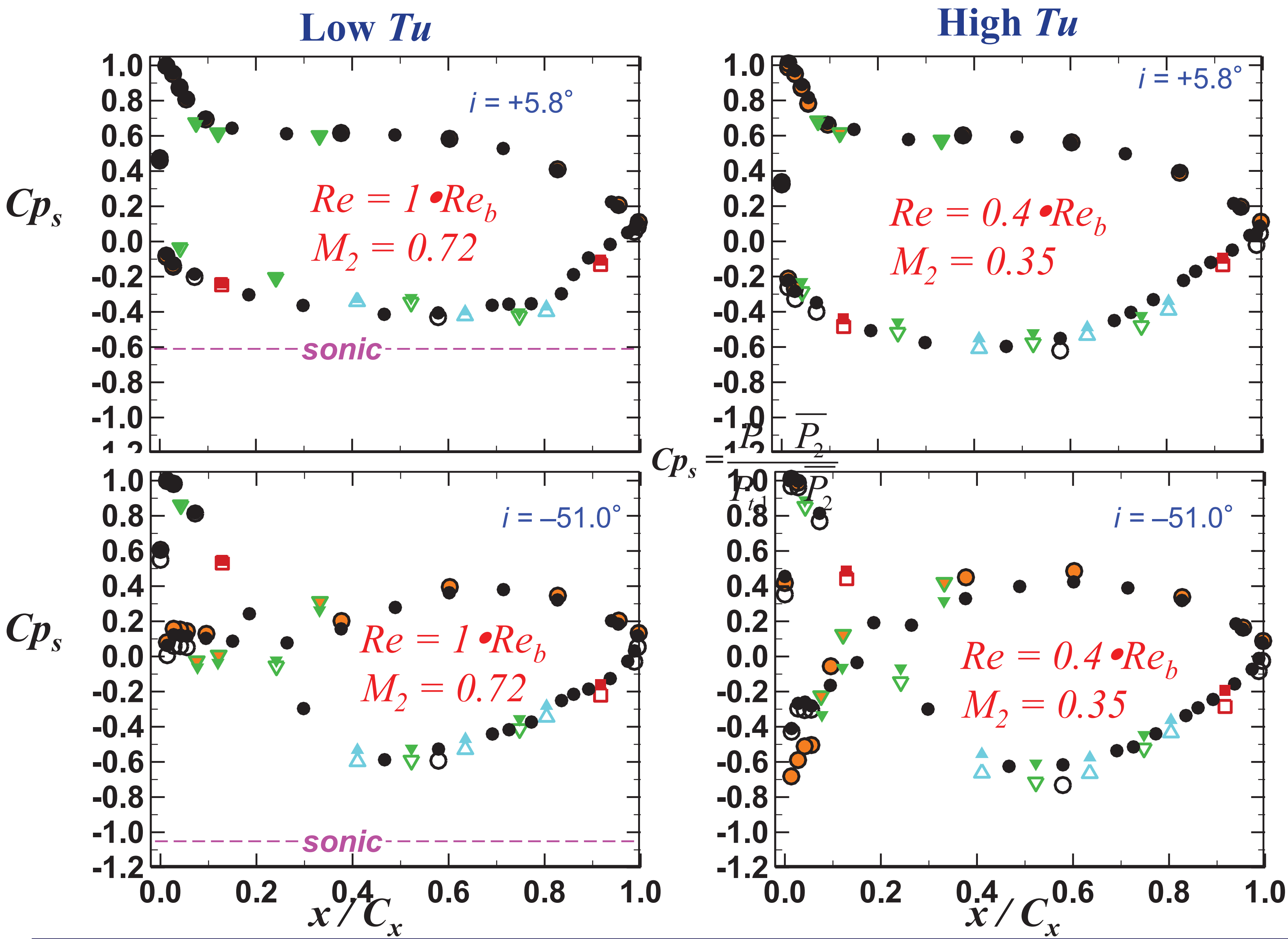
Blade Loading – Effects of Incidence at High *Tu*



$$Cp_s = \frac{P \quad \overline{P_2}}{P_{t,1} \quad \overline{\overline{P_2}}}$$

all data at $Re_{Cx,2}$ = Re_b and nominal design exit Mach number

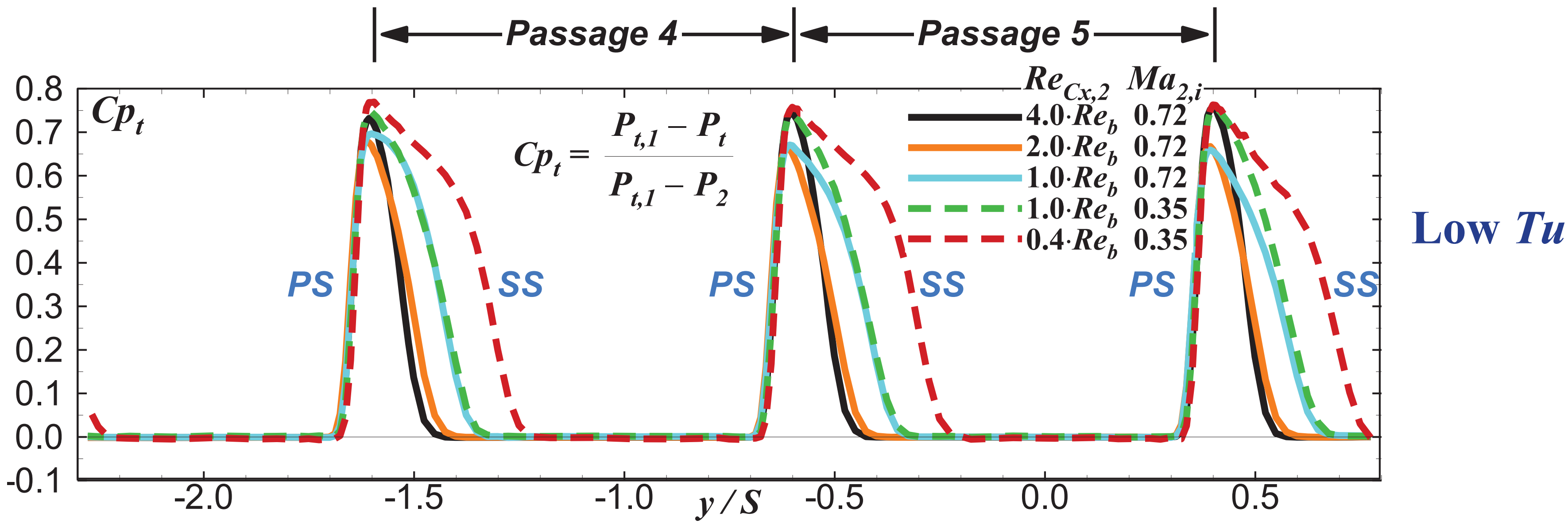
Blade Loading – Indicators of Separation

