Simulation of VSPT Experimental Cascade under High and Low Free-Stream Turbulence Conditions

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Motivation

- A key goal of NASA's **Rotary Wing (RW)** project is to ***enhance use of civil rotorcraft to relieve airport congestion and increase capacity.***

- A concept advocated is use of **tilt rotor aircraft** for vertical takeoff and landing.
- For fuel efficiency, the main-rotor speed needs to vary from 100% at takeoff to 55% at cruise.
- To avoid the added weight and complexity of transmission a variable speed *power turbine* **(VSPT)** can be used with a fixed gear ratio transmission.
- Such variations in the shaft speed of the VSPT lead to a wide range of incidence.

Conditions of VSPT

- Flow in the power turbine is characterized by:
  - – Low Reynolds number < 100,000 (Re_{Cx2})
  - – High turbulence intensity > (6%)
  - – Unsteadiness- Multi-Stage
  - – Large excursions from optimal incidence > 60 degrees
- Analysis tools are needed to handle physics of the VSPT.
- *A need for models capable of predicting transition and responding to separation has been identified.*

Our Earlier Work

- **Selected and implemented** transition/ turbulence model in our codes.
- **Validated** using *available three-dimensional blade heat transfer data at high turbulence levels, indicating transition.*
- Specifically, "GE2" blade data from earlier work of Giel et al. (GT2003-38839)

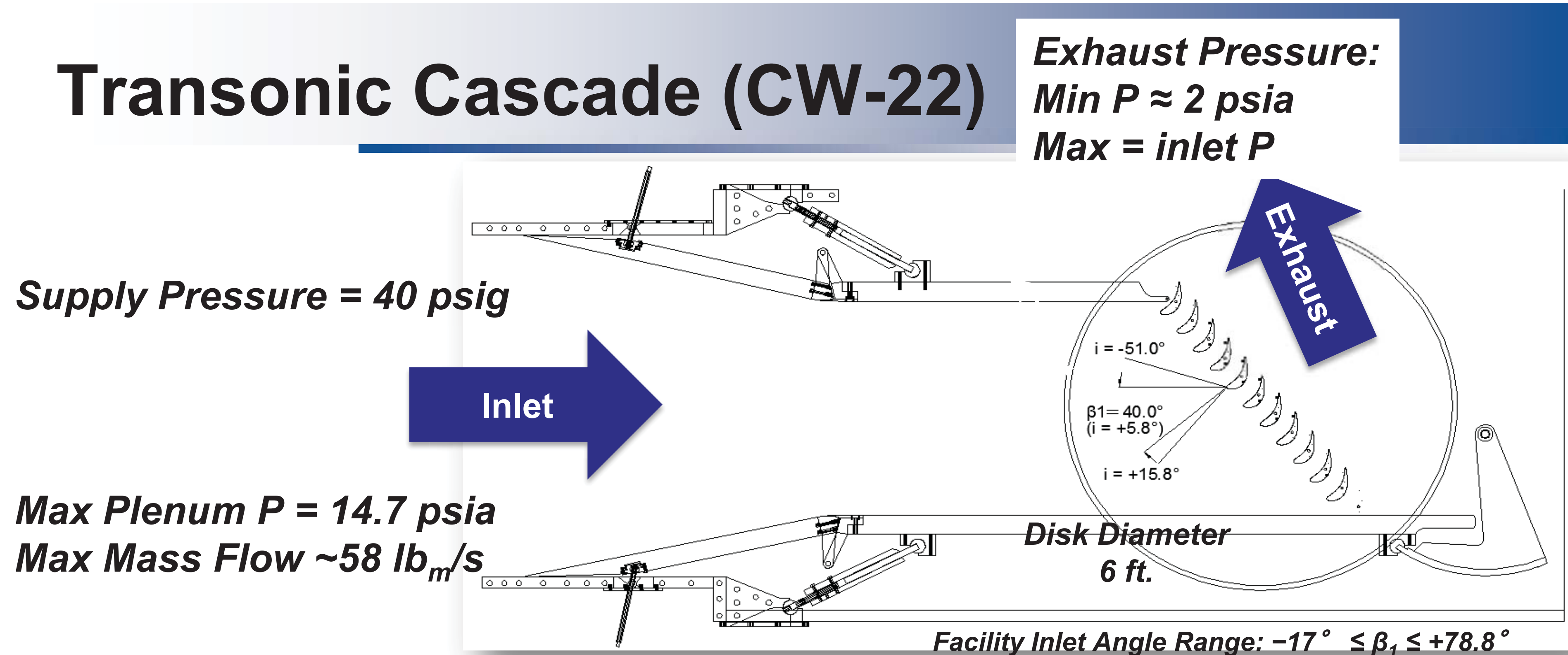
Present Work

- NASA has developed notional VSPT blade-set through previous study contract with Rolls-Royce.

- NASA has documented blade performance over wide incidence angle range at mission-relevant Reynolds numbers and Mach numbers.

- We need **To Validate** CFD tools for effect of incidence using NASA data from the notional blade.

Transonic Cascade (CW-22)

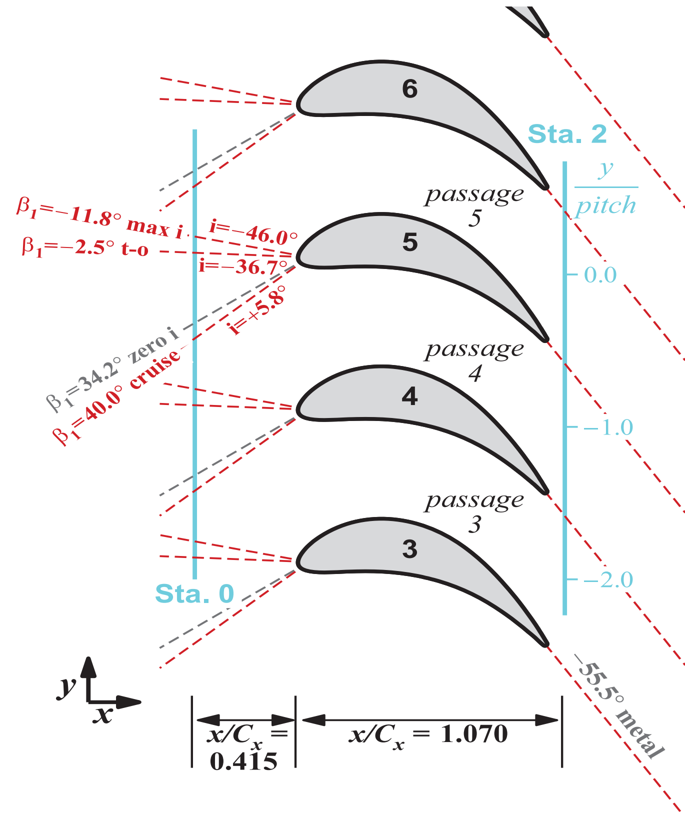


- Data were obtained in NASA-GRC's Transonic Turbine Blade Cascade CW-22
- Large-scale, continuous running facility capable of wide range: Re, M, Tu with adjustable inlet angle.
- Blade/Tip/Endwall aero and heat transfer measurements.

Test Blade

Midspan section of VSPT second stage rotor: Dimensions and measurement stations.

Geometry	Value, mm (in)
Axial Chord, C_x	180.57 mm (7.109”)
True Chord	194.44 mm (7.655”)
Pitch, S	130.00 mm (5.119”)
Span, H	152.40 mm (6.000”)
Throat Diameter	72.85 mm (2.868”)
Leading Edge Dia.	15.16 mm (0.597”)
Trailing Edge Dia.	3.30 mm (0.130”)
Stagger Angle	20.35°
Inlet Metal Angle	34.2°
Uncovered Turning	19.47°
Exit Metal Angle	-55.54°



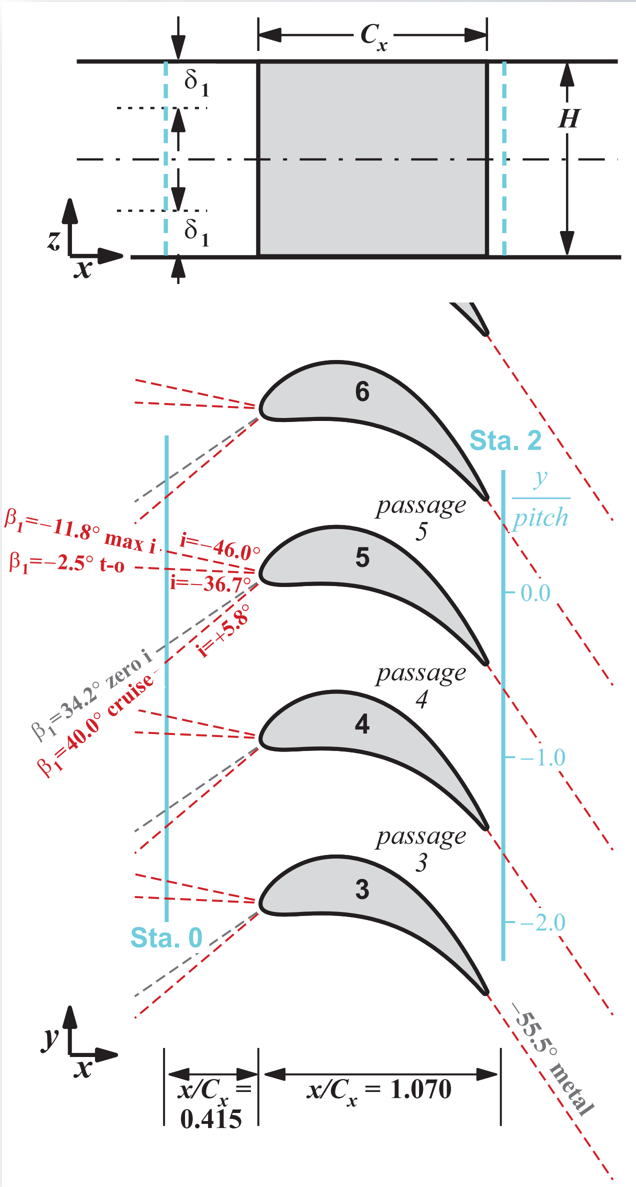
Experimental Cases for Num. Validation

- A wide Range of variables at various *Reynolds numbers*, *Mach numbers* and *incidence angles* and two *turbulence levels* were measured. (Full data was presented **earlier in this session**)

- **Two cases representing *cruise* and *take off* were documented in detail and are used for this exercise.**

- **3d** Blade surface pressure, wake total pressure and blade exit angle distributions were measured.

