Aerodynamic Investigation of Incidence Angle Effects in a Large Scale Transonic Turbine Cascade

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Aerodynamic measurements showing the effects of large incidence angle variations on an HPT turbine blade set are presented. Measurements were made in NASA's Transonic Turbine Blade Cascade Facility which has been used in previous studies to acquire detailed aerodynamic and heat transfer measurements for CFD code validation. The current study supports the development of variable-speed power turbine (VSPT) speed-change technology for the NASA Large Civil Tilt Rotor (LCTR) vehicle. In order to maintain acceptable main rotor propulsive efficiency, the VSPT operates over a nearly 50% speed range from takeoff to altitude cruise. This results in 50° or more variations in VSPT blade incidence angles. The cascade facility has the ability to operate over a wide range of Reynolds numbers and Mach numbers, but had to be modified in order to accommodate the negative incidence angle variation required by the LCTR VSPT operation. Using existing blade geometry with previously acquired aerodynamic data, the tunnel was re-baselined and the new incidence angle range was exercised. Midspan exit total pressure and flow angle measurements were obtained at seven inlet flow angles. For each inlet angle, data were obtained at five flow conditions with inlet Reynolds numbers varying from 6.83×10^5 to 0.85×10^5 and two isentropic exit Mach numbers of 0.74 and 0.34. The midspan flowfield measurements were acquired using a three-hole pneumatic probe located in a survey plane 8.6% axial chord downstream of the blade trailing edge plane and covering three blade passages. Blade and endwall static pressure distributions were also acquired for each flow condition.

AERODYNAMIC INVESTIGATION OF INCIDENCE ANGLE EFFECTS IN A LARGE SCALE TRANSONIC TURBINE CASCADE

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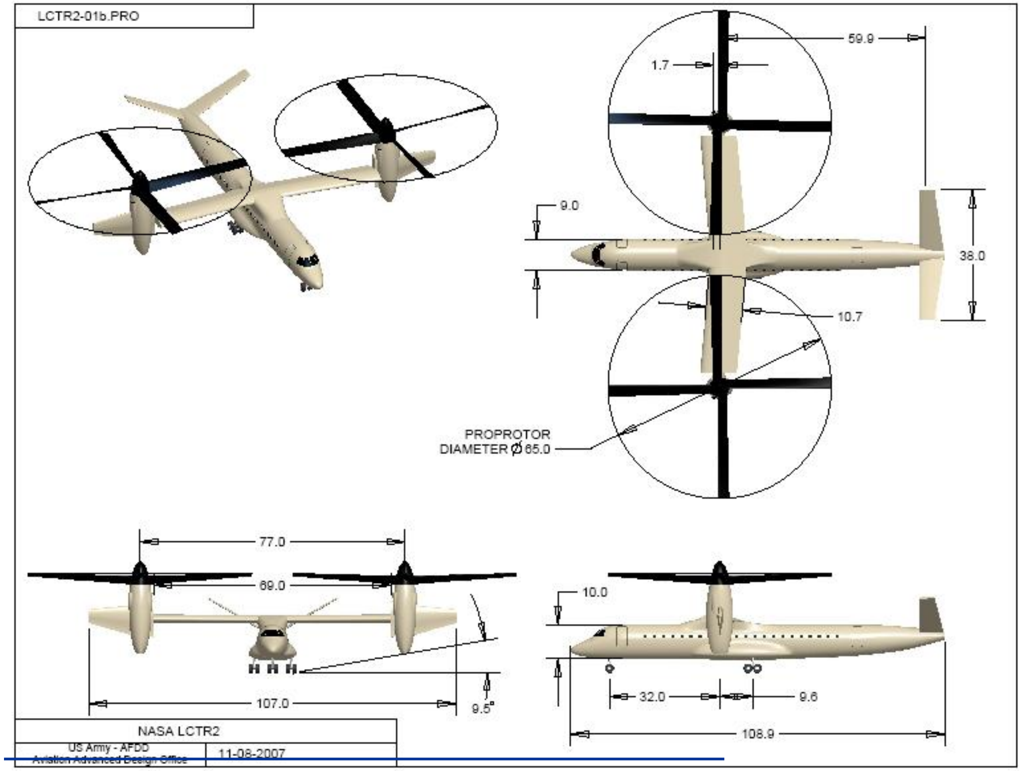
Motivation for VSPT Technology



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

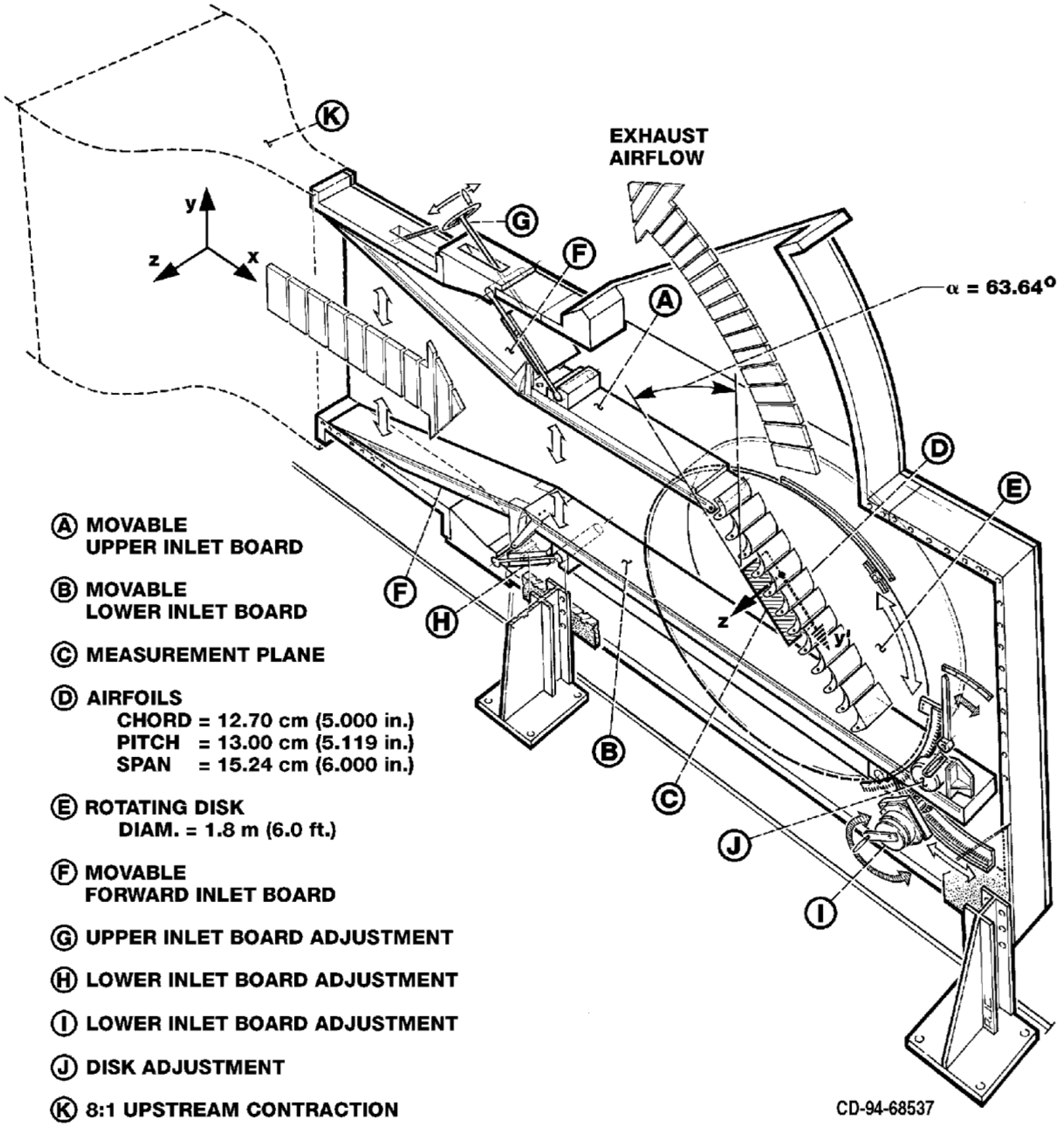
- Wide incidence variation
- Transitional Reynolds numbers

VSPT Approach

- Develop IT blade-set
- Modify cascade
- Re-baseline cascade
- Document blade performance over large Reynolds number and incidence angles variations

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

Transonic Turbine Blade Cascade



Blades:

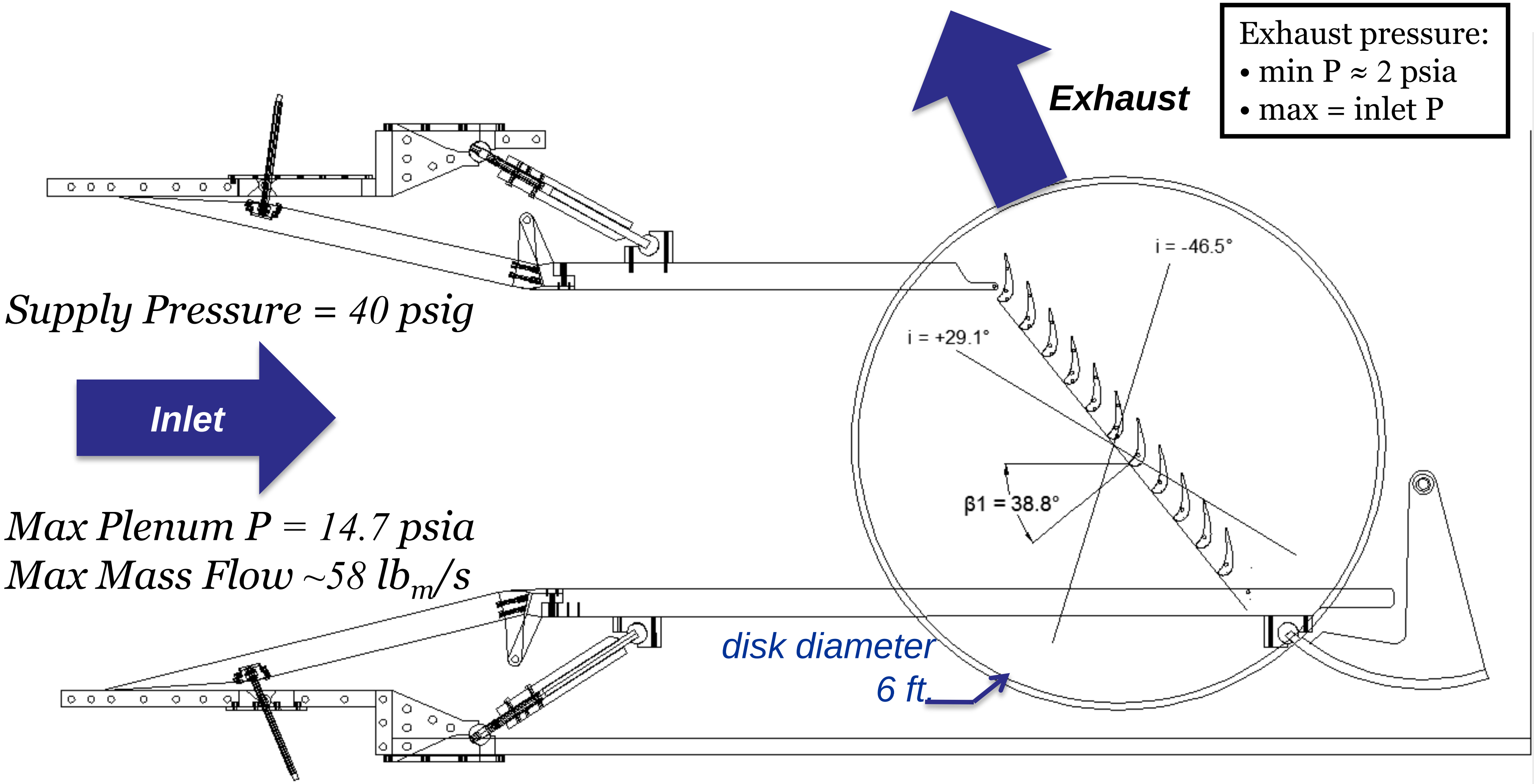
- 11 blade passages
- span = 6.000" (fixed)
- pitch = 5.119" (fixed)
- axial chord = 5.119"

Inlet:

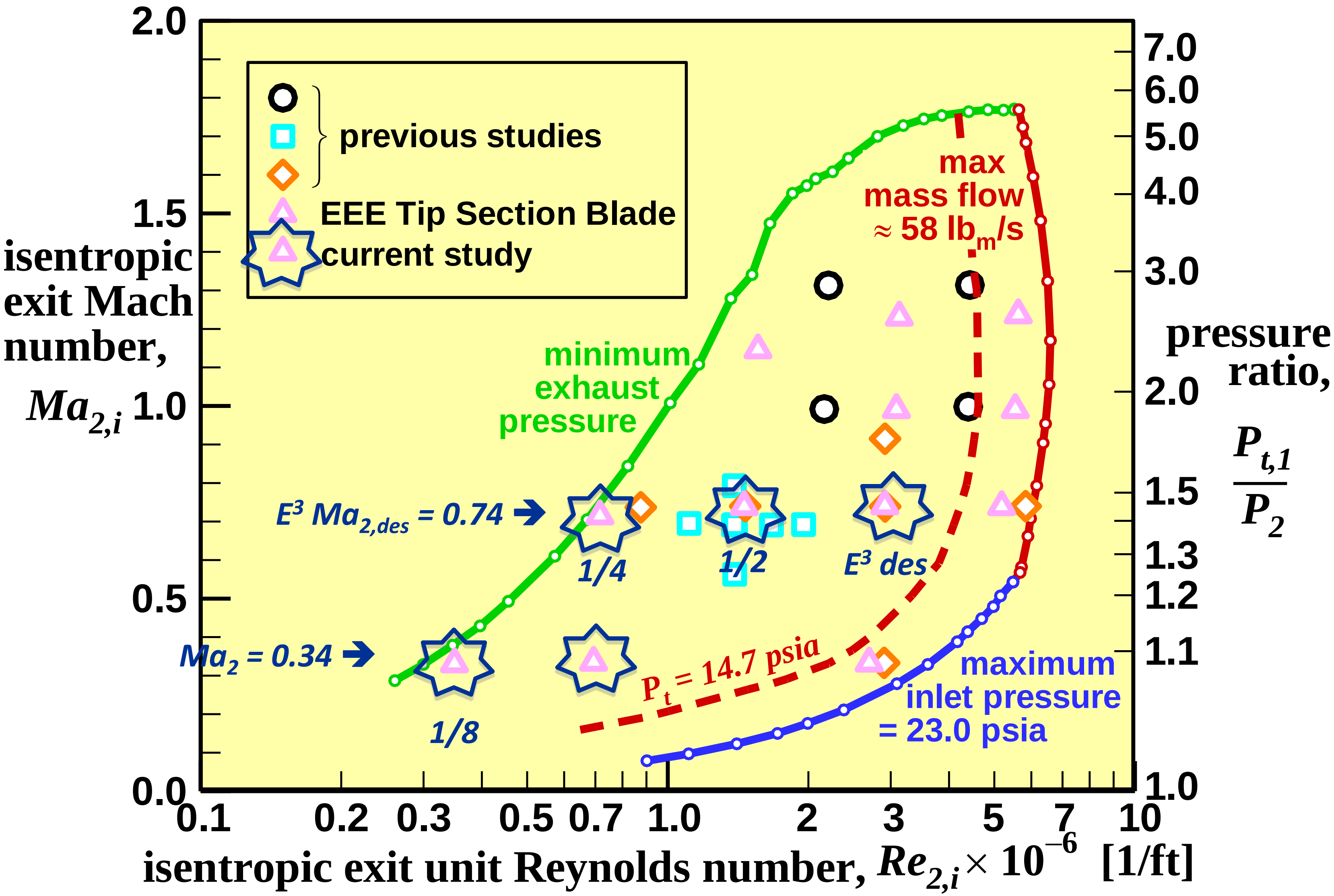
- dry, clean, ambient *T* (filtering: 98% of 0.35μm 99.9% of 2 μm)
- well-documented inlet; nominal $\delta_{in} \approx$ 1.0 inch
- various static and blown turbulence generating grids available.