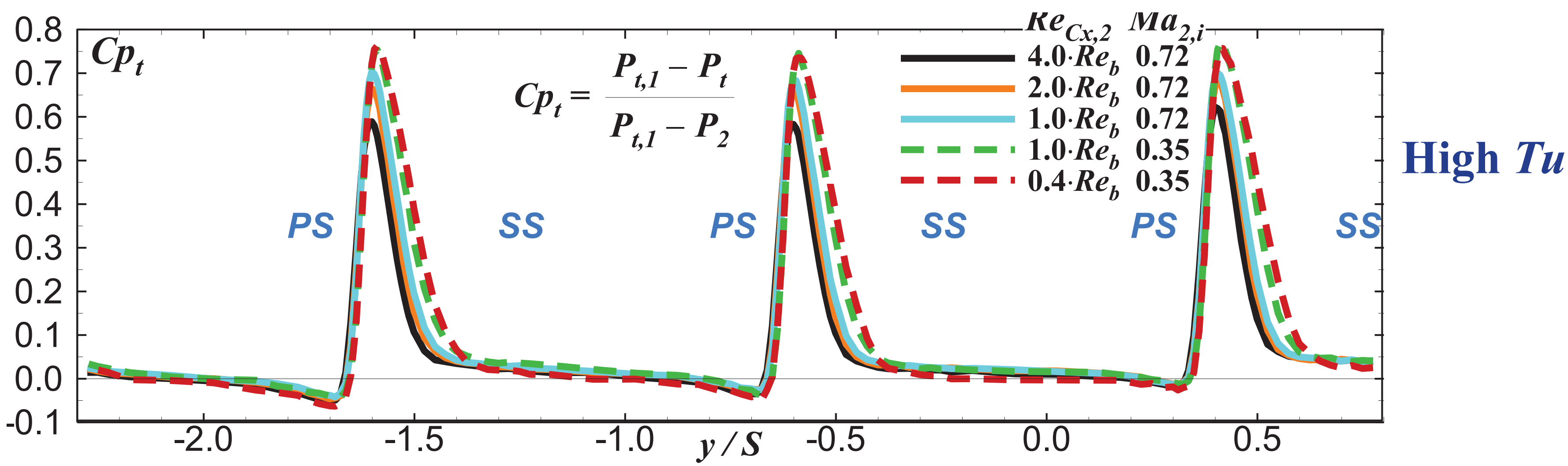


$$Cp_s = \frac{P_s - \overline{P_2}}{P_{t1} - \overline{P_2}}$$

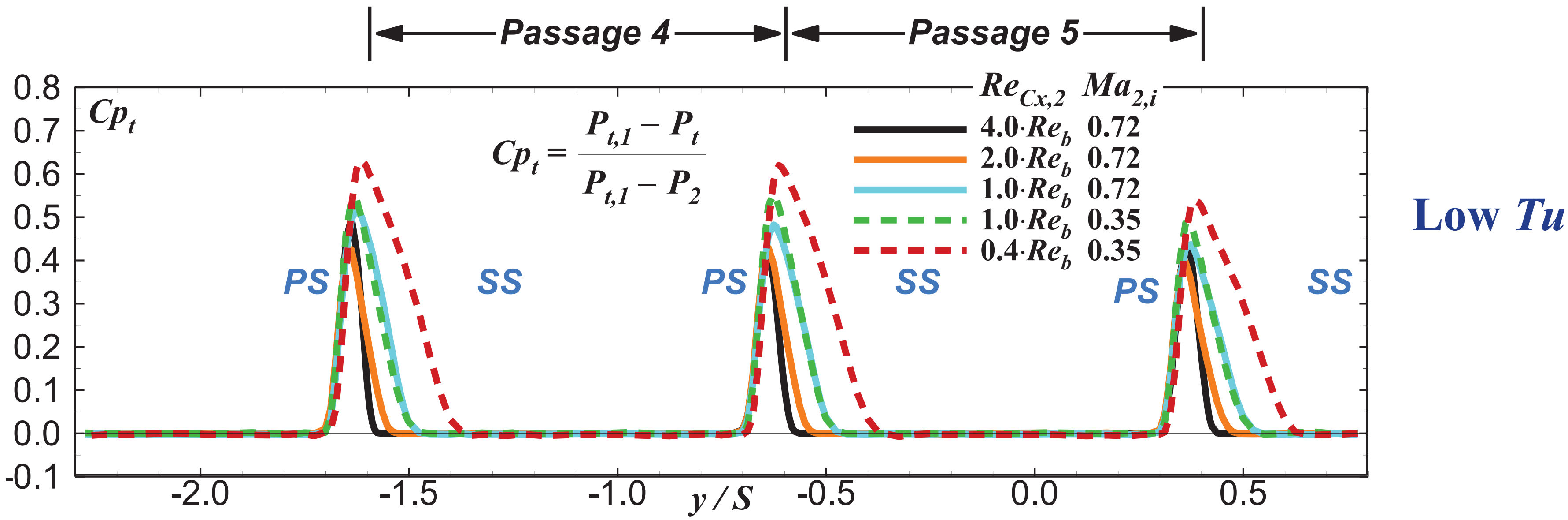
EFFECTS OF REYNOLDS NUMBER AND EXIT MACH NUMBER ON MIDSPAN EXIT SURVEYS

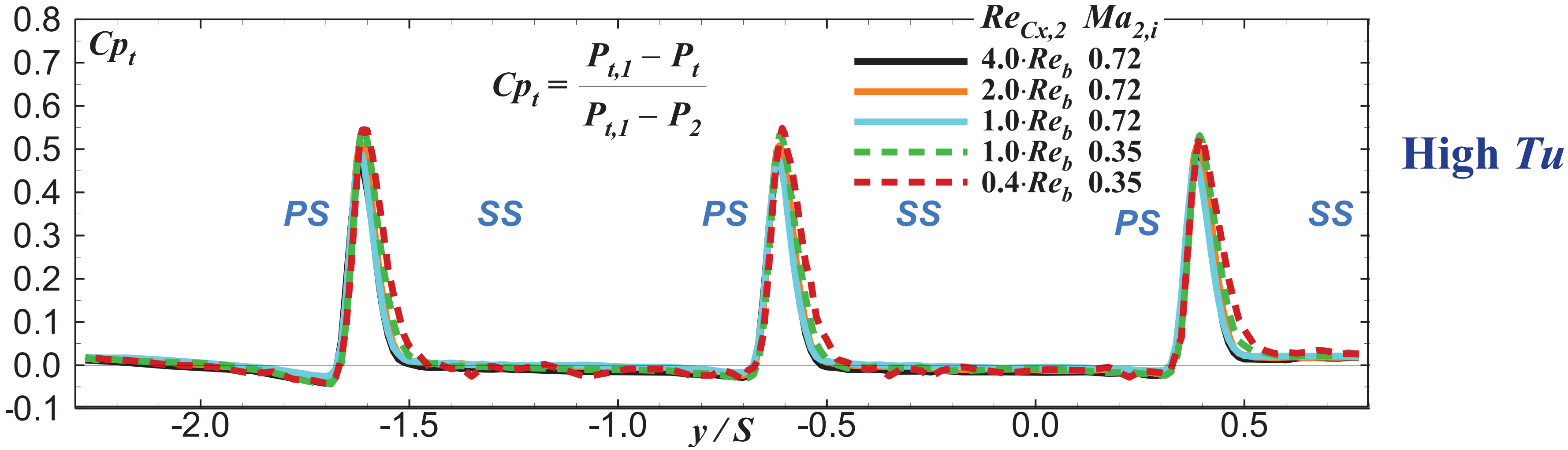
Effects of Reynolds Number and Mach Number at *i* = +10.8°