Test Configuration



- VSPT midspan section blade, $\beta_{1,des}$= 34.2°
- Ten incidence angles: +15.8° to −51.0°
- 5 flow conditions each
- Inlet δ range: 1.16 – 1.69 inches for Low Tu
- Inlet δ range: 0.58 – 0.86 inches for High Tu
- Free-Stream Turbulence, Two conditions:
  - **One with no turbulence grid installed**
  - **One with "blown grid" upstream (*Tu* = 0.24% - 12.0%)**

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

Choice of Transition Model (Our Earlier Work)

- Surveyed the literature for suitable models.
- Eliminated models which use integral parameters (non-local) such as δ, Θ or any parameter that requires surveying the boundary layer profiles which would limit applicability to *3d* flows.
- Identified k_L-k-ω models of Walters and Leylek as candidates (3 equation model.)
- Chose this model based on:
  - Ease and generality of use
  - Recommendations in the literature
  - Tests with transitional heat transfer blade surface data

Application to VSPT

- At low turbulence, WL model results were surprising! Did not agree with data.
- Identified improved k_L-k-ω model of Walters and Cokljat (3 equation model.)
- Results to compare with WL model at high and low turbulence models.

CFD Tool, Glenn-HT

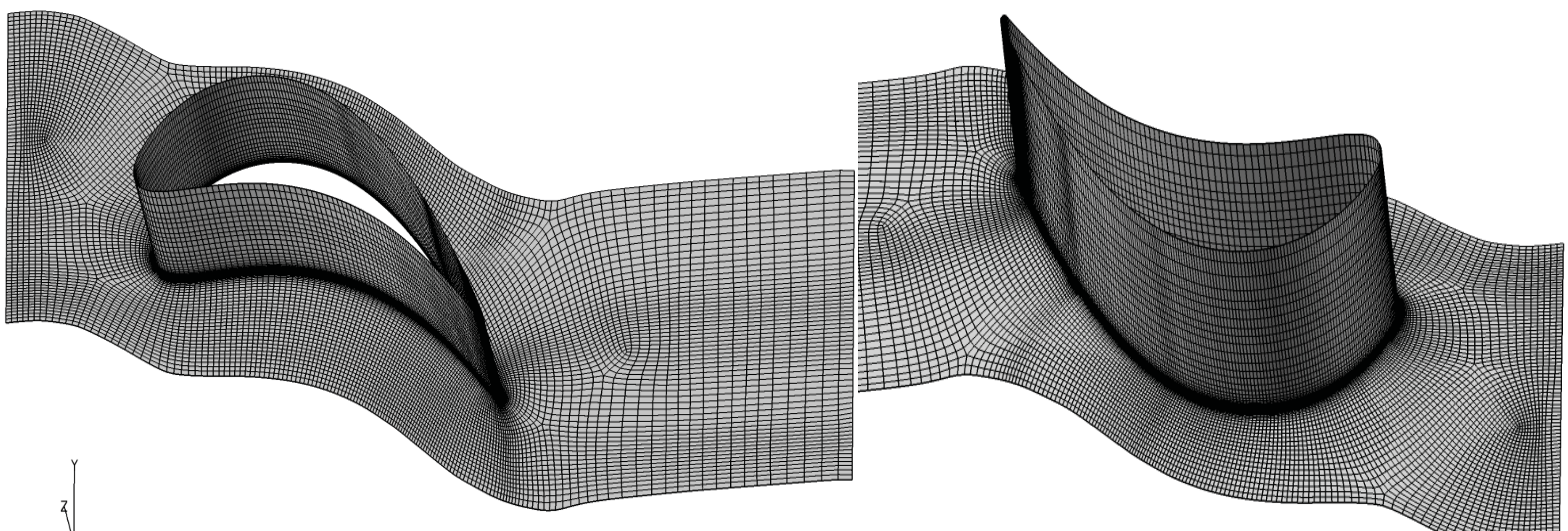
- Full compressible Reynolds-Averaged Navier-Stokes Formulation and Conjugate Heat Transfer
- Multi-block structured grids
- Finite Volume formulation
- Second order central differencing, 4^{th} order artificial dissipation with eigenvalue scaling or,
- Second order upwind schemes, Hunyh, AUSM
- Multi-stage explicit Runge-Kutta time integration with local time stepping
- Multi-grid convergence acceleration
- Dual-Time-Stepping for unsteady simulations
- Parallel processing via MPI

3-D Grids

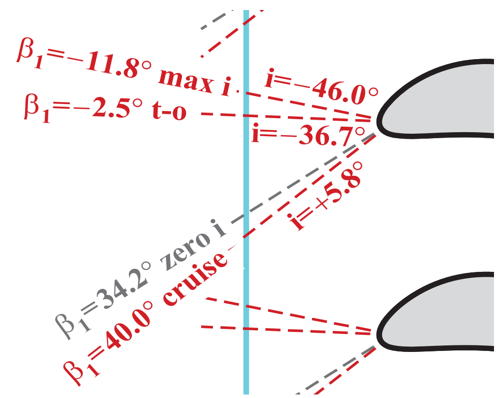
For this work a fine grid was generated (half-span):

- Grid ~ $7x10^6$ nodes and a stretching ratio of 1.1 away from the walls with y+<1

- A coarse grid was also used for startup and for ensuring grid convergence by coarsening Grid by a factor of 2 in each index direction.



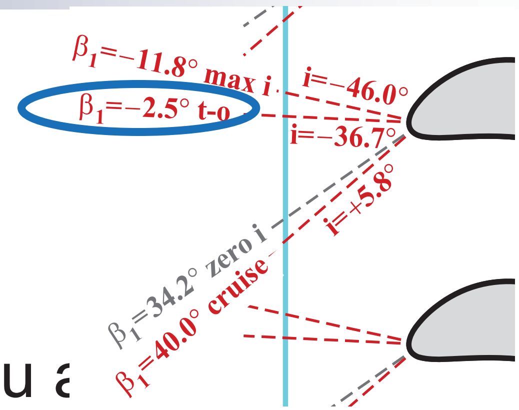
Cruise Condition



- Blade is operated at i =+5.8° as would occur due to slowing down of rotation
- Reynolds number=5.4e5
- Tu_{in} = 0.3%, 12.0%
- Turbulence length scale
  - computed from matching *Tu* at the two stations.
- δ_{in} at the end walls=25% Span at Low Tu, leads to highly 3d flow. At high Tu 12.0% Span

Inlet Angle β_1	Exit Re_{Cx}	Press. Ratio	Exit M_{IS}	δ_{inlet} [inch]	Tu_{in}% at -1.5 C_x	Tu_{in}% at -0.5 Cx
40.0°	536,000	1.412	0.72	1.44	0.4	0.3
40.0°	536,000	1.412	0.72	0.7	19	12

Takeoff Conditions



- Blade incidence is *i*=-36.7°
- Nominal Reynolds number=5.3e5.
- *Tu* =0.3%, 8.5%
- δ_{in} at the endwalls=25% span at Low Tu a

12% span at high Tu.

- Turbulence length computed from matching *Tu* at the two stations.

Inlet Angle β_1	Nominal Exit Re_{Cx}	Press. Ratio	Exit M_{IS}	δ_{inlet} [inch]	Tu_{in}% at -1.5 C_x	Tu_{in}% at -0.5 Cx
-2.5°	532,000	1.348	0.67	1.50	0.4*	0.3*
-2.5°	532,000	1.348	0.67	0.75	15.0	8.5

Turbulence Length Scale

In general:

- Turbulence length scale is input at the inflow boundary.
- Value is usually guessed based on heuristic arguments,

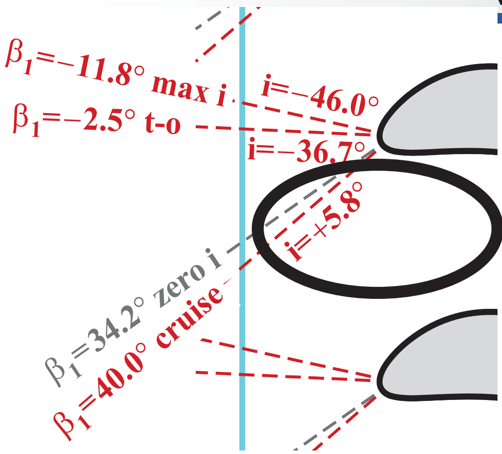
-- examples include, size of turbulence generator bar, span of the passage or the hydraulic diameter of the passage, …

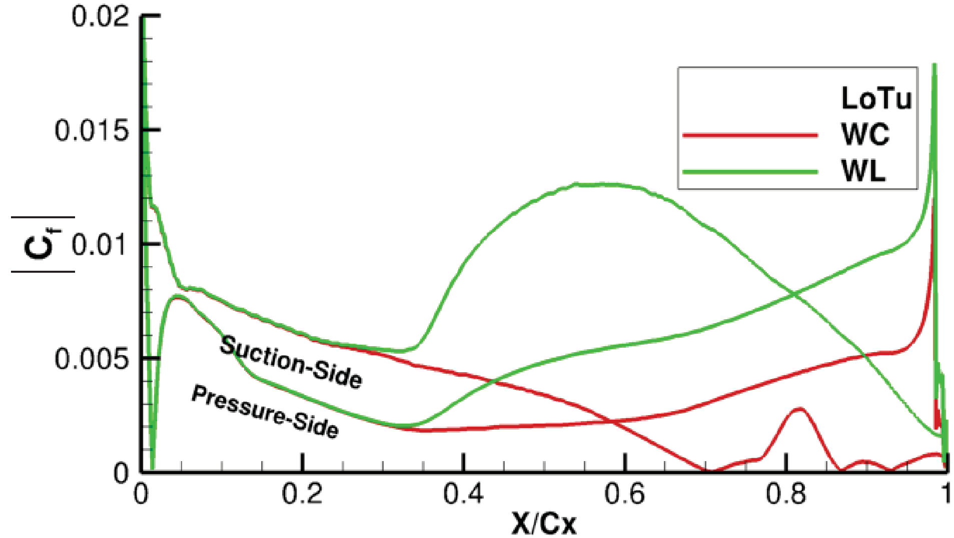
- In this case Tu was measured at X=-1.50*Cx and at -0.5*Cx.
- By matching the decay of turbulence, length scale was computed at the inlet to the computational domain at -0.5*Cx .