Transonic Turbine Blade Cascade Facility

Current Configuration with E^3 Tip Section Blades at inlet flow angle of 38.8°

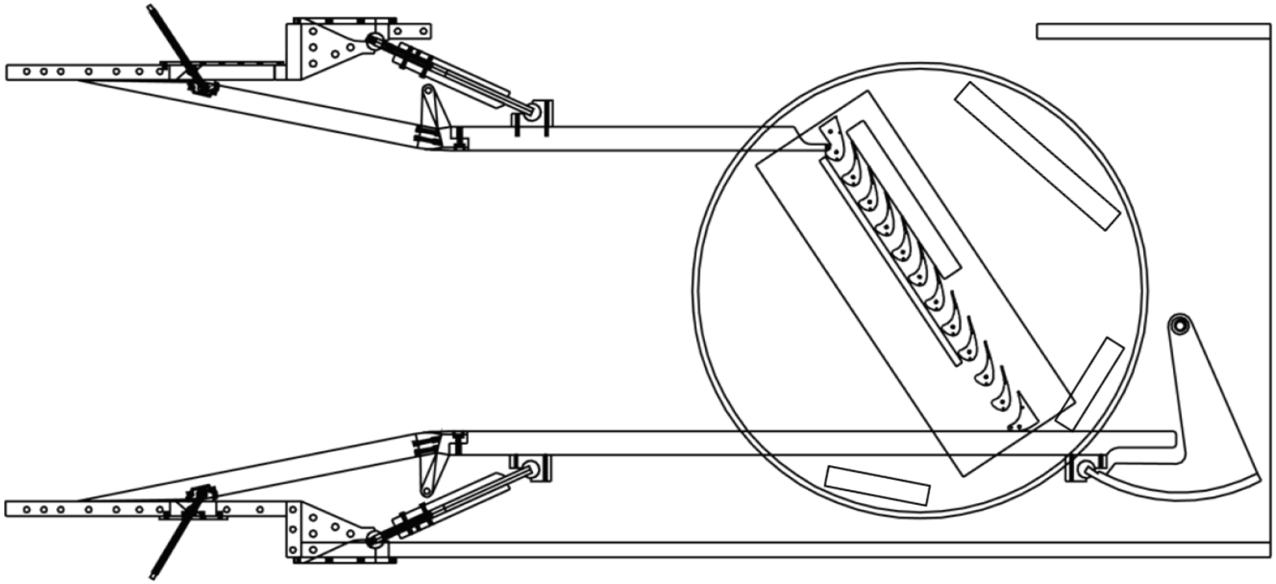


Facility Operating Envelope

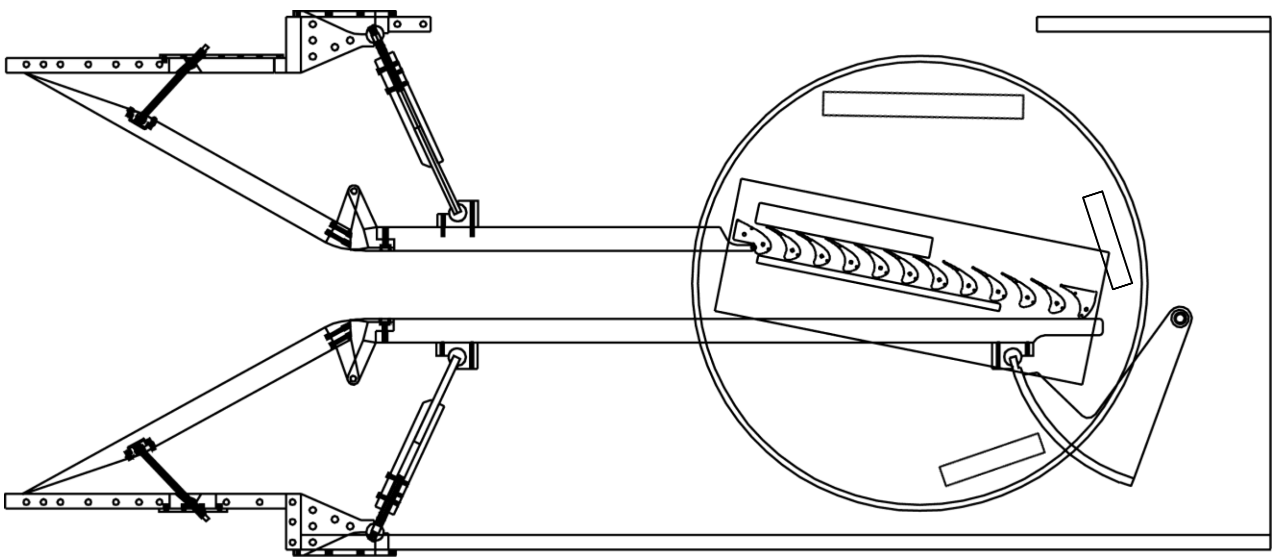


Original Facility at Min & Max Incidence Angles

minimum inlet flow angle = 33.8° from axial

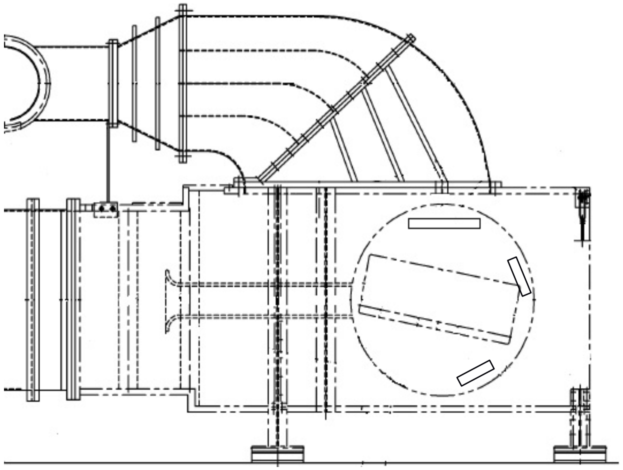


maximum inlet flow angle = 78.6° from axial



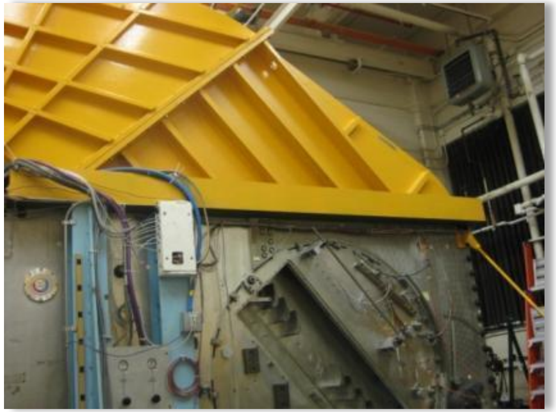
Facility Modifications

- Extended exhaust duct
- New support bars
- Discrete upper board extensions
- Added 12 exit static pressure taps
- ~ 95°inlet angle variation

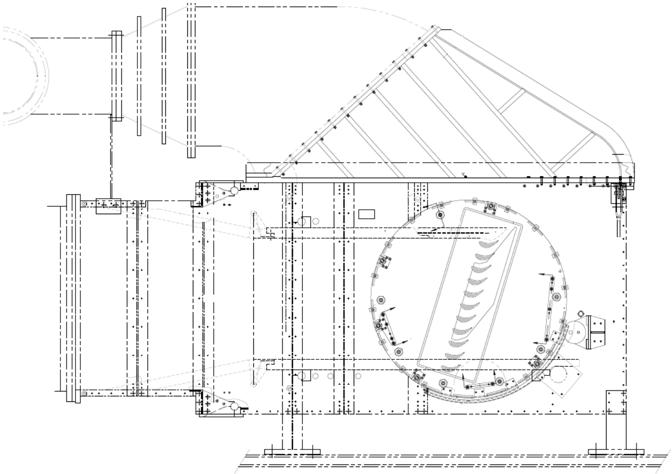


CW-22 Before Modifications

New Support Bars



New Exhaust Section



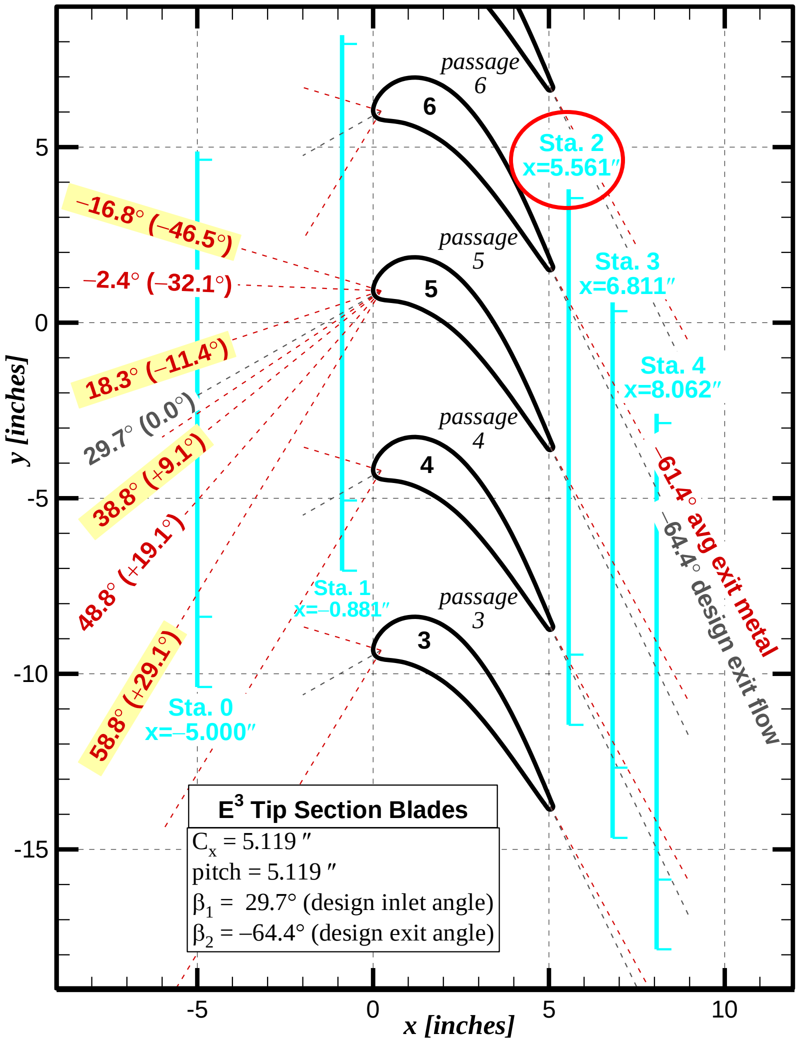
CW-22 After Modifications

Test Objectives

- Re-baseline cascade using existing geometry with previously acquired data.
- Develop initial experimental dataset that documents the trends of incidence angle and Reynolds number variations.
  - Improve understanding of effects of extreme incidence with wide Reynolds number variations
  - Generate dataset to be used for CFD code and model validation

Test Configuration

CW-22 Probe Slots with E³ Blades



- GE EEE tip section blade, $\beta_{1,des} = 29.7°$
- Seven incidence angles: +29.1° to −46.5°
- Re-baseline measurements acquired for *i* = +29.1° and *i* = +9.1°
- 5 flow conditions each

Inlet Flow Angles

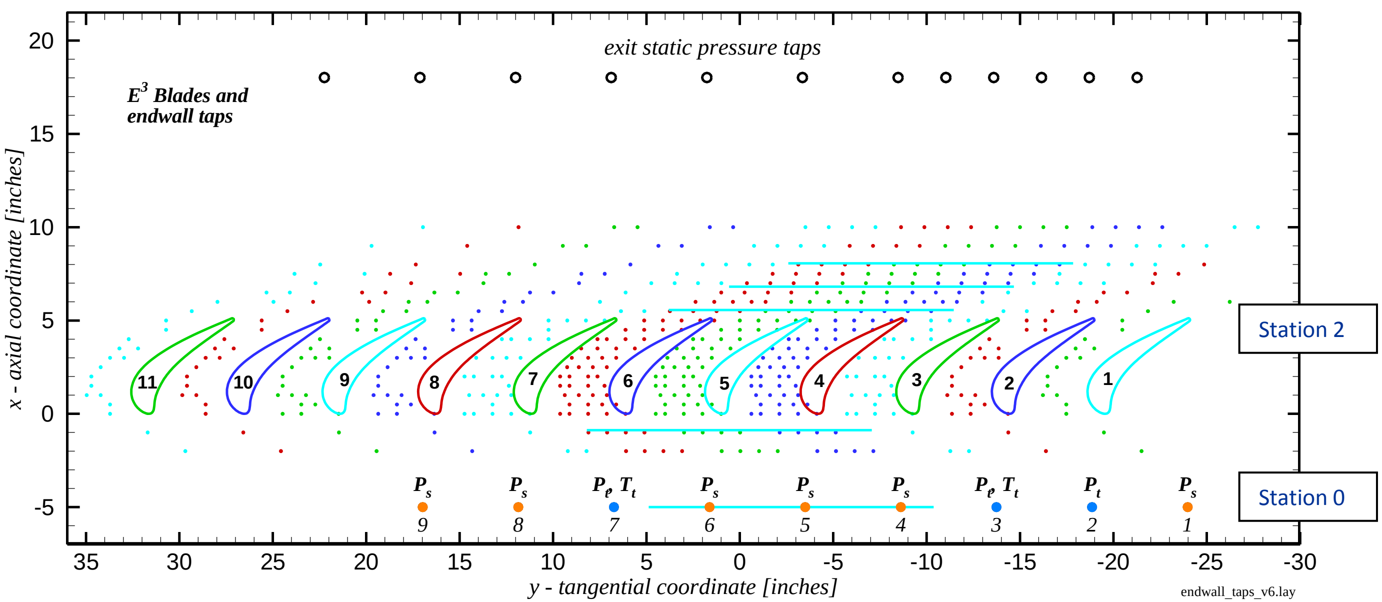
Inlet Angle β_1	Incidence Angle B1-βdesign
58.8°	29.1°
48.8°	19.1°
38.8°	9.1°
33.8°	4.1°
18.3°	-11.4°
-2.4°	-32.1°
-16.8°	-46.5°