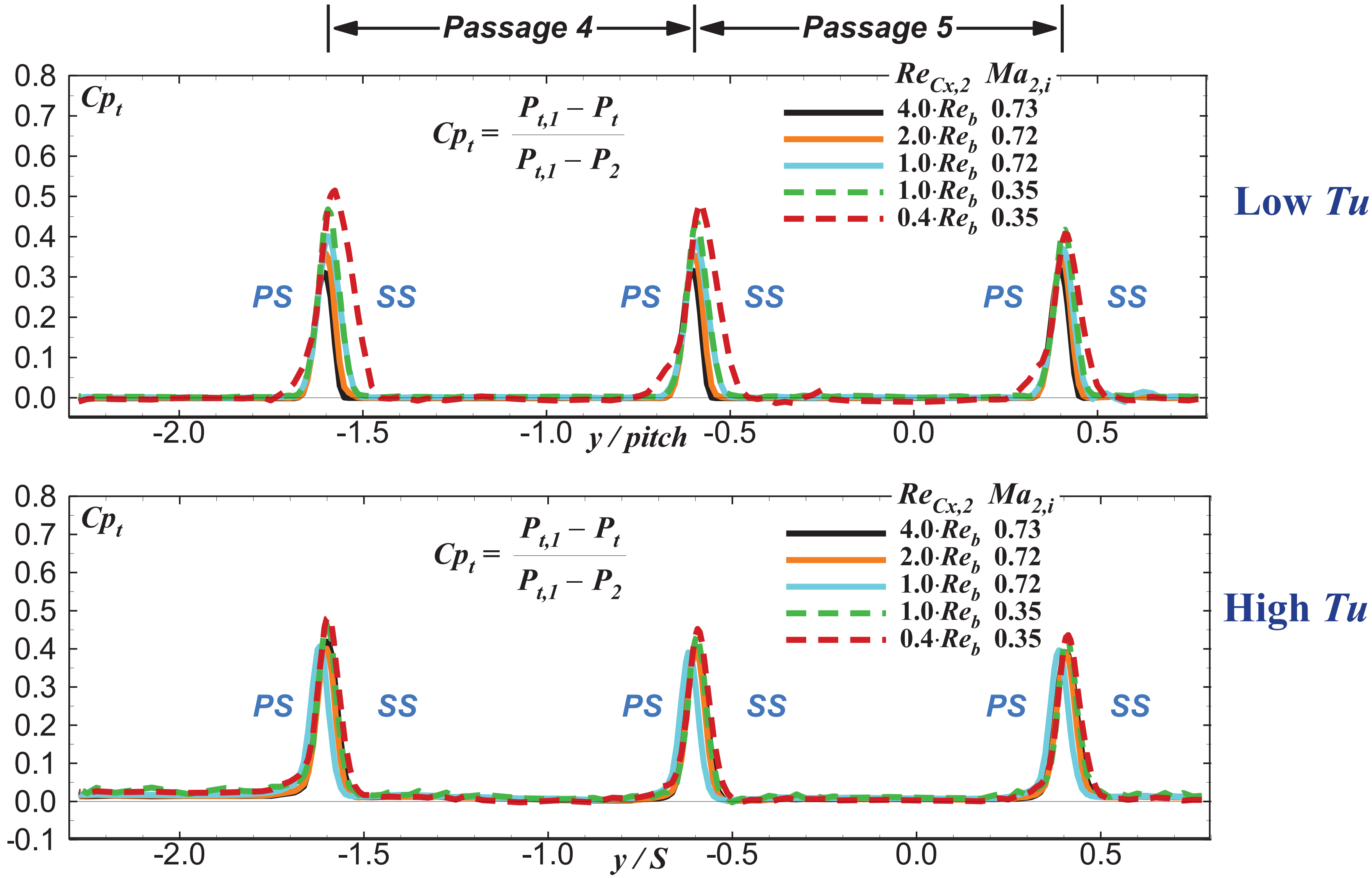


Effects of Reynolds Number and Mach Number at i = 0.0°

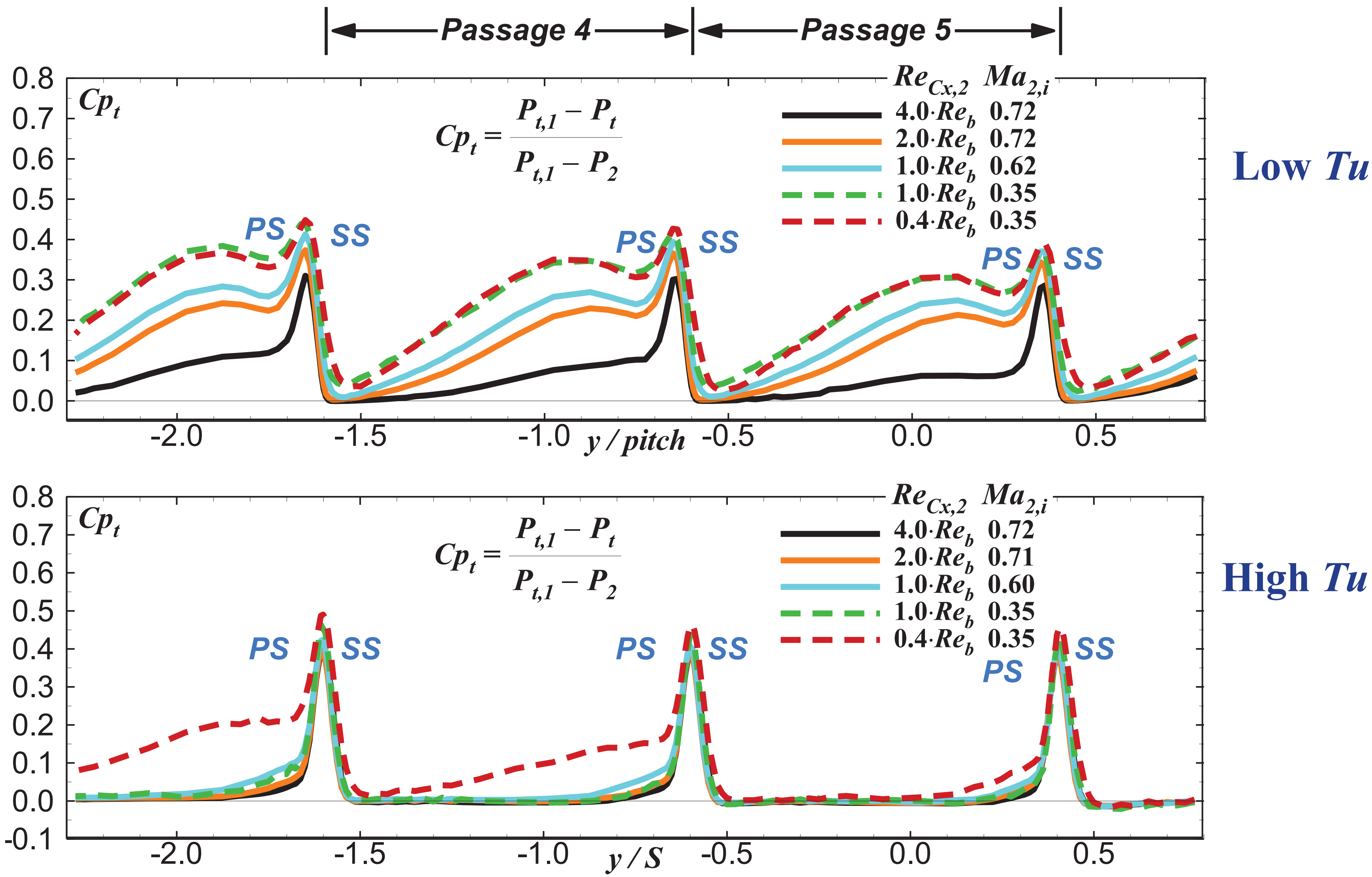




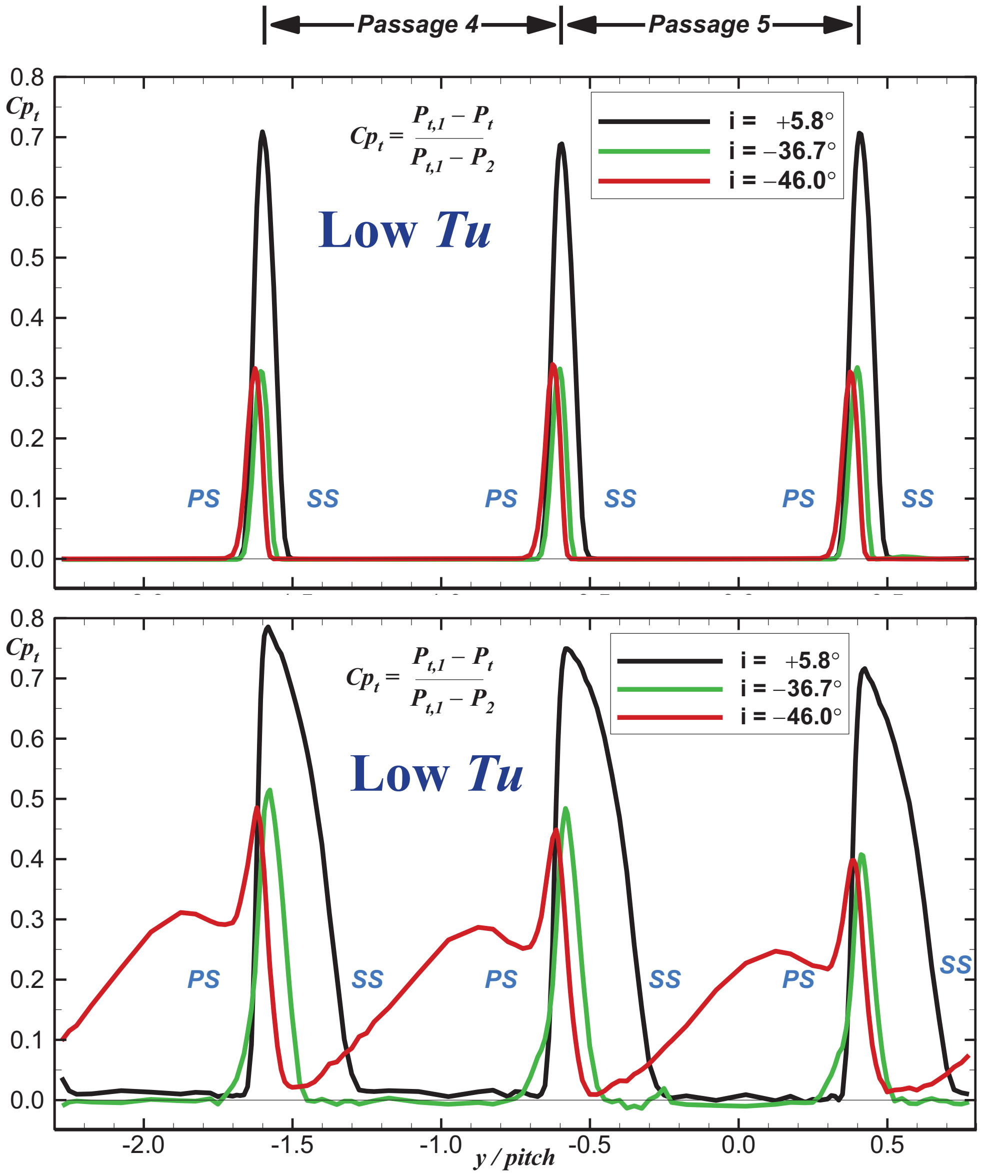