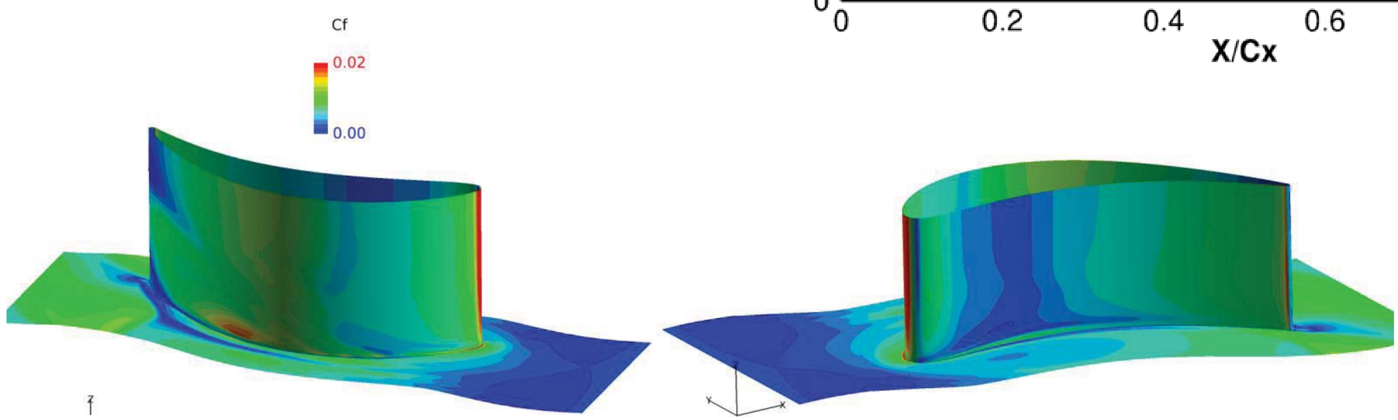
Turbulence Length Scale- Issues

- Issues arise when FST (12%) is present and the decay is to be matched using large values of length scale.
- The problem arises due to excessive entropy generation in the flow at high turbulence intensities.
- For one of the conditions, length scale was dialled down to avoid this excessive loss while the transition location held steady.
- Experiments (Mahallati et al.) suggest that at higher FST the effect of length scale is negligible on transition.
- However, this is still an open issue and needs to be resolved but can be handled.