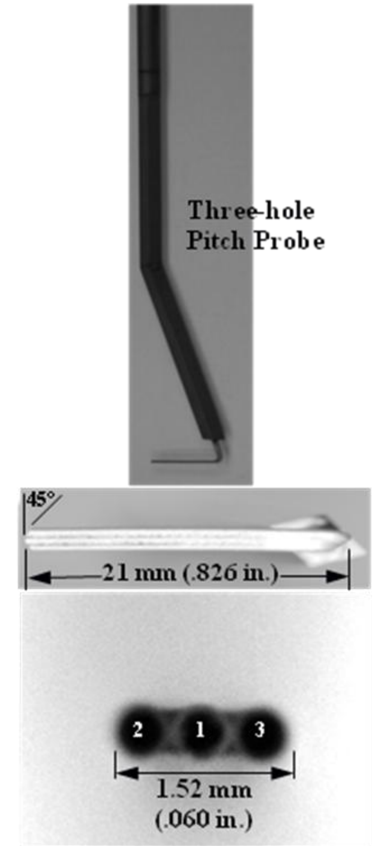
Nominal Test Conditions

Inlet Reynolds Number	Pressure Ratio	Exit Isentropic Mach Number
683,000 (Design)	1.44	0.74
341,500 (1/2 Design)	1.44	0.74
170,700 (1/4 Design)	1.44	0.74
170,700 (1/4 Design)	1.08	0.34
85,000 (1/8 Design)	1.08	0.34

Measurements

- Total pressure and flow angles measured 8.5% C_x downstream of trailing edge
- Blade and endwall static pressure measurements
- 12 new exit static taps located 3.5 axial chords downstream
- Inlet P_t, P_s, and T_t measured 1.0 C_x upstream