Effects of Reynolds Number and Mach Number at $i = -36.7°$



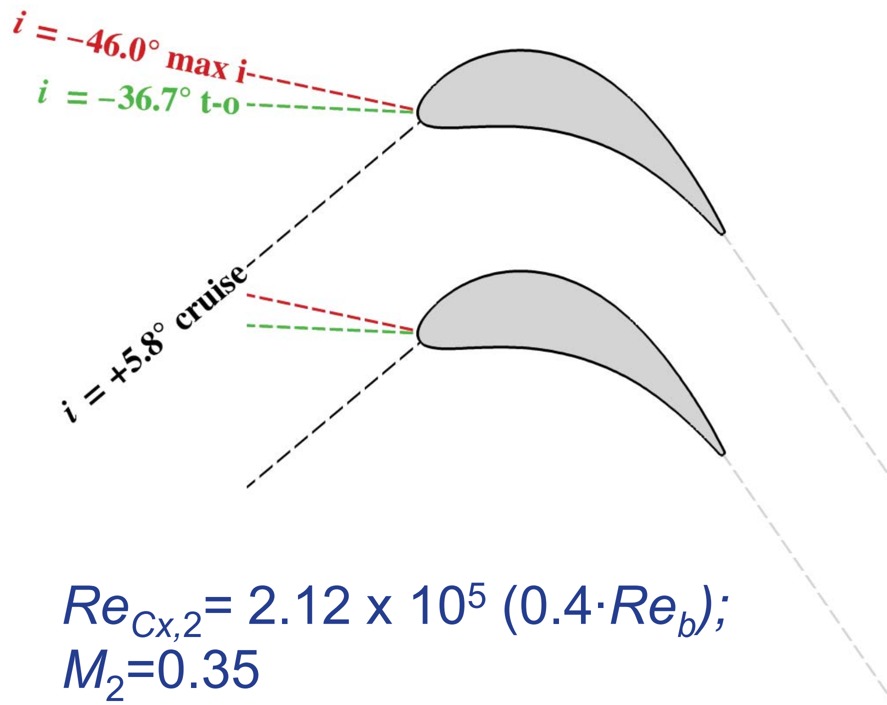
Effects of Reynolds Number and Mach Number at $i = -51.0°$