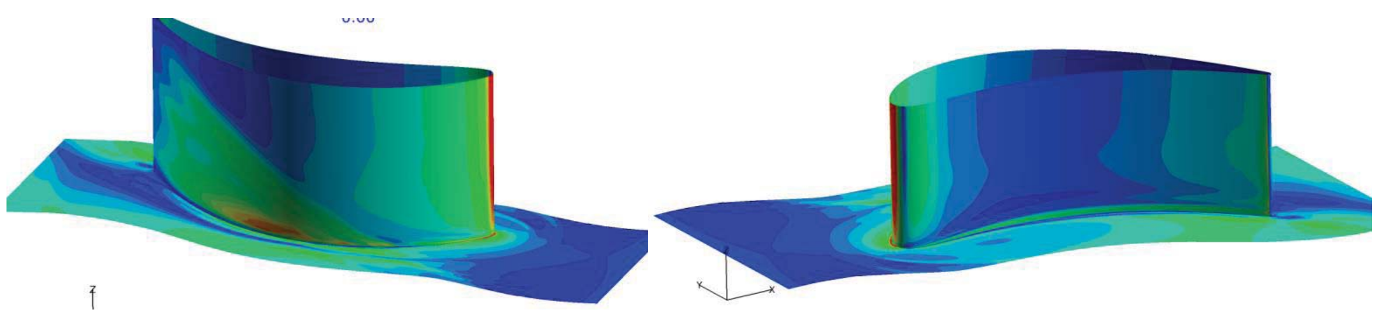
Transition, Cruise, Low Tu





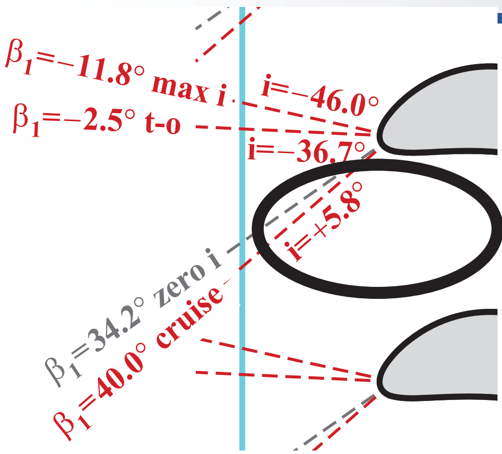


WL

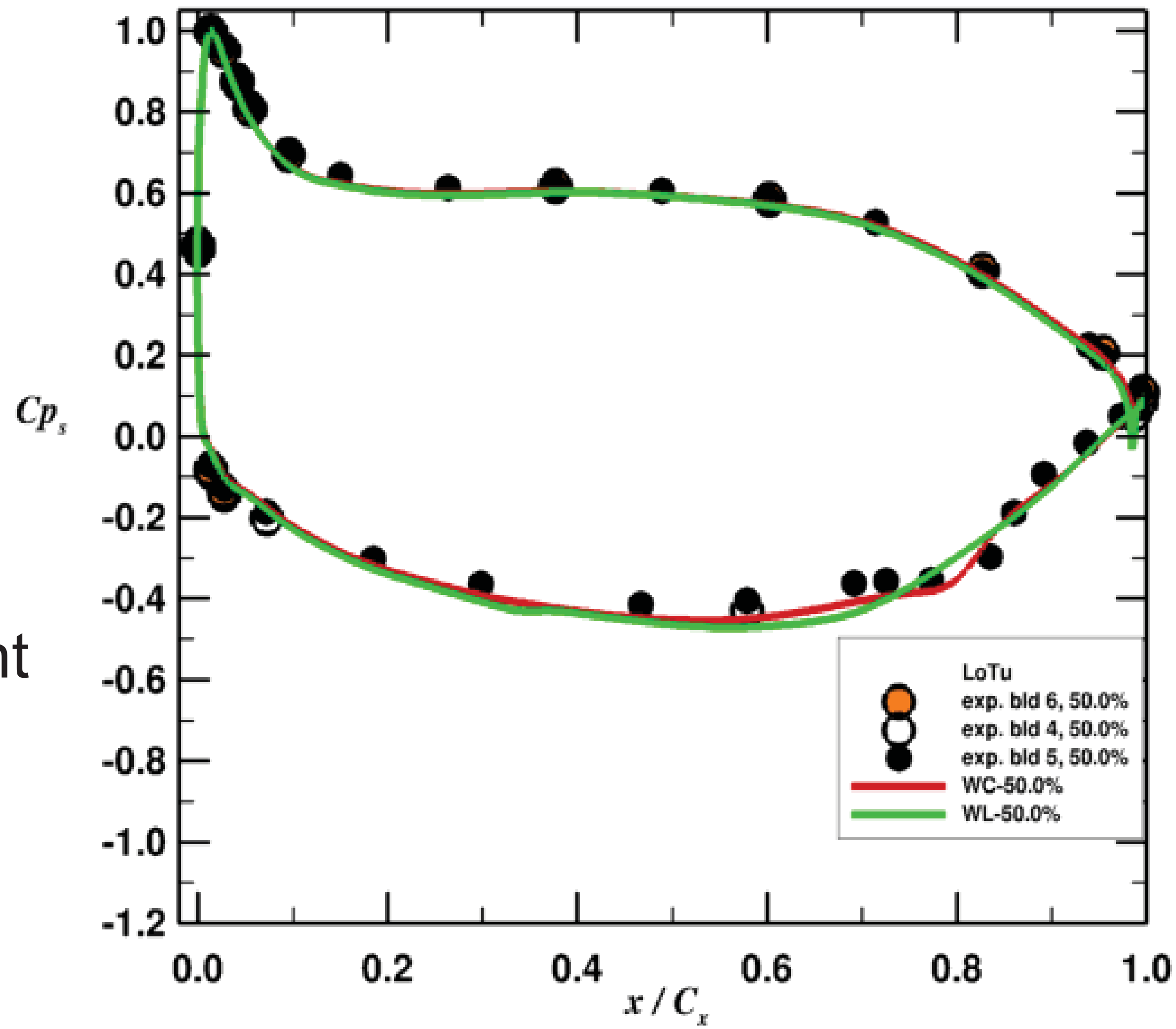


WC

Pressure Distribution- Cruise, Low Tu

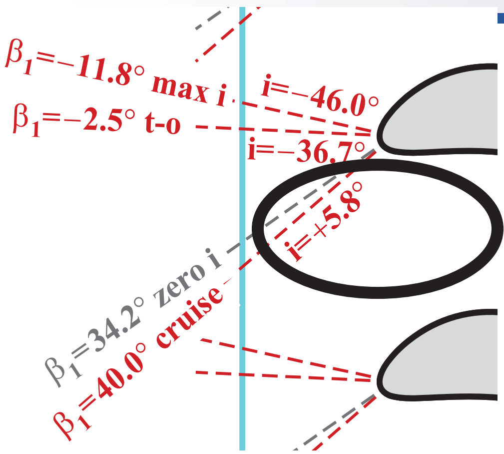


$$C_{ps}=(P-P_{s2})/(P_{t1}-P_{s2})$$



Mid-Span Static Pressure Coefficient

Pressure Distribution- Cruise, Low Tu



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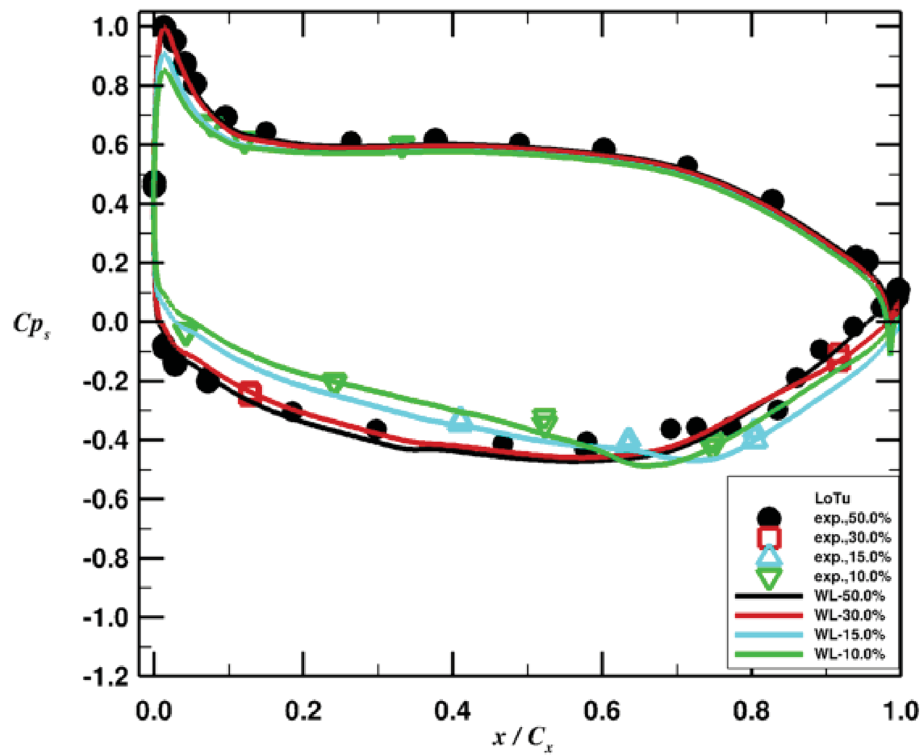
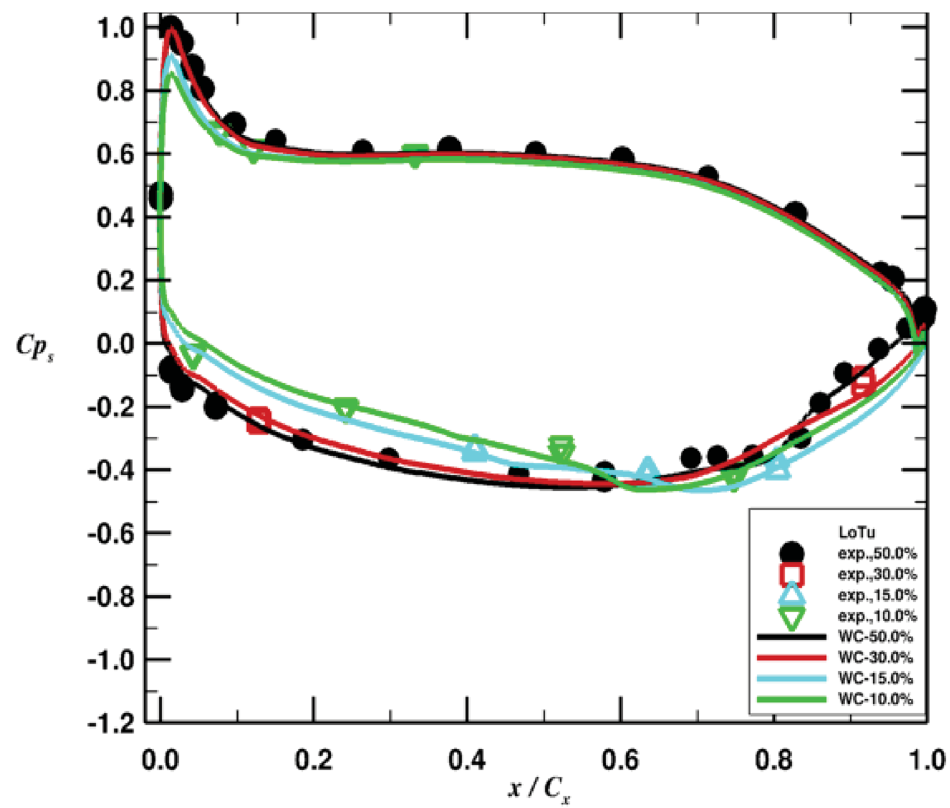
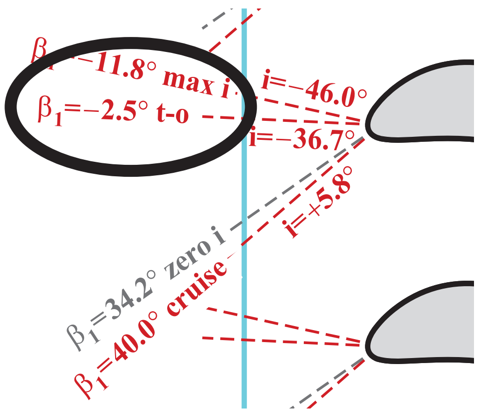
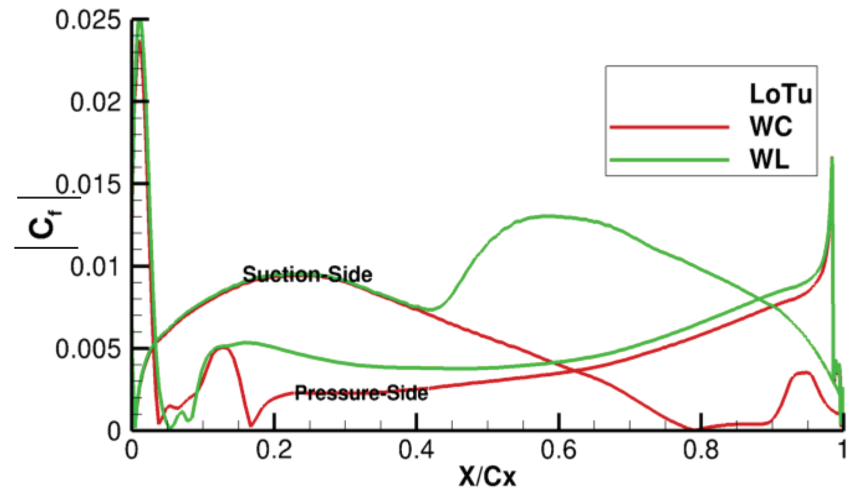
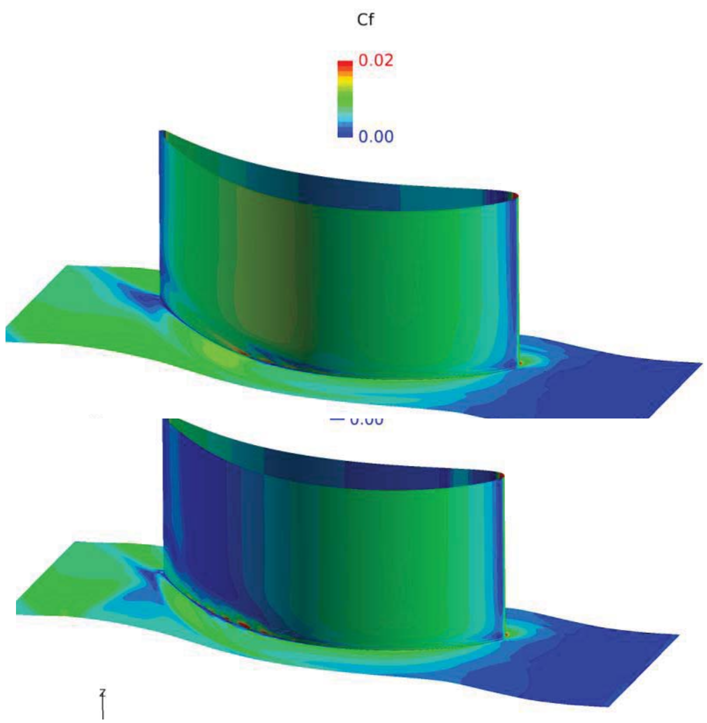