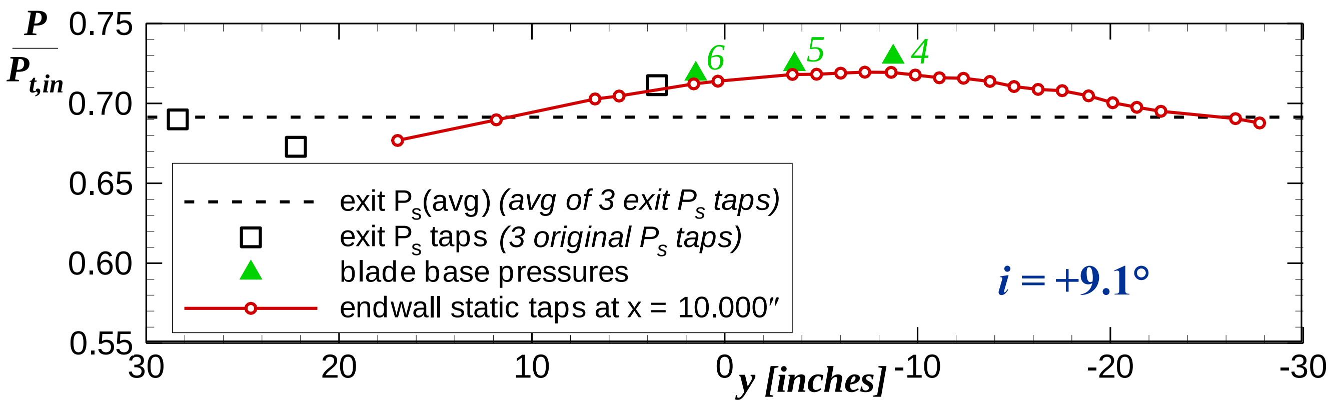


3-Hole Probe Details

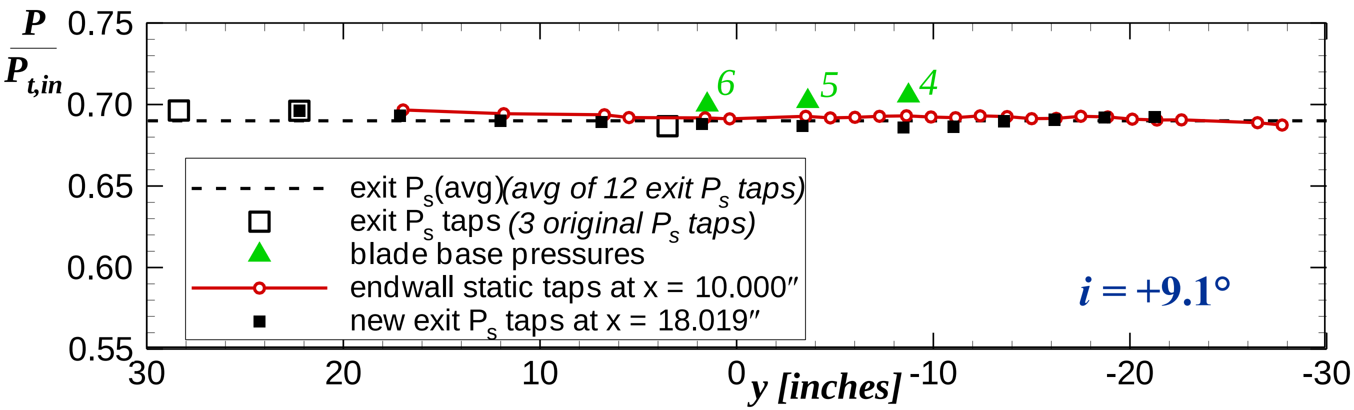
RE-BASELINE MEASUREMENTS

Exit Static Pressure Measurements

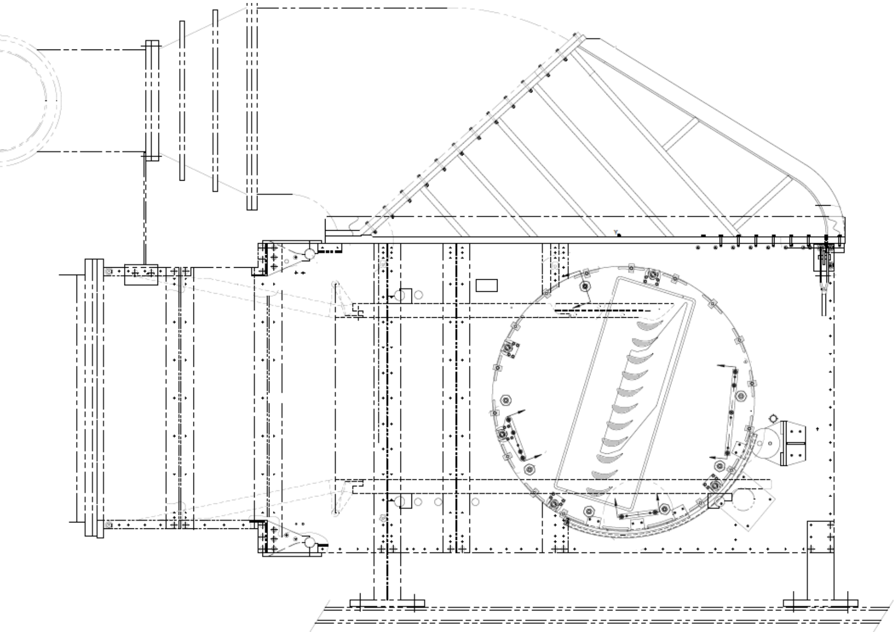
Original Exhaust Configuration



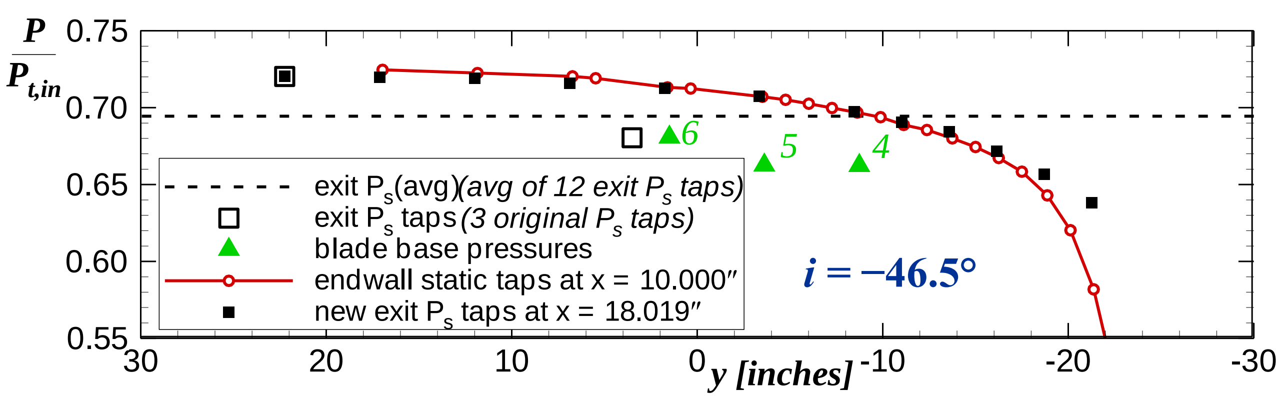
New Exhaust Configuration



Exit Static Pressure Measurements

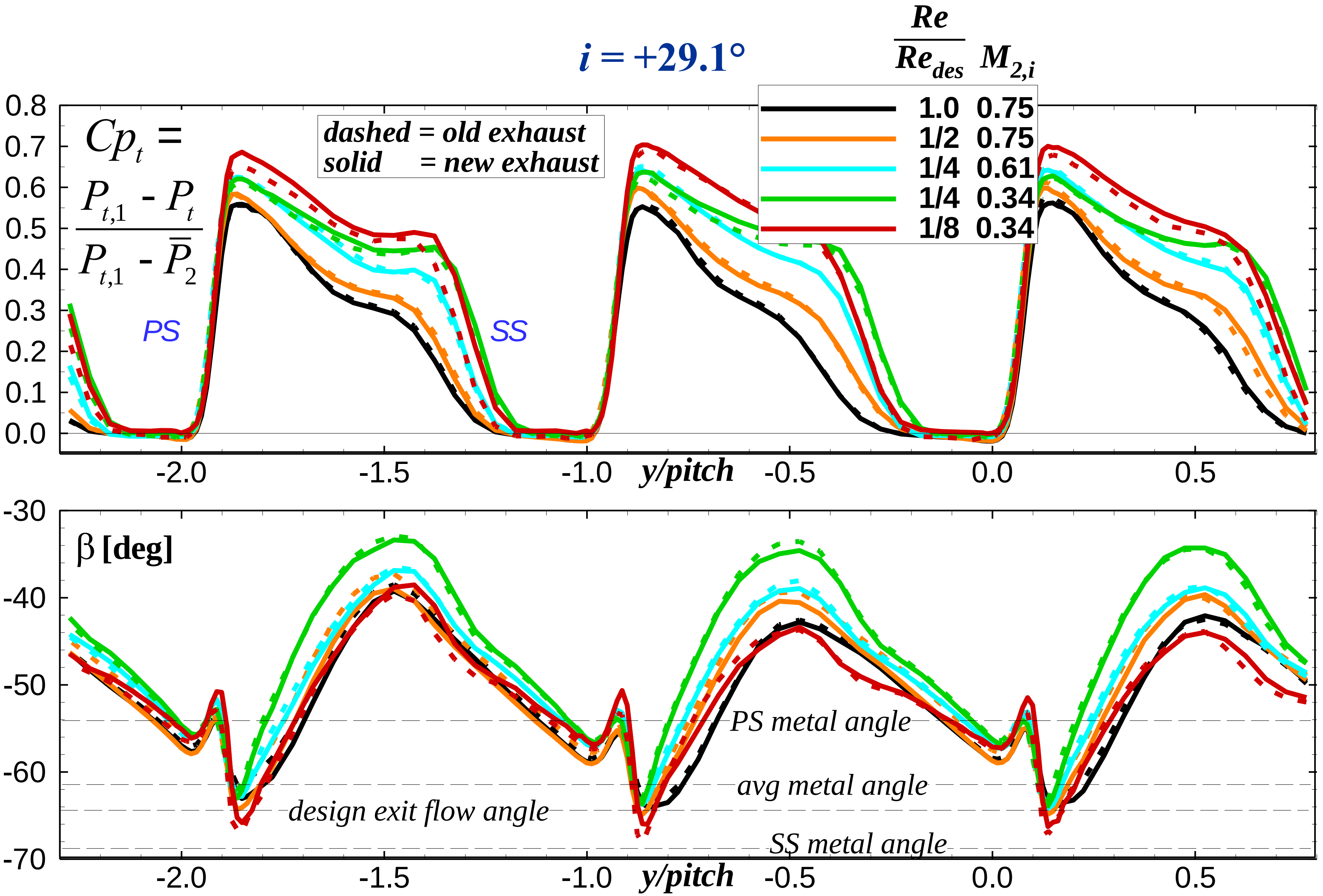


- Non-uniform exit static pressures at negative incidence angle.
- Blade row and back wall establish a converging exhaust section.
- Flow field is accelerated creating a negative pressure gradient.

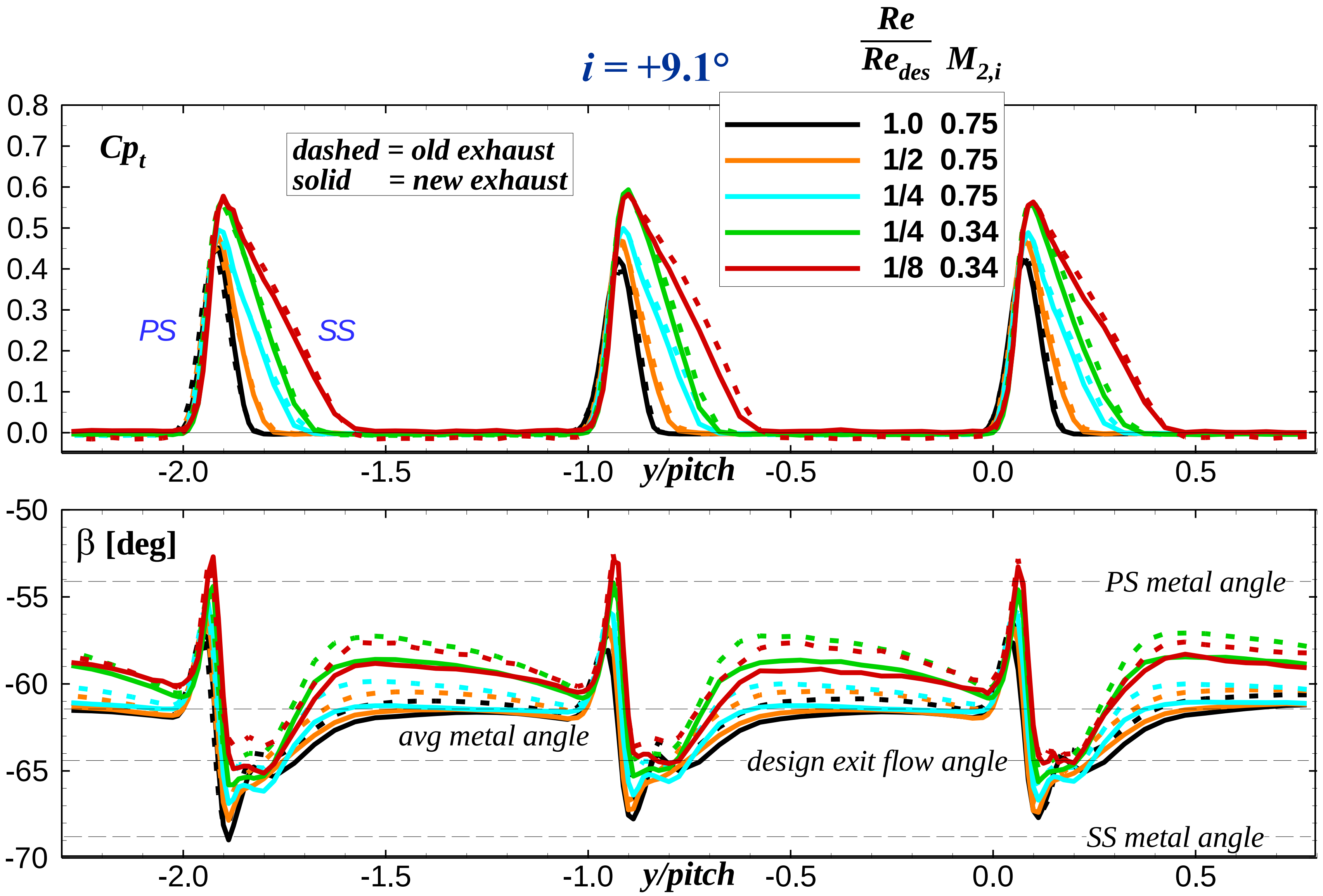


IMPACT OF INCIDENCE ANGLE AND REYNOLDS NUMBER ON EXIT SURVEYS

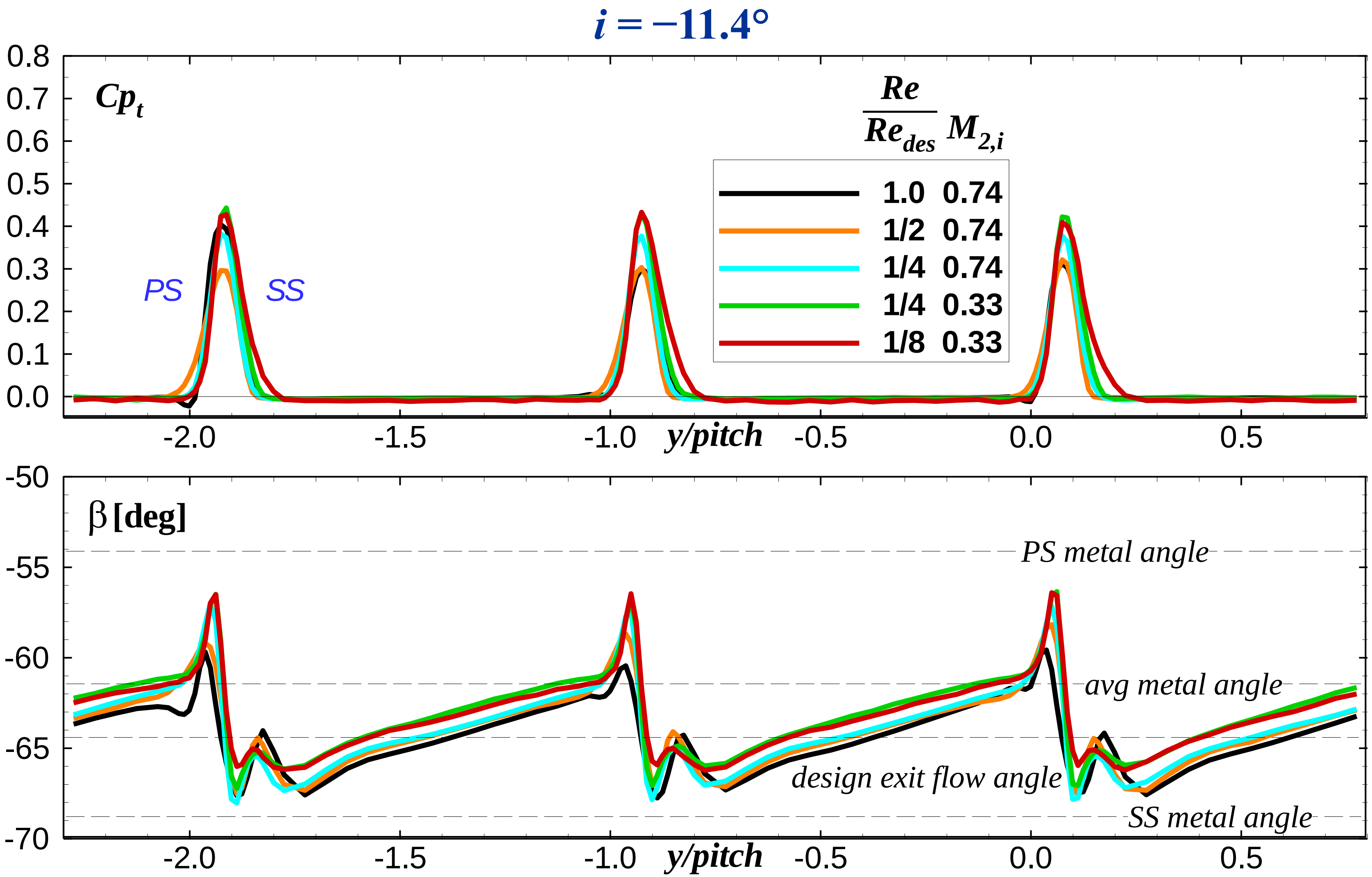
Effects of Reynolds Number and Pressure Ratio