Effects of Inlet Flow Angle

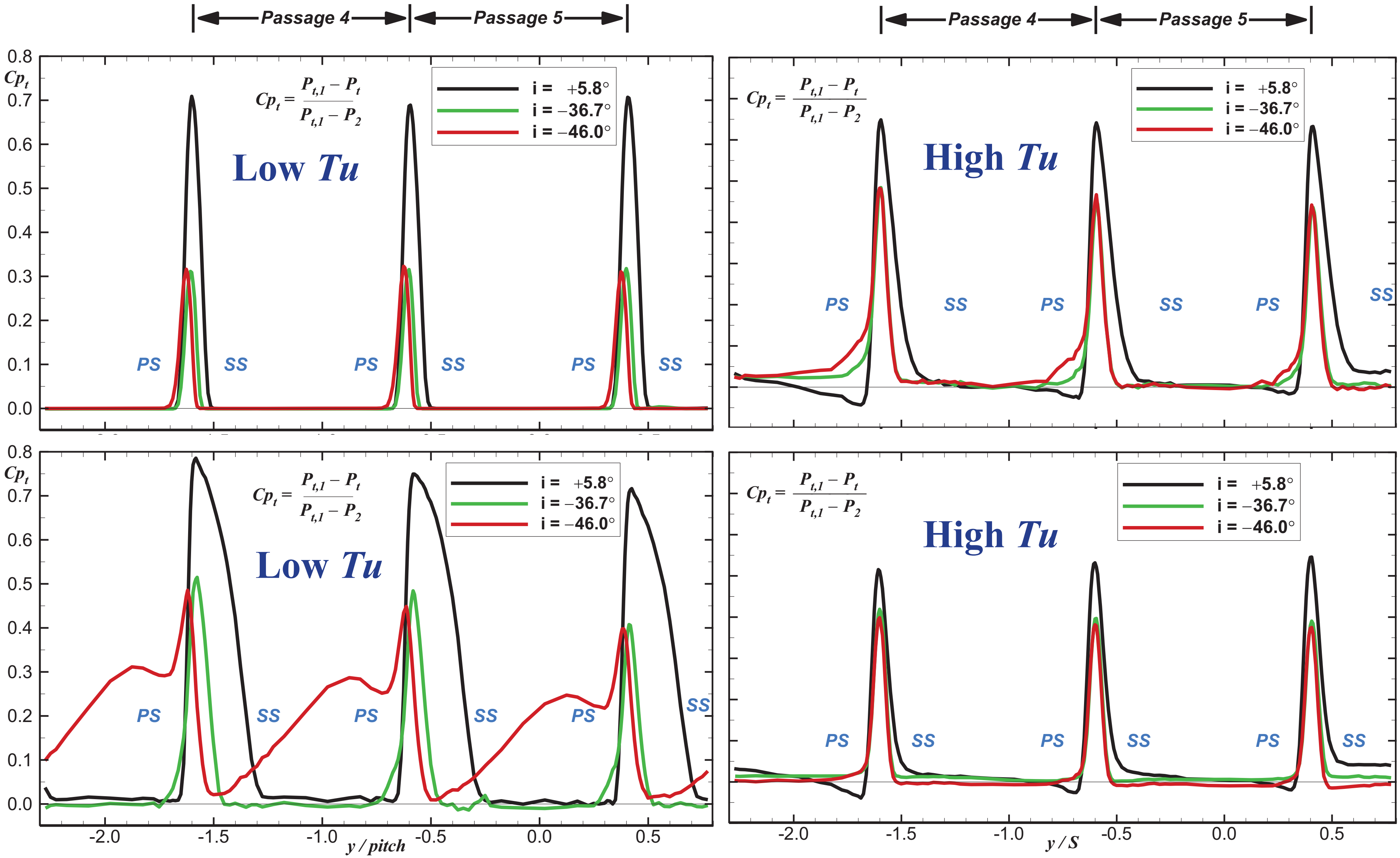


$Re_{Cx,2}$= 2.12 x 10^6 (4·Re_b);
M_2=0.72



$Re_{Cx,2}$= 2.12 x 10^5 (0.4·Re_b);
M_2=0.35

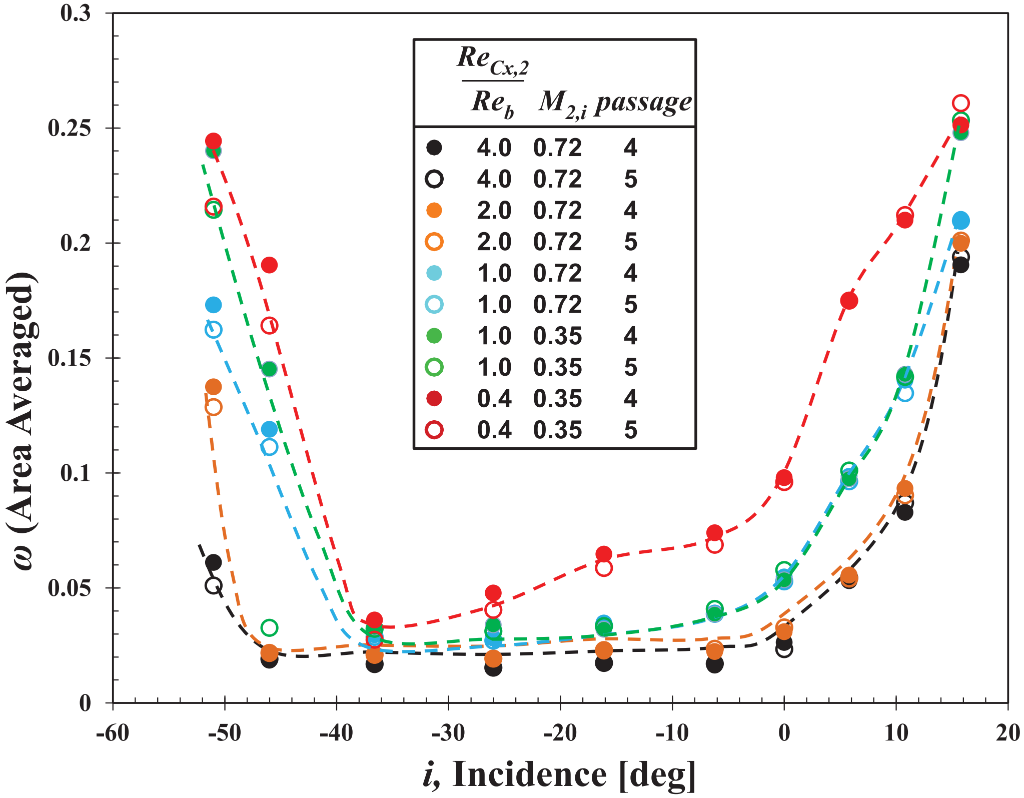
Effects of Inlet Flow Angle



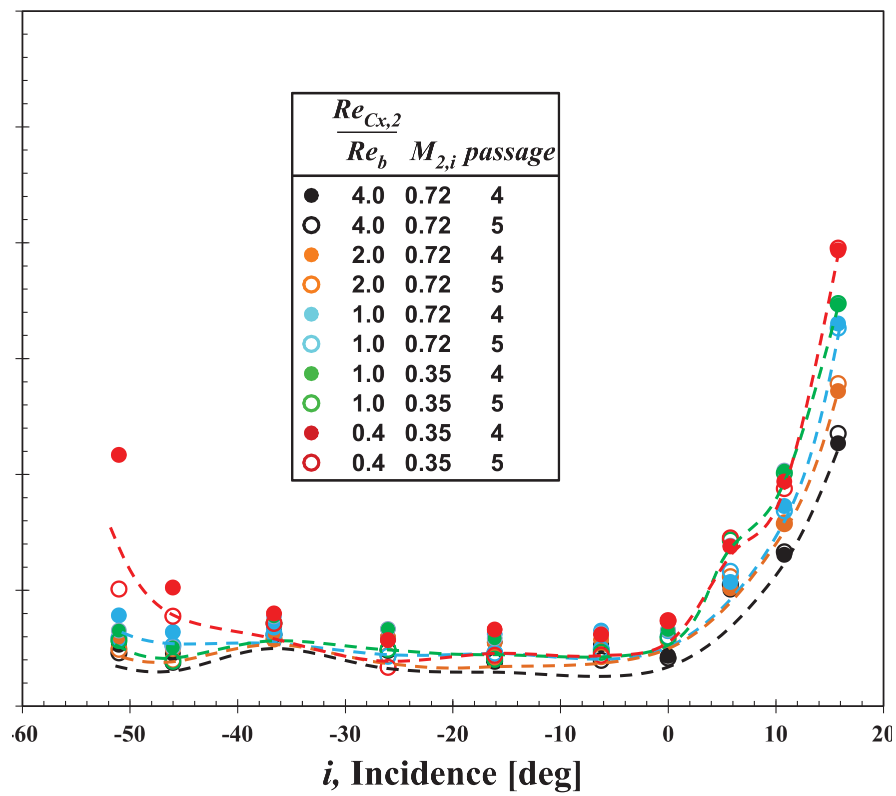