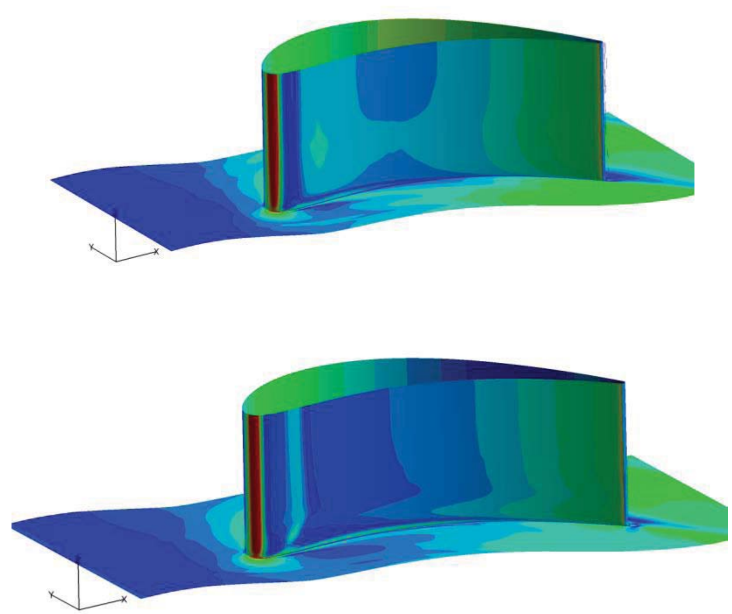


Transition Takeoff, Low Tu





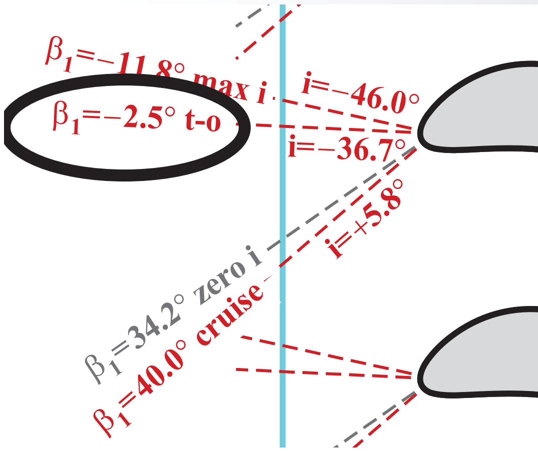




WL

WC

Pressure Distribution- Takeoff , Low Tu



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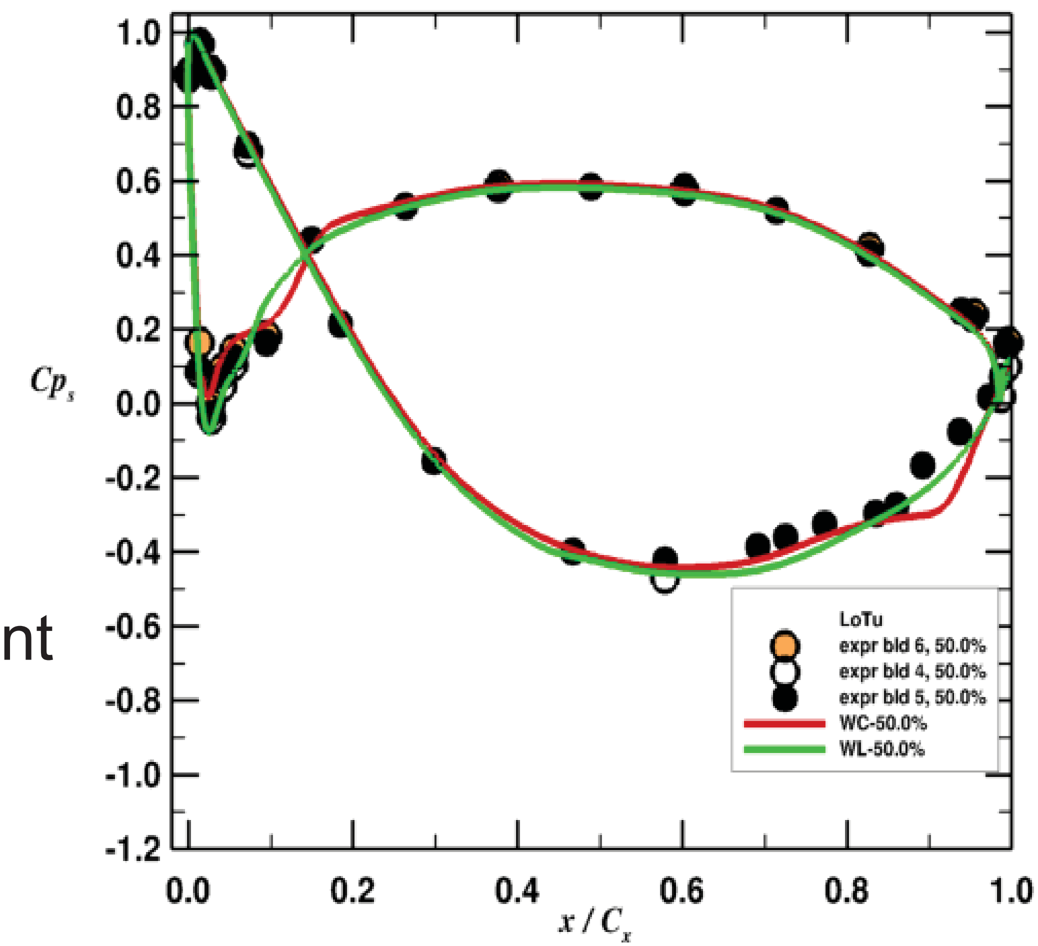
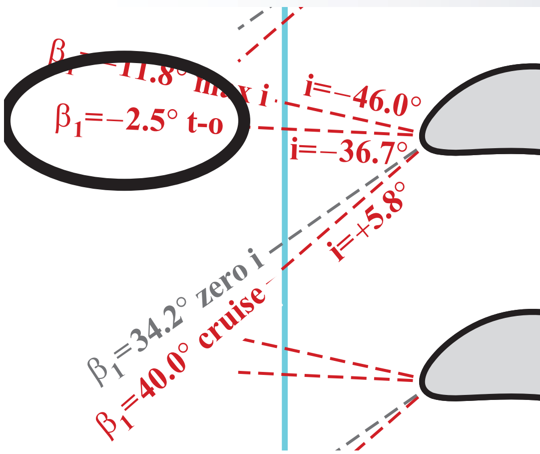
Mid-Span Static
Pressure Coefficient



Pressure Distribution- Cruise, Low Tu



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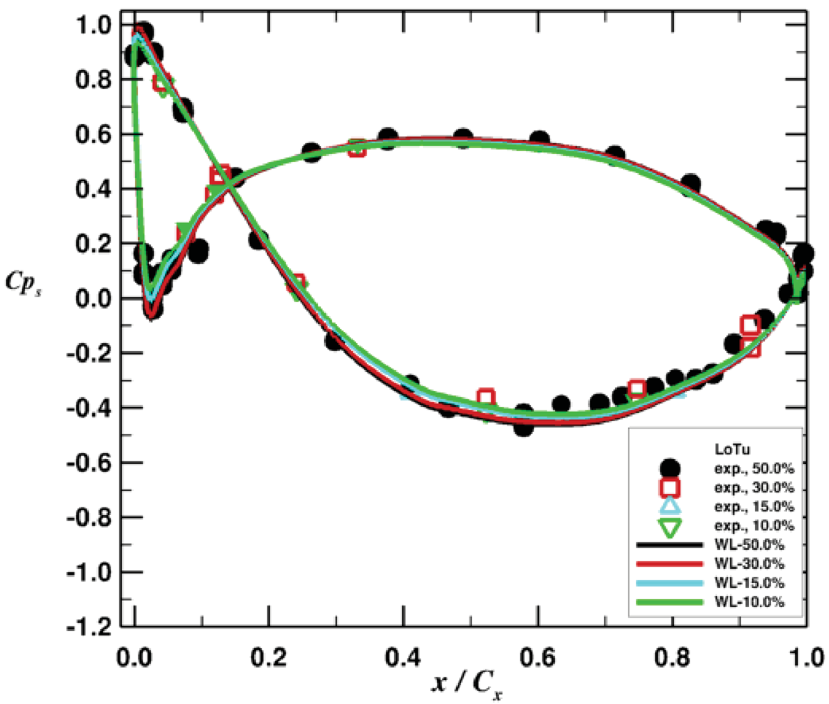
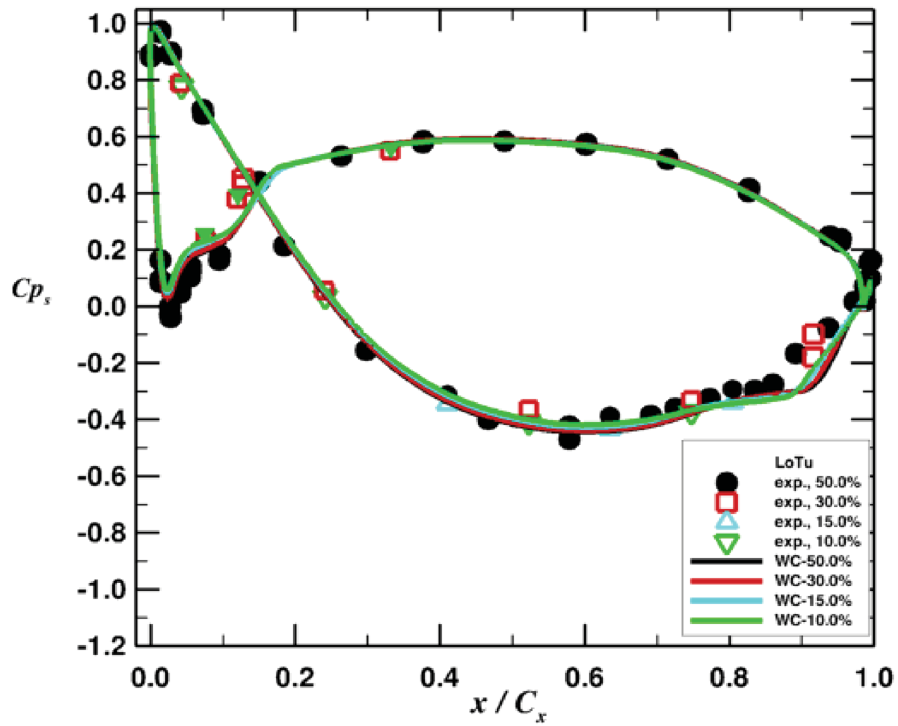
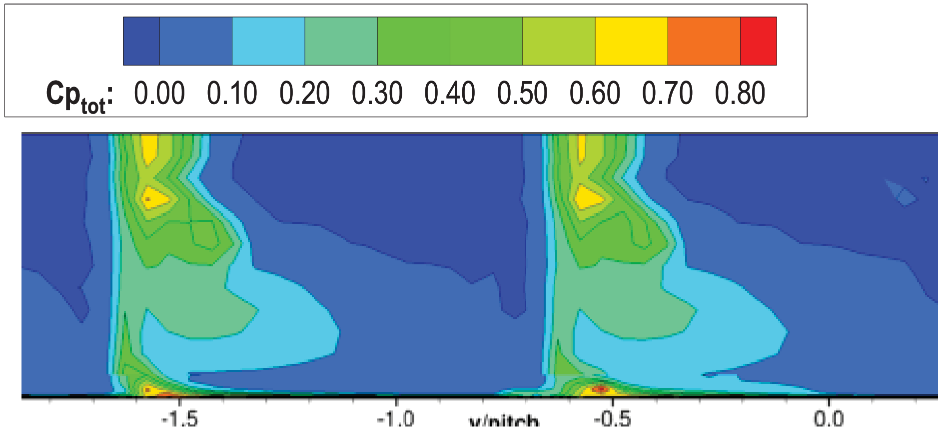
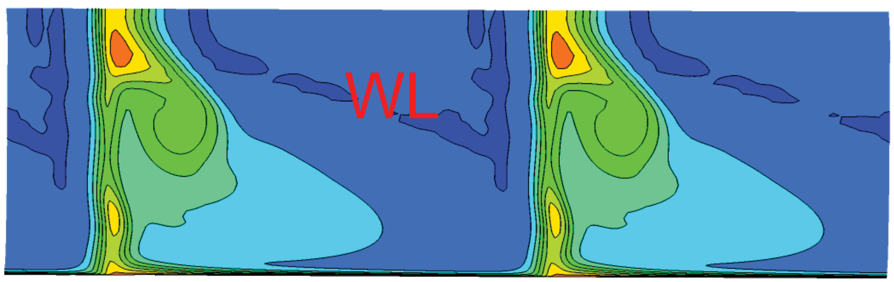
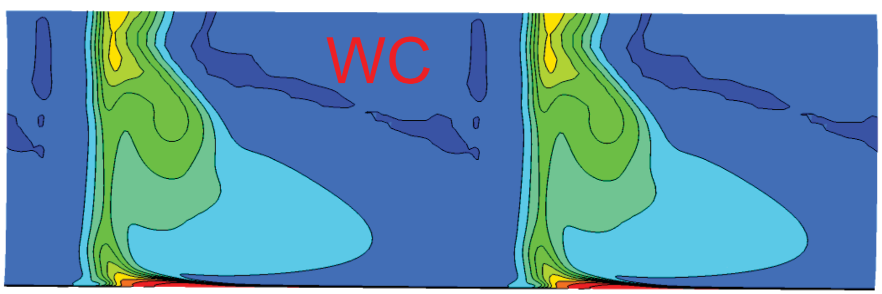