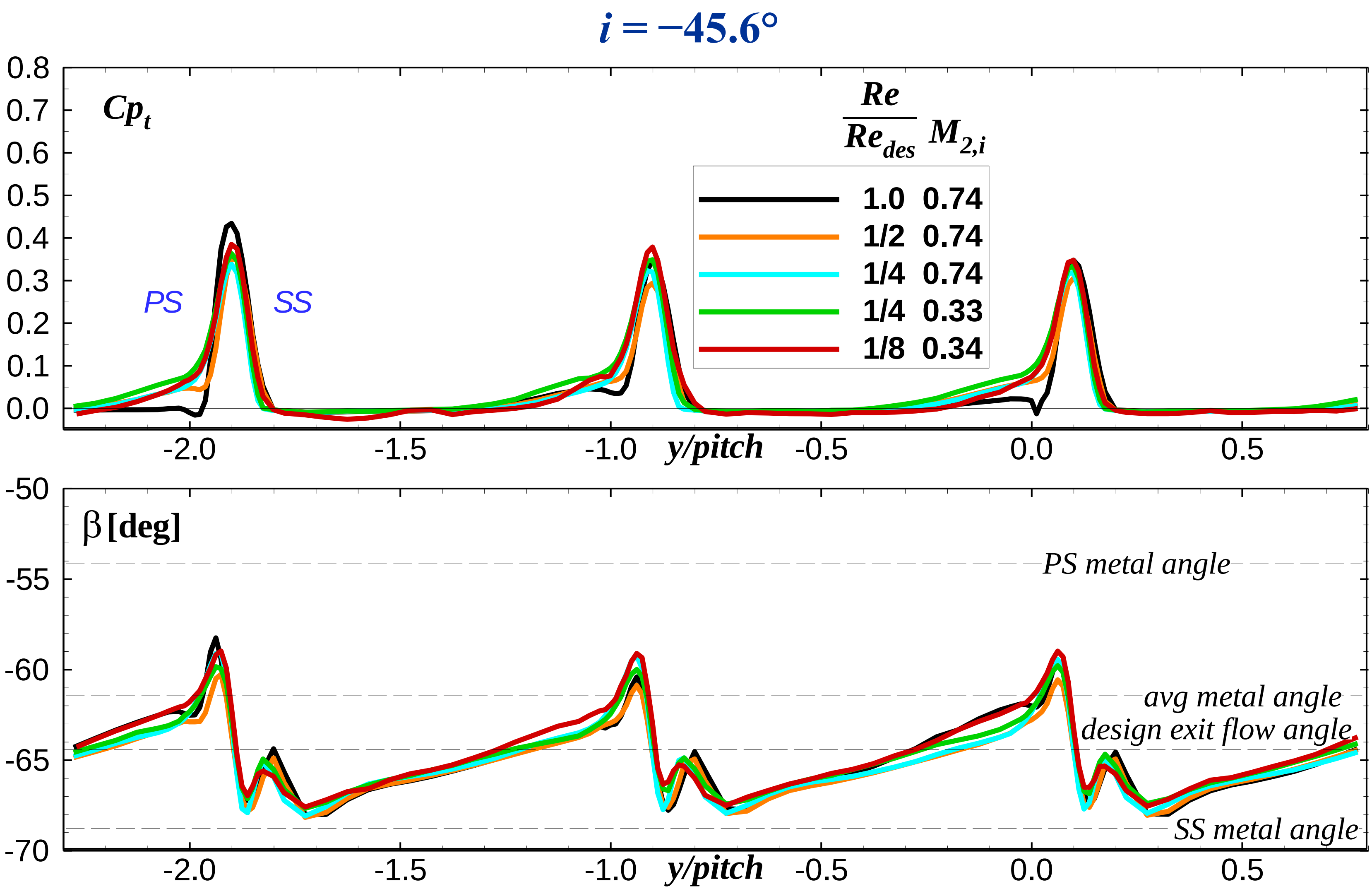
Effects of Reynolds Number and Pressure Ratio



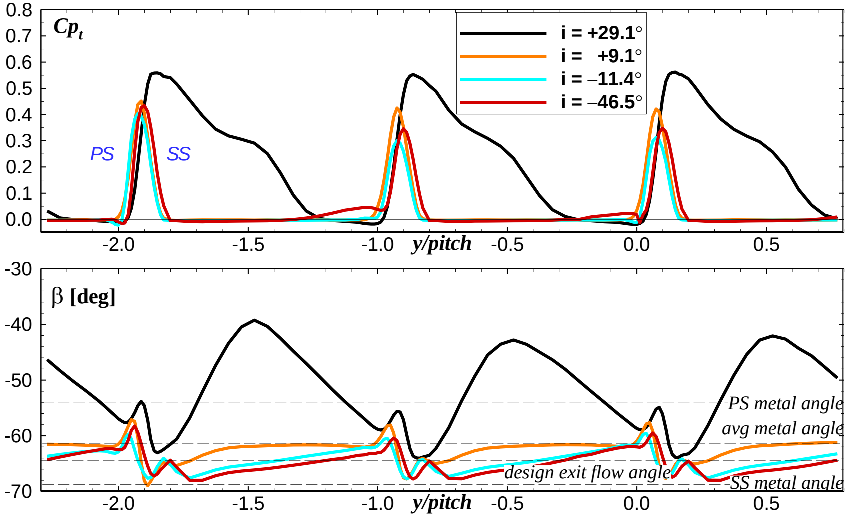
Effects of Reynolds Number and Pressure Ratio



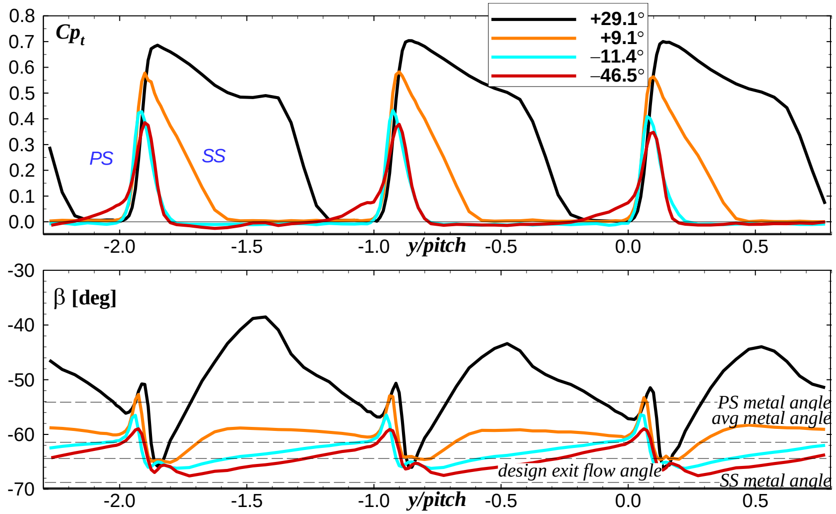
Effects of Reynolds Number and Pressure Ratio