IMPACT OF INCIDENCE ANGLE AND REYNOLDS NUMBER ON MIDSPAN LOSS

Midspan Loss Bucket

Low *Tu*



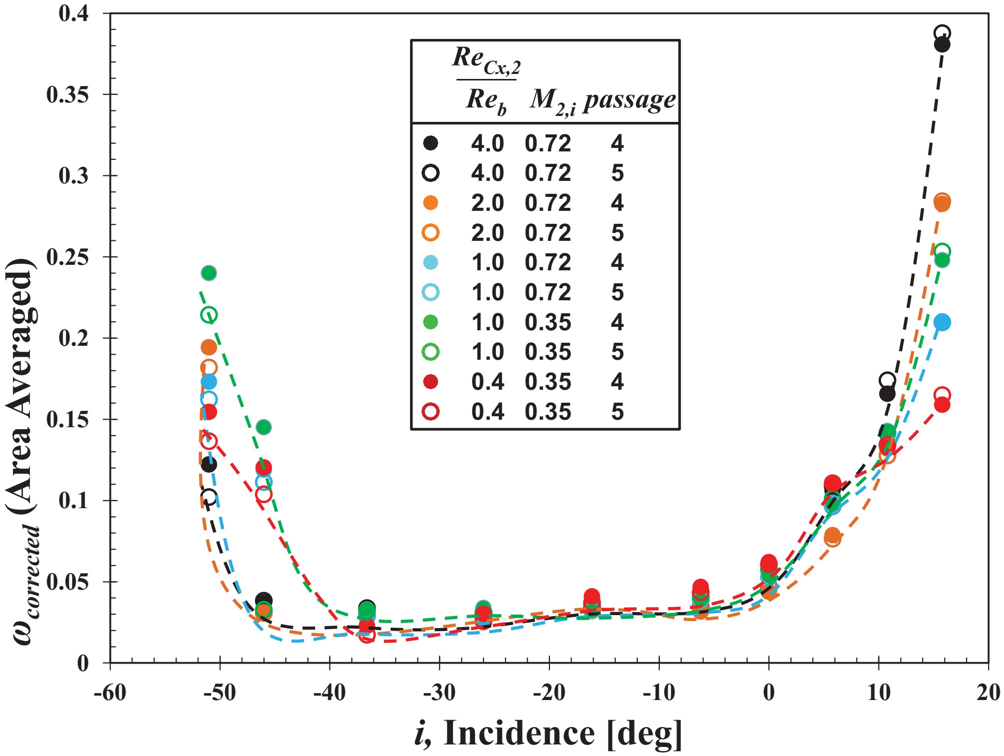
High *Tu*



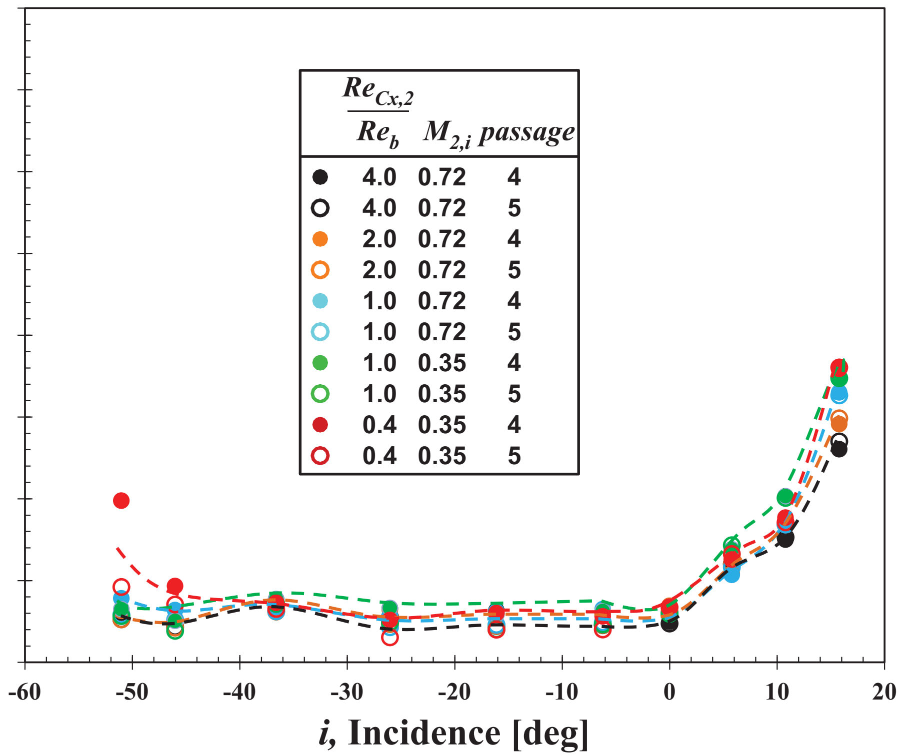
$$\omega = \frac{(P_{t,1} - \overline{P_{t,2}})}{(P_{t,1} - \overline{P_2})}$$