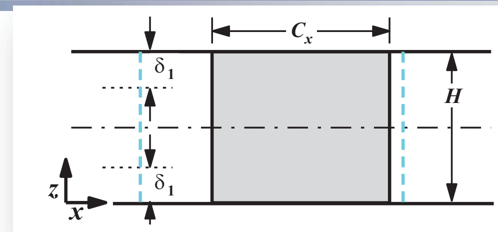


C_{pt} for the Cruise incidence, Low Tu









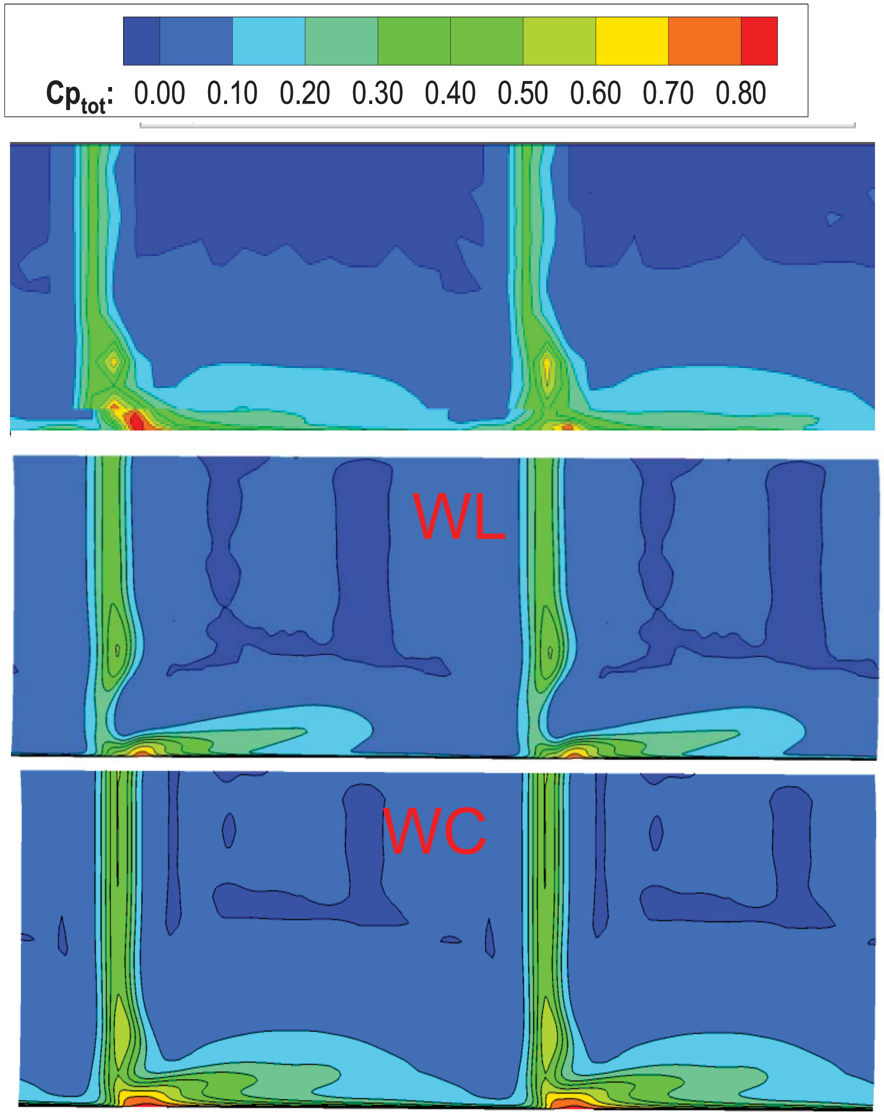
Probe Data 7% x=1.07CX

CFD

$$C_{pt} = \frac{P_{t1} - P_{t\_x}}{P_{t1} - P_{s2}}$$

- The wake total pressure loss coeff. measure C_{pt} over the half-span is well predicted.

C_{pt} for the Takeoff incidence, Low Tu



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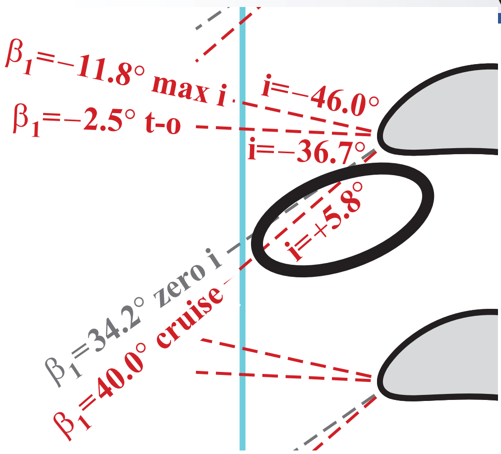
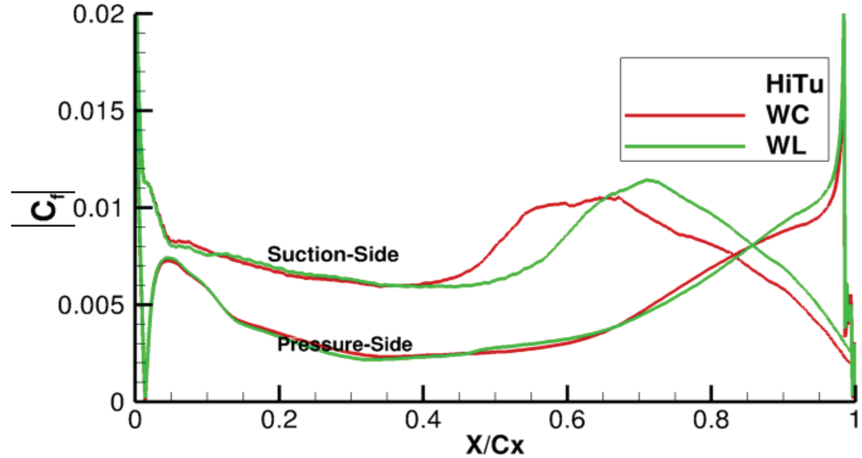
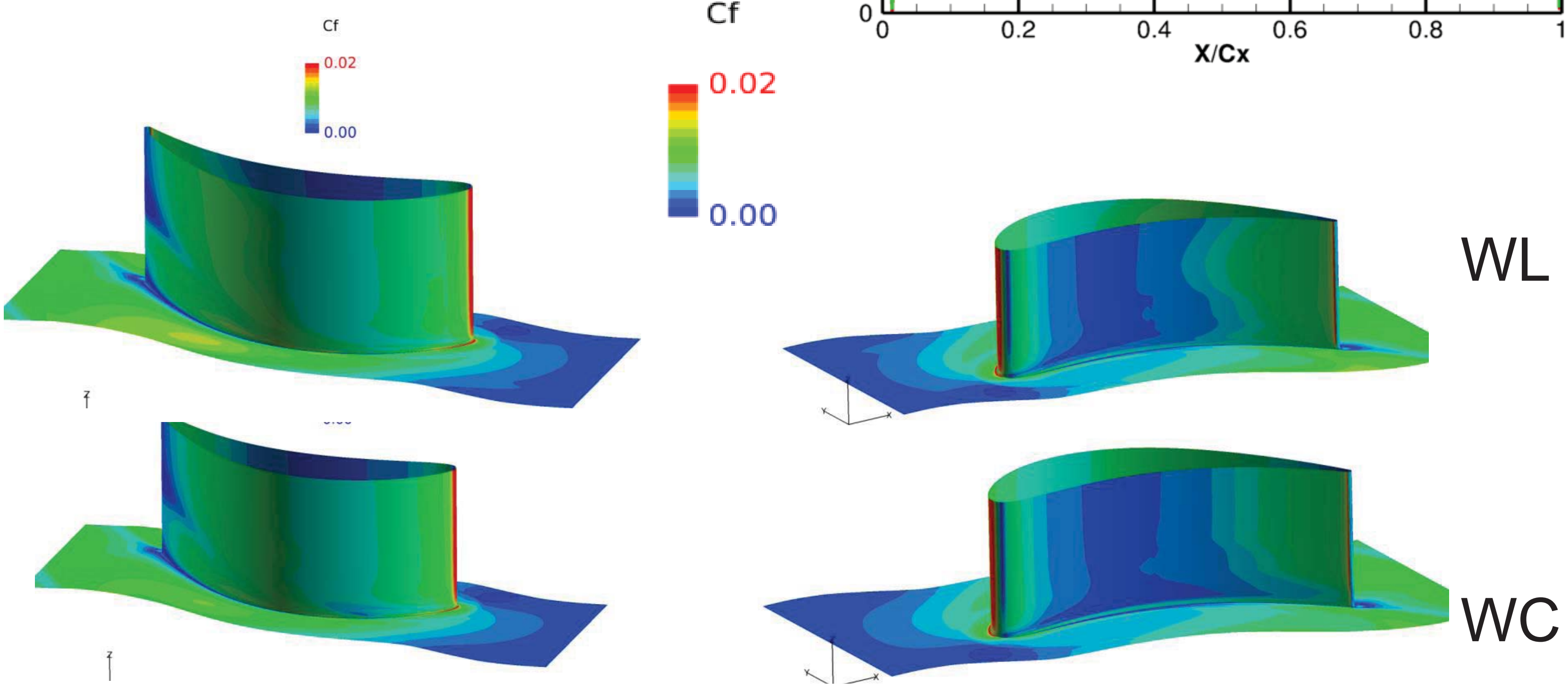
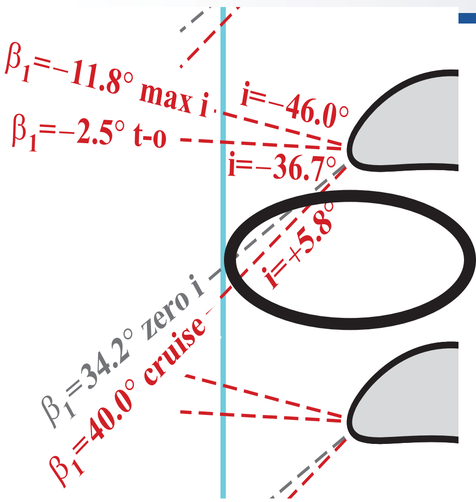
Transition, Cruise, High Tu