Effects of Inlet Flow Angle



$Re_{cx,2}$=683,000 (design)
M_2=0.74

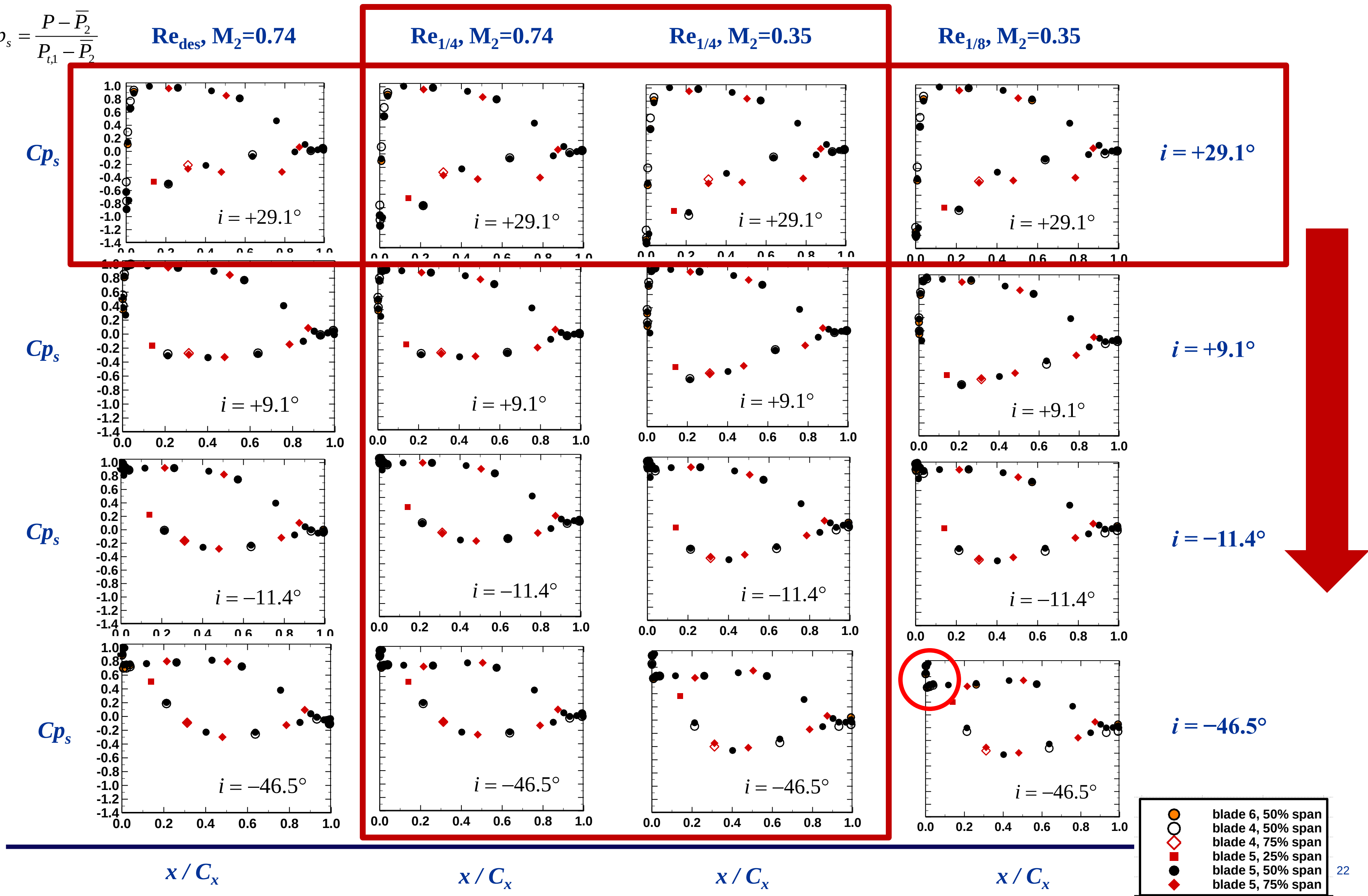


$Re_{cx,2}$=85,000 (1/8 design)
M_2=0.35

IMPACT OF INCIDENCE ANGLE AND REYNOLDS NUMBER ON BLADE LOADING

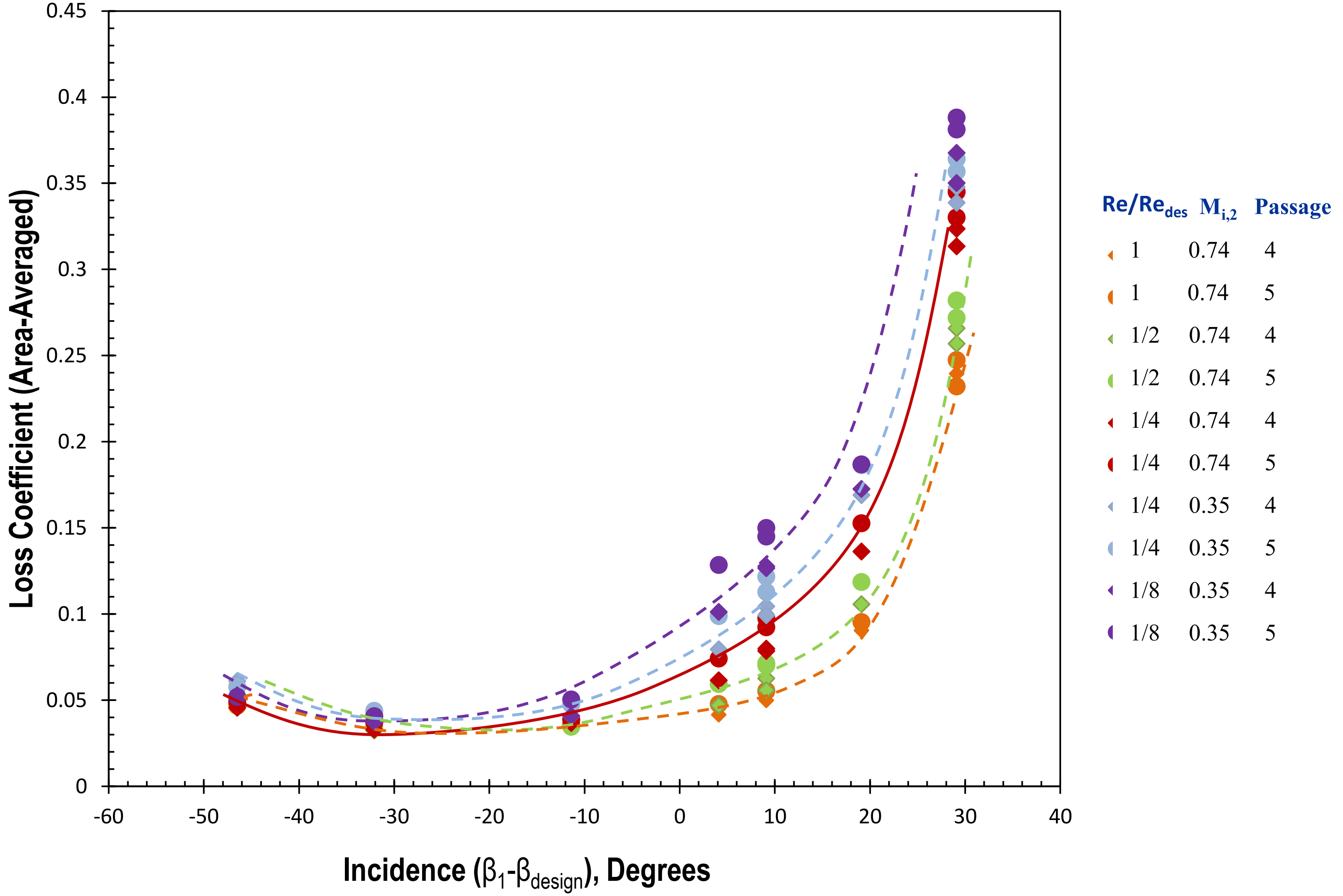
Blade Loadings

$$Cp_s = \frac{P - \overline{P}_2}{P_{t,1} - \overline{P}_2}$$



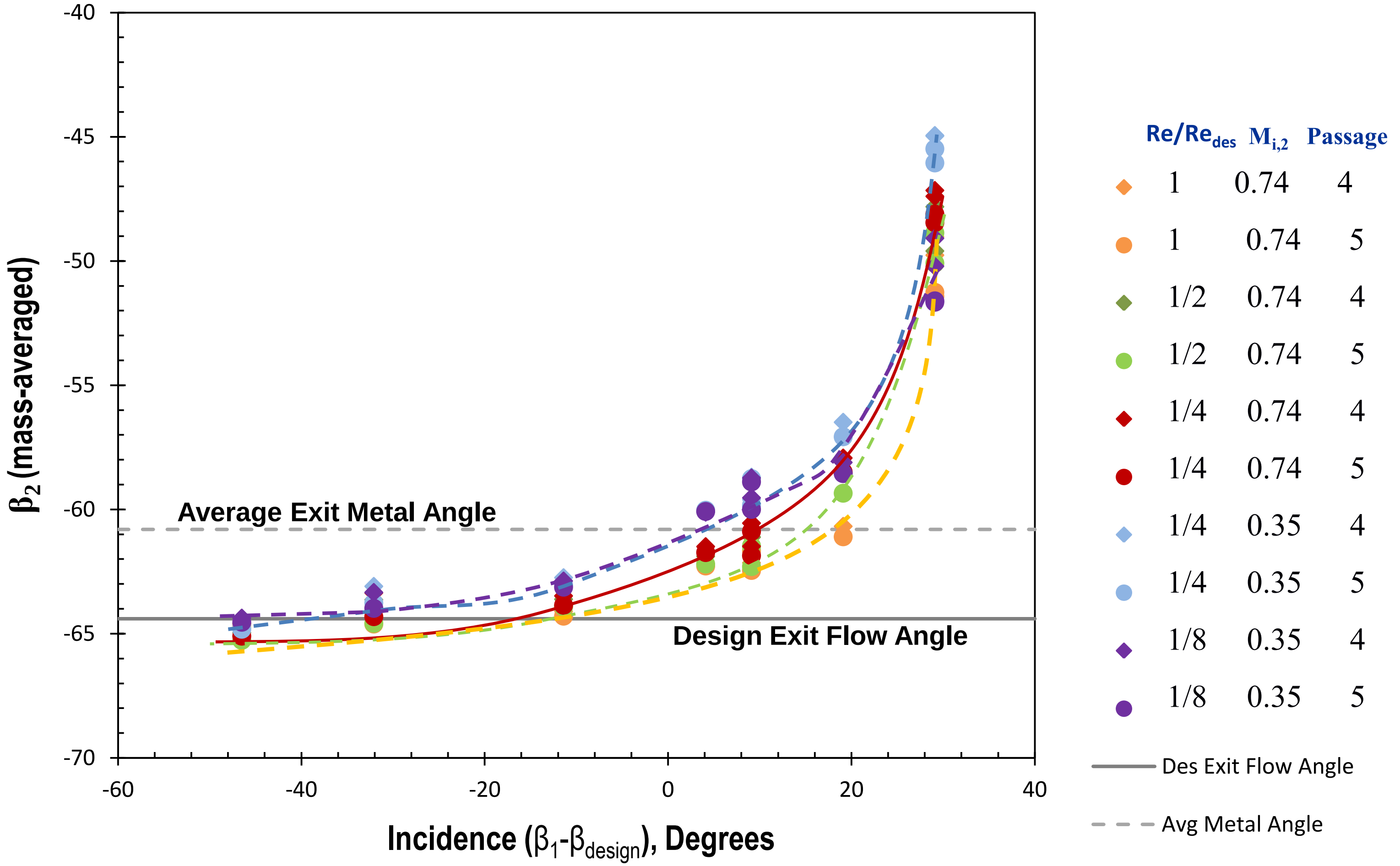
IMPACT OF INCIDENCE ANGLE AND REYNOLDS NUMBER ON INTEGRATED LOSSES AND FLOW EXIT ANGLES