Midspan Loss Scaling

Low *Tu*
$Re^{-0.5}$ Scaled Loss Bucket

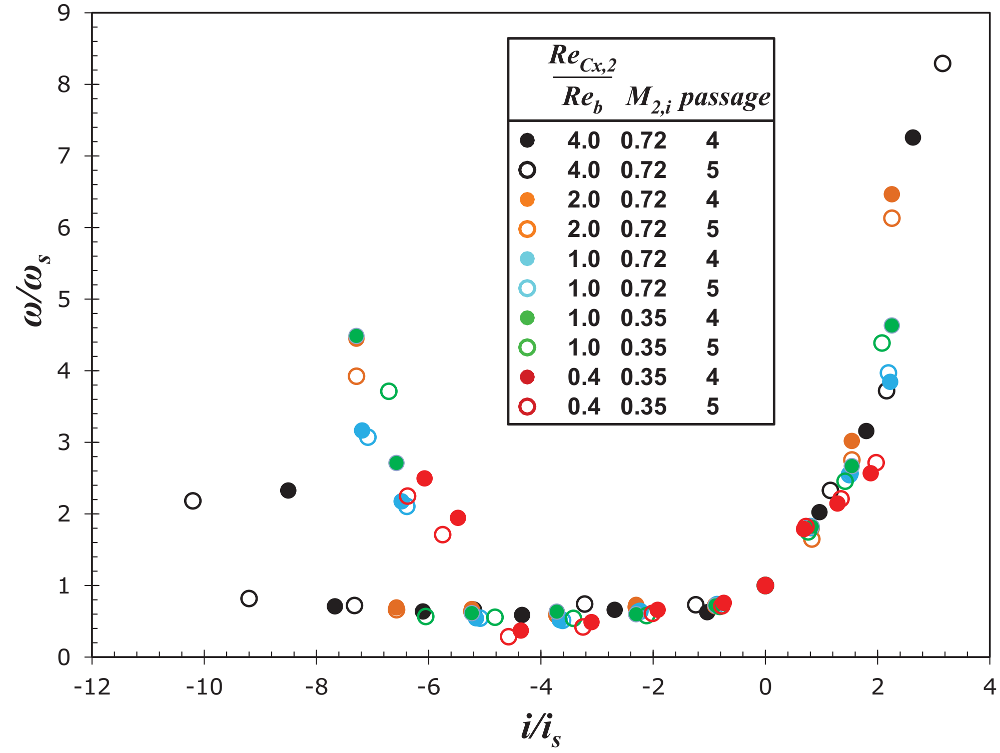


High *Tu*
$Re^{-0.1}$ Scaled Loss Bucket

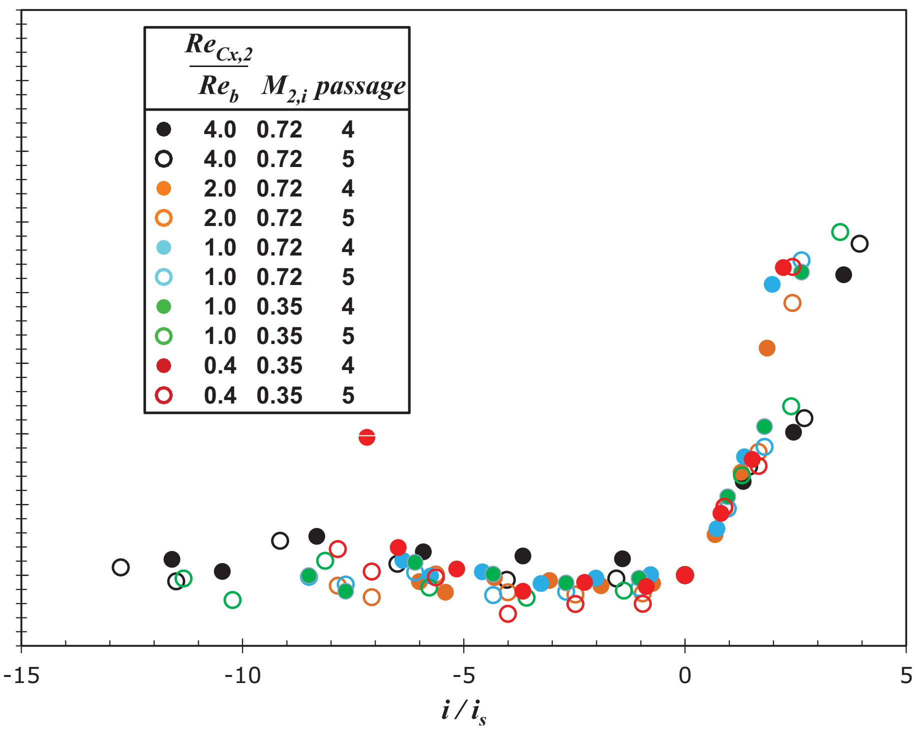


Ainley-Mathieson Midspan Loss Scaling

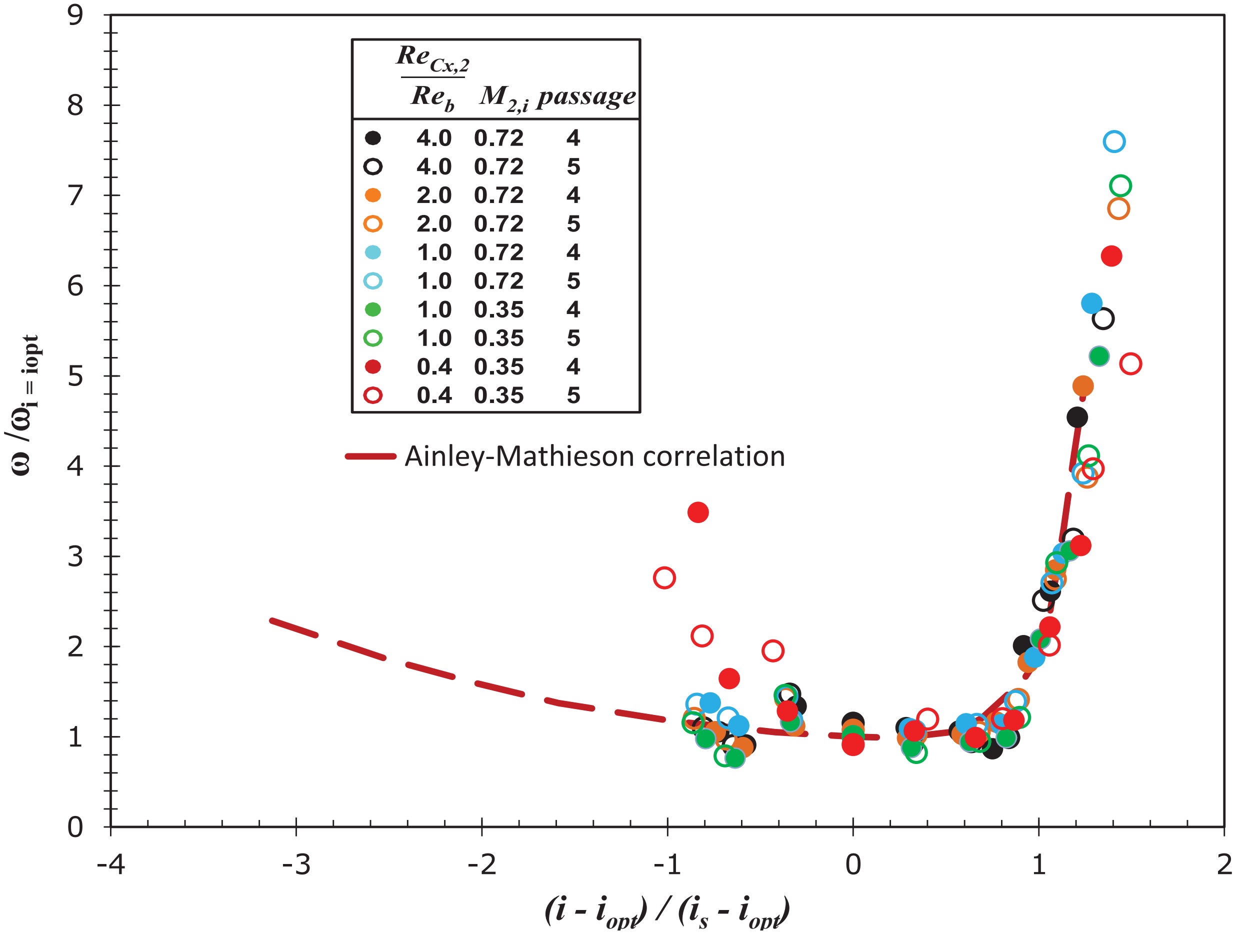
Low *Tu*



High *Tu*



Ainley-Mathieson Midspan Loss Scaling at High *Tu*



Conclusions

- Well documented dataset that spans a large incidence range at engine relevant transonic flow conditions at two different turbulence conditions.

- Low *Tu* test admits suction side transitional flow within wide Reynolds number range tested.
  - Transitional flow makes this a valuable and challenging data set for CFD code validation and turbine designers.

- The turbulence grid effectively reduced the inlet boundary layer thickness by half, leading to less aerodynamic blockage in the test section.

- For the high *Tu* test, the flow remains largely attached over all the flow and incidence conditions.

Acknowledgement

The authors would like to acknowledge the contributions of
Dr. Steven G. Gegg of Rolls-Royce North American Technologies.