Pressure Distribution, Cruise, Hi Tu



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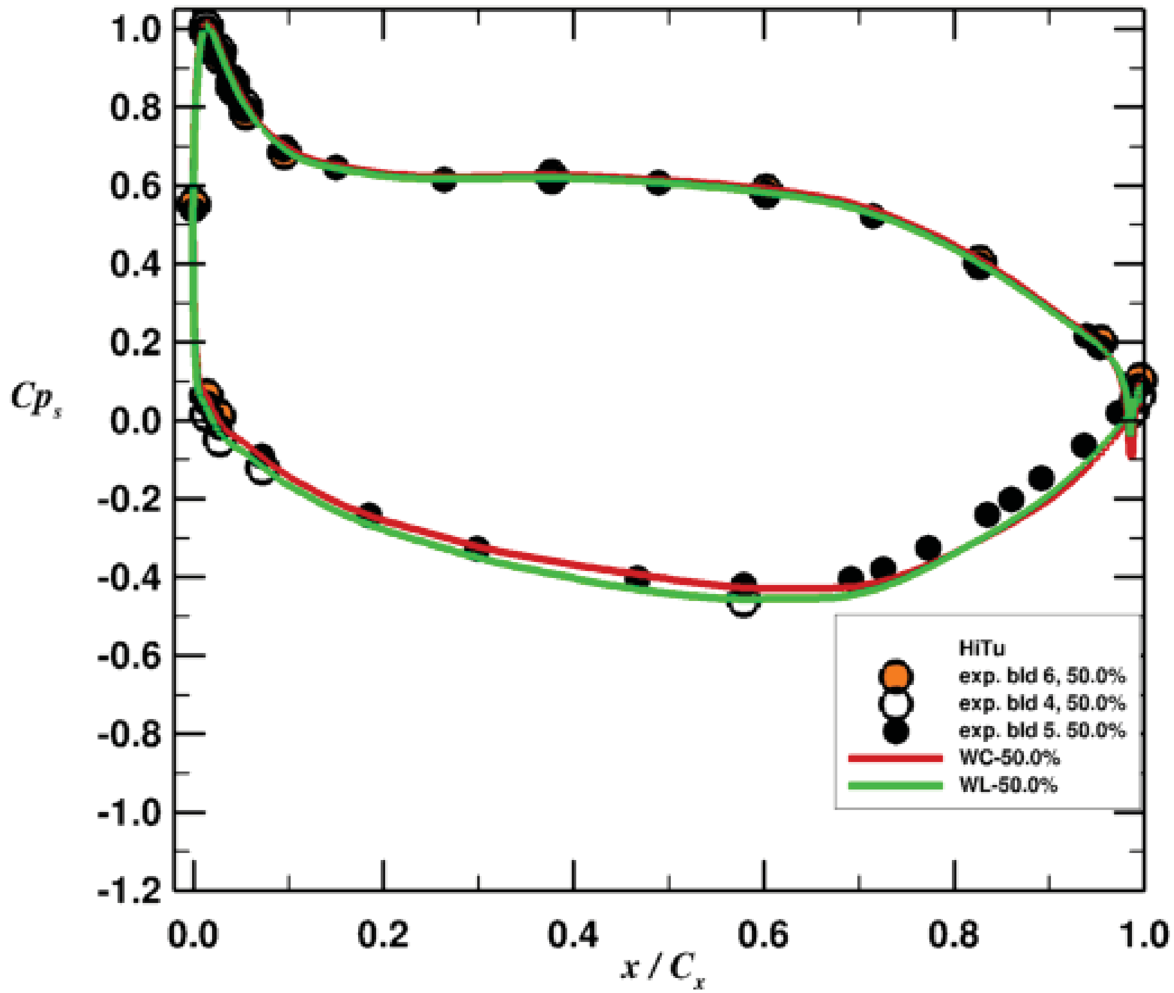
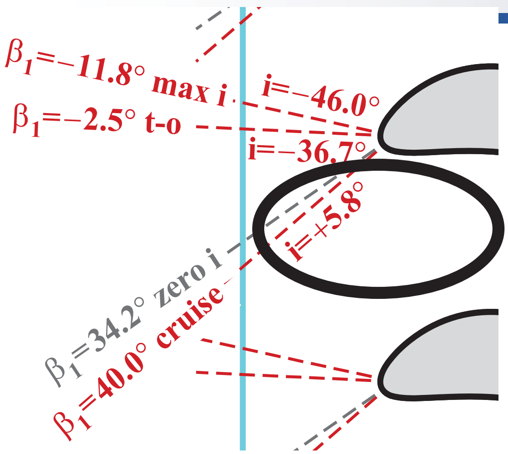


Pressure Distribution, Cruise, Hi-Tu



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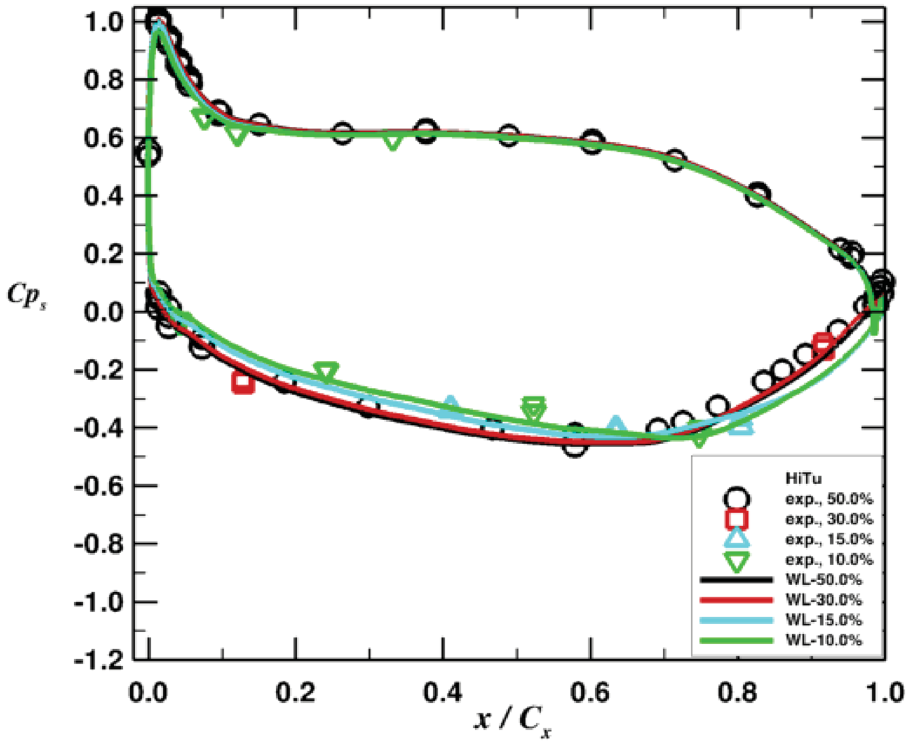
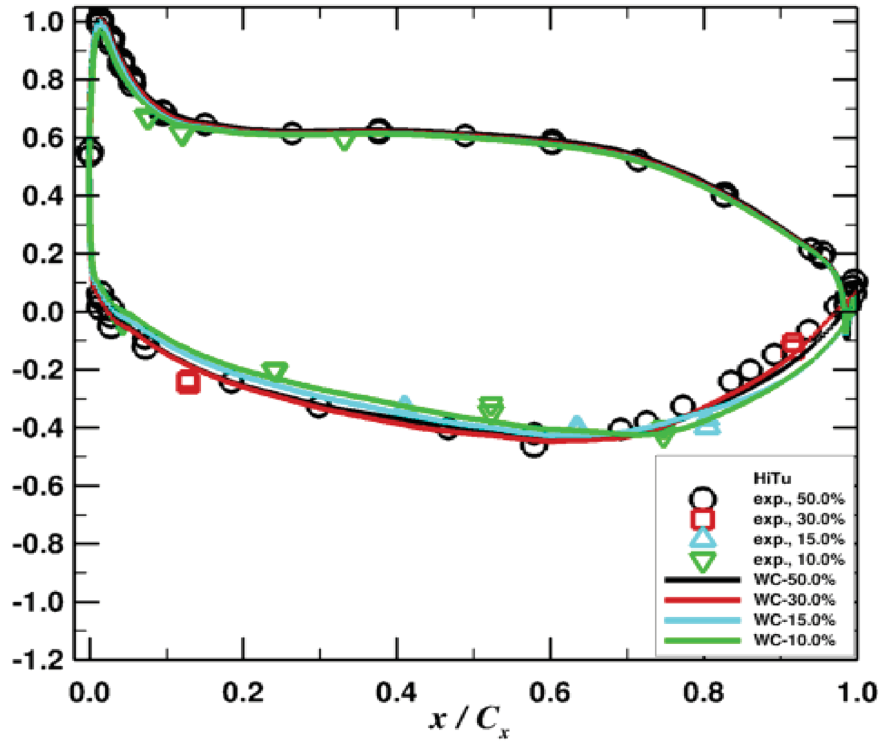
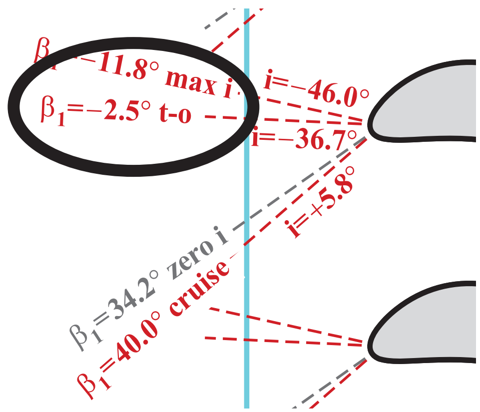
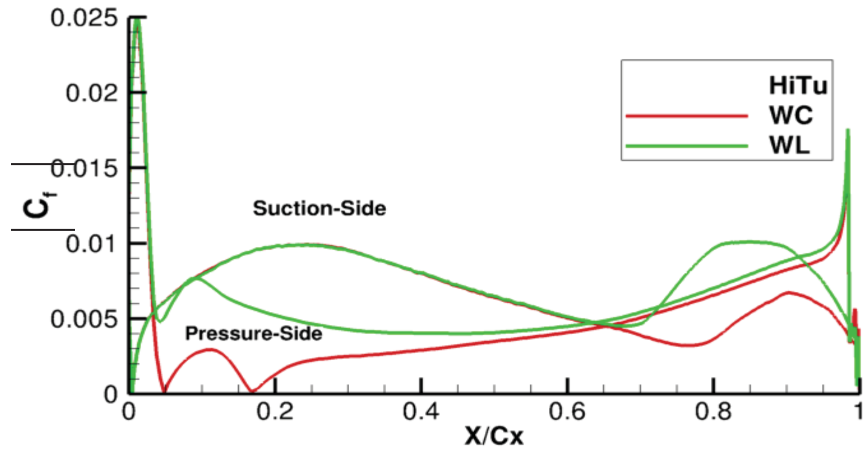
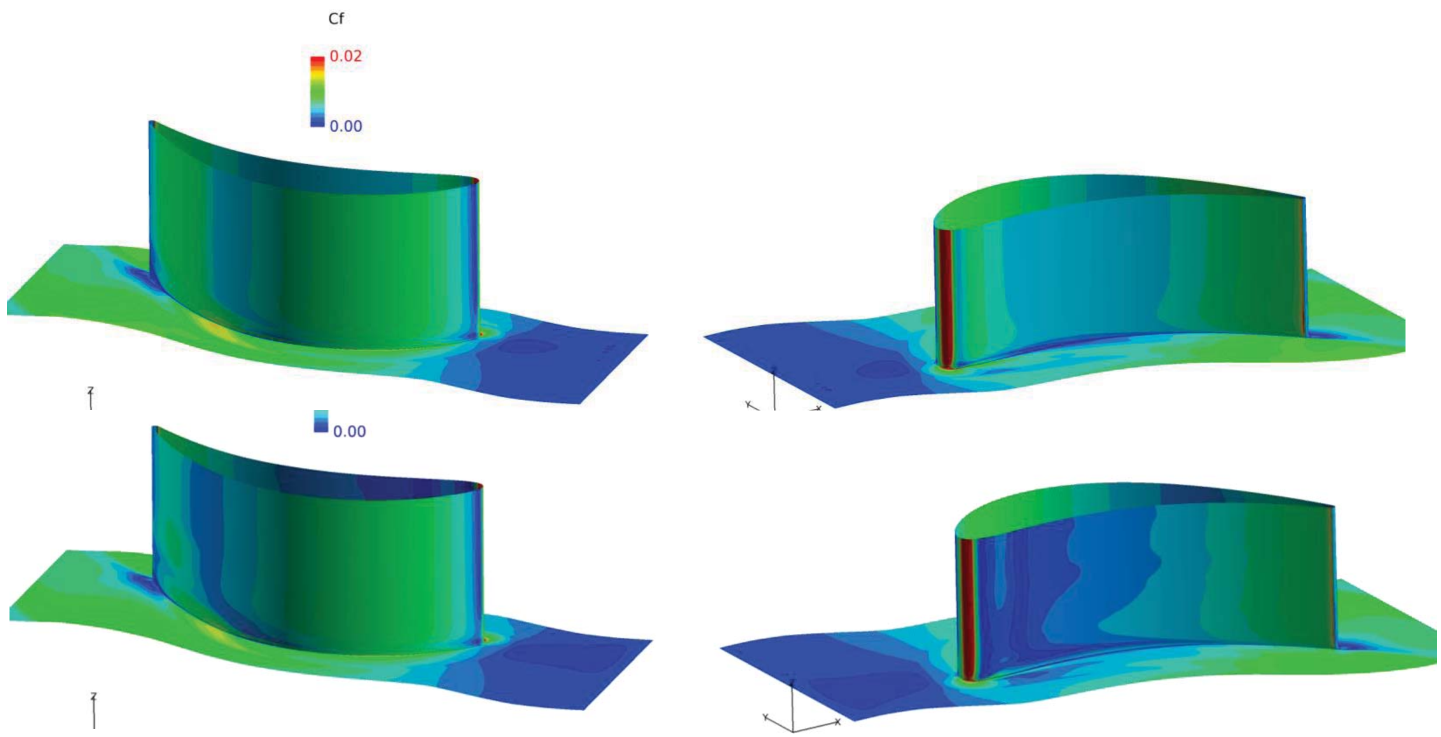




Transition, Takeoff, Hi Tu



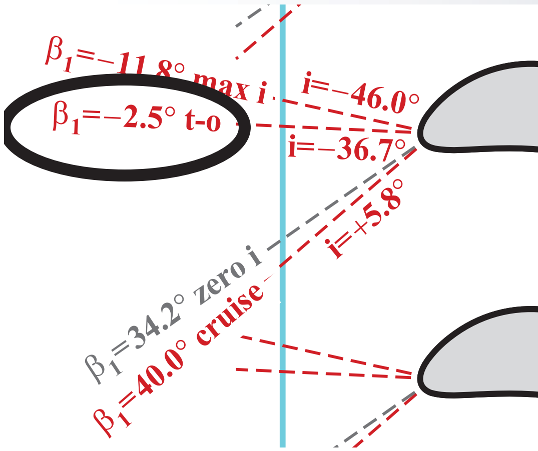




WL

WC

Pressure Distribution, Takeoff, High Tu



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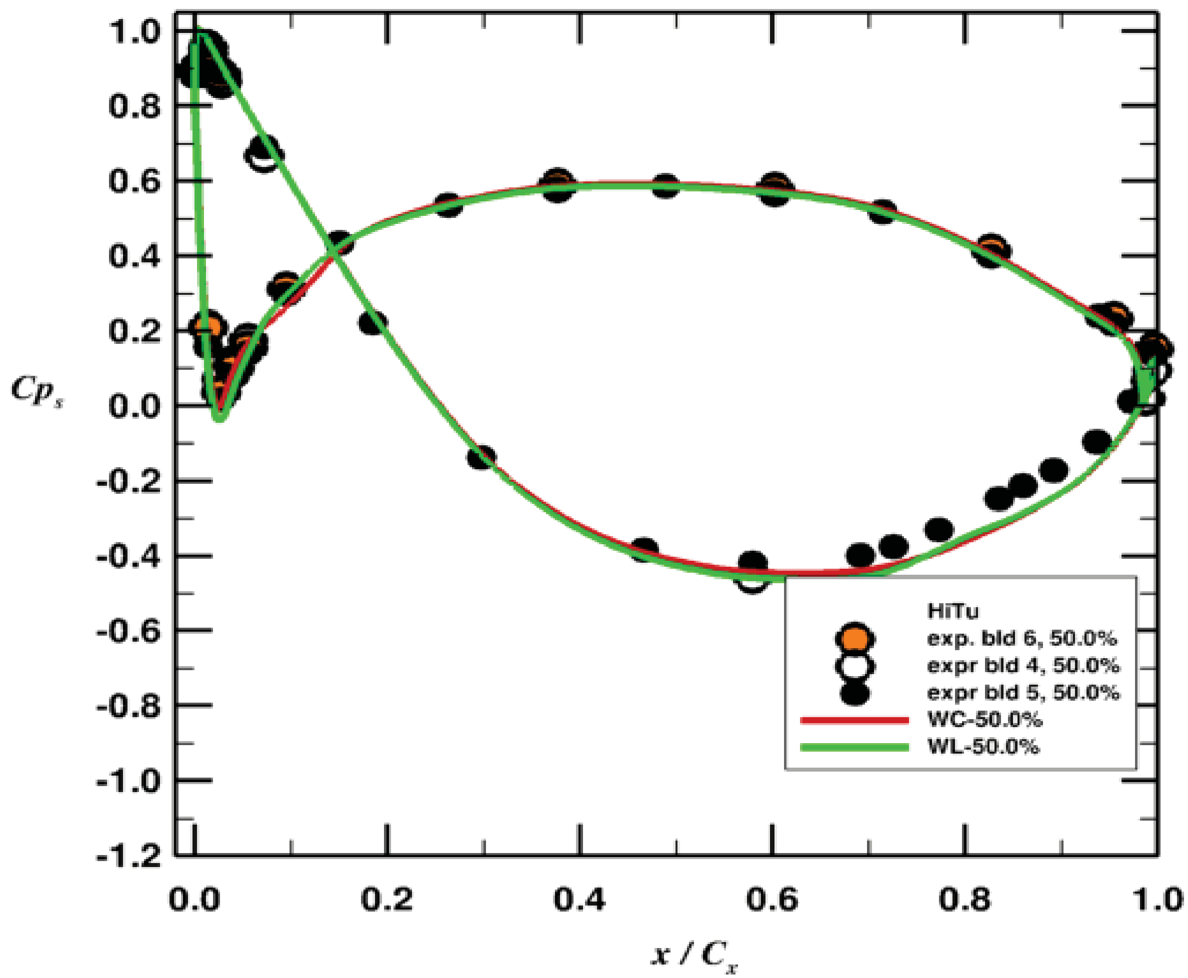