Loss Bucket

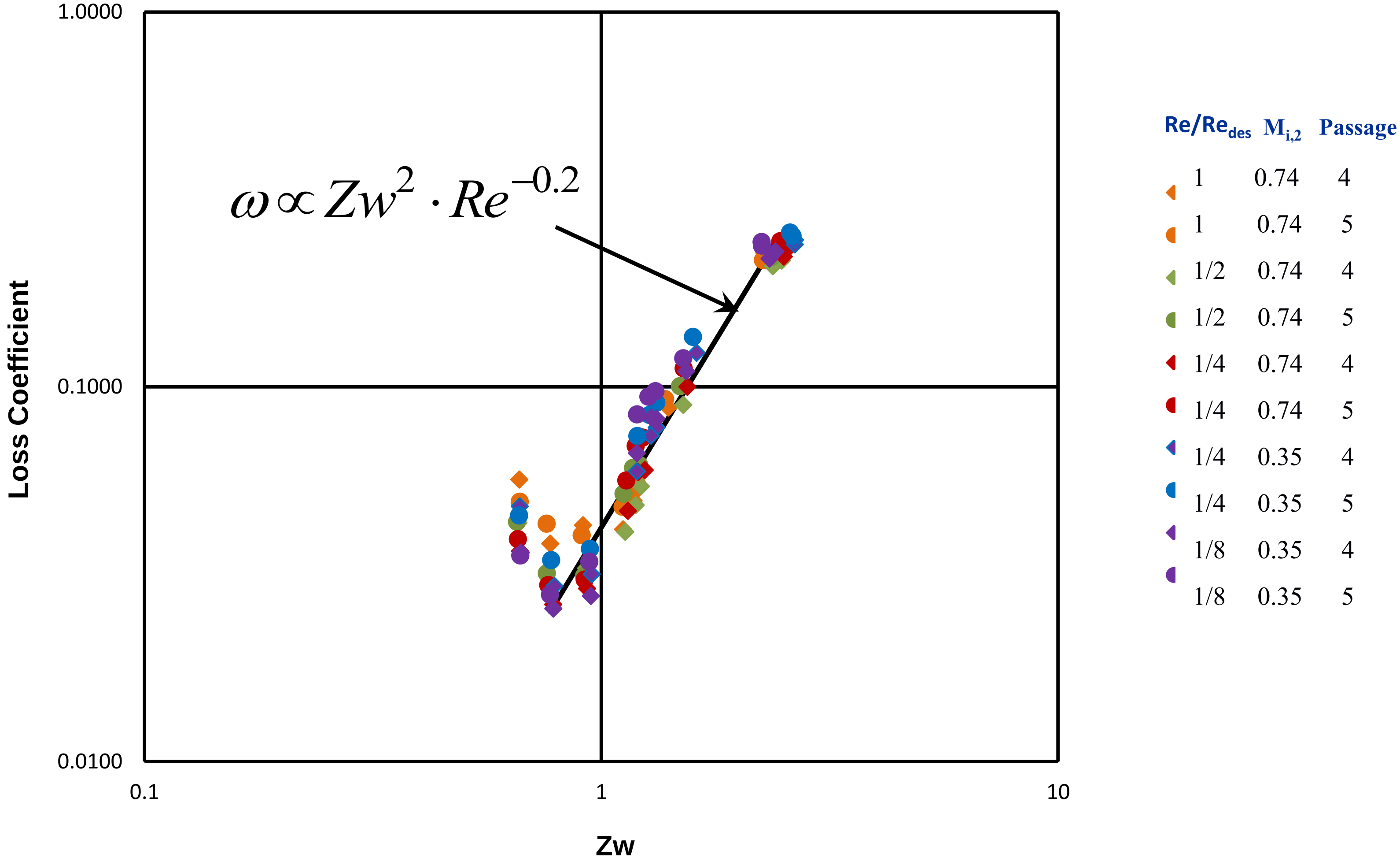


Loss Coefficient (Area-Averaged)
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-60
-50
-40
-30
-20
-10
0
10
20
30
40
Incidence (β1-βdesign), Degrees
Re/Redes Mi,2 Passage
1 0.74 4
1 0.74 5
1/2 0.74 4
1/2 0.74 5
1/4 0.74 4
1/4 0.74 5
1/4 0.35 4
1/4 0.35 5
1/8 0.35 4
1/8 0.35 5

Exit Flow Angle



Loss as a Function of Zweifel Coefficient



Conclusions

- Successful modifications of the facility.
- Facility better suited for large incidence range measurements.
- Detailed exit total pressures, flow angles, and blade loading were documented over a wide range of incidence angles and flow conditions.
- Data show good repeatability, periodicity, and consistency with scaling laws.
- Loss levels decrease with negative incidence and increase with decreasing Reynolds number – narrower loss bucket at lower Reynolds number
- Valuable and challenging data set for CFD Code Validation.

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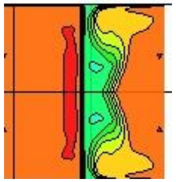
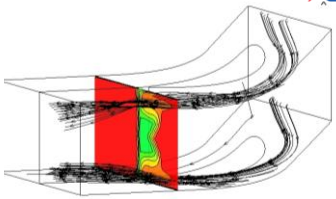
BACKUP SLIDES

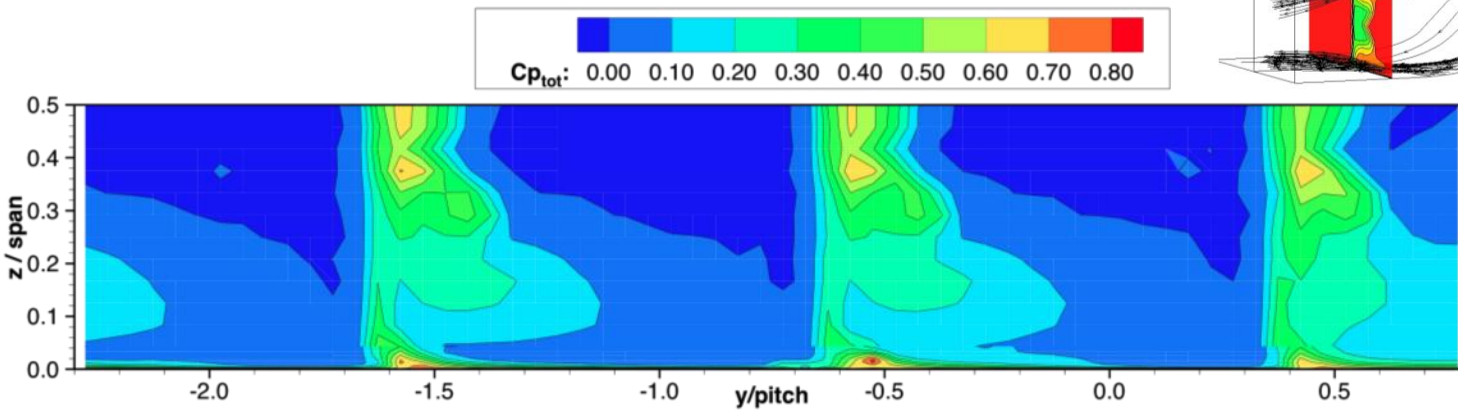
3-D flow field measurements

3-D RANS



Total pressure coefficient



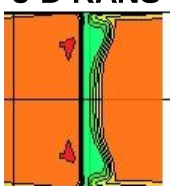


5-hole probe

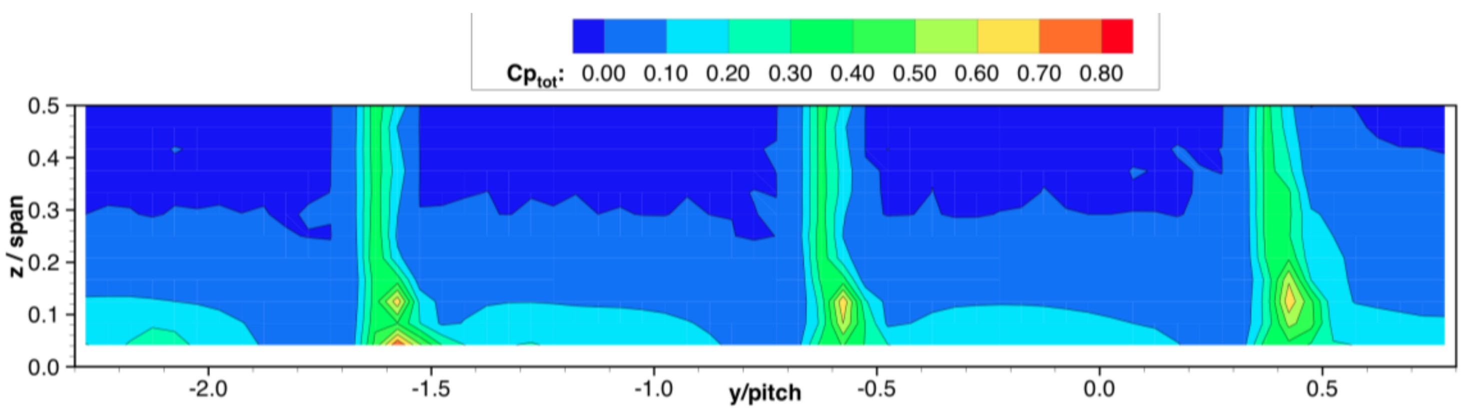
3-hole probe

$Re_{Cx,2}$ = 530 k, M_2 = 0.72, β_1 = 40.0º (*N** 54%, cruise), *i* =+5.8º

3-D RANS



Total pressure coefficient



$Re_{cx,2}$ = 530 k, M_2 = 0.67, β_1 = -2.5 (*N** 100%, takeoff) *i* = -36.7º