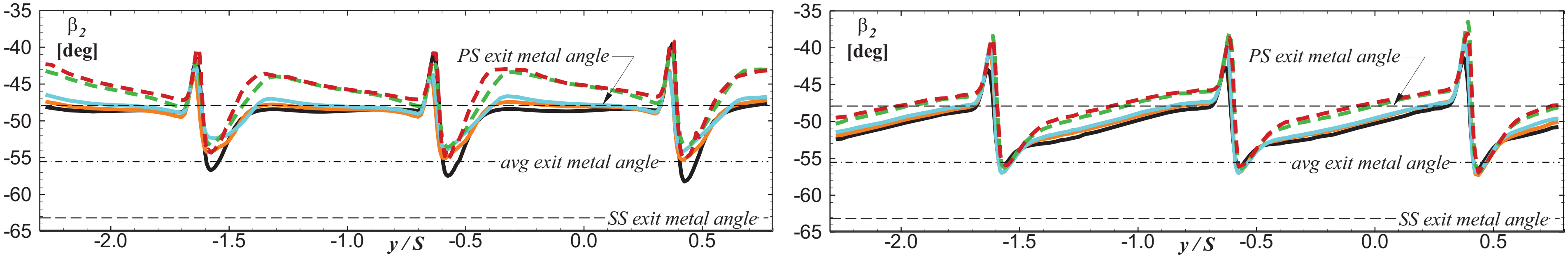
It was our great honor to have worked with him.

NASA

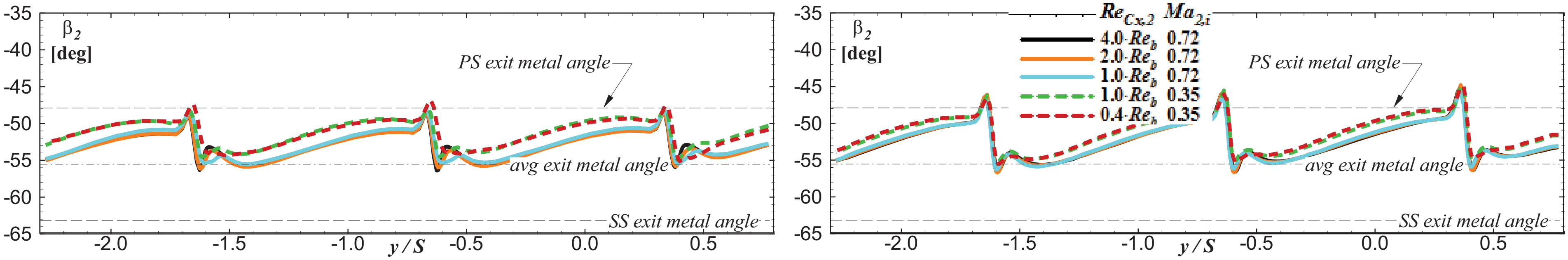
Exit Flow Angles

Low *Tu* | High *Tu*

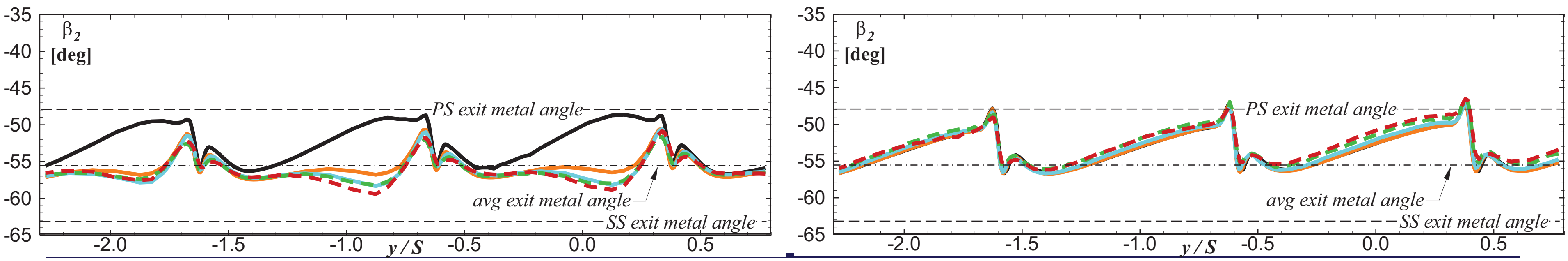
$i = +10.8°$



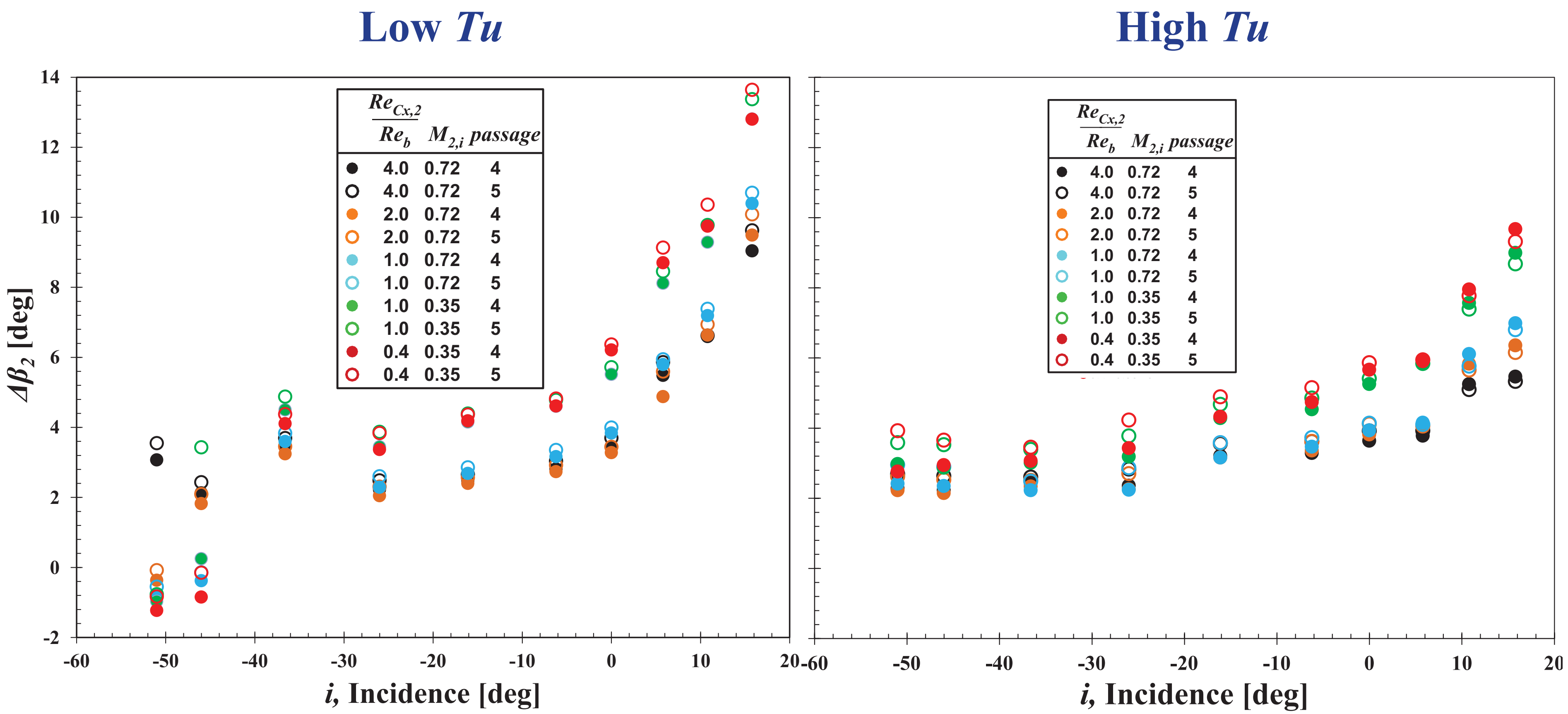
$i = -16.1°$



$i = -51.0°$



Average Exit Flow Angle



$$\Delta\beta_2 = \beta_2 + 55.54°$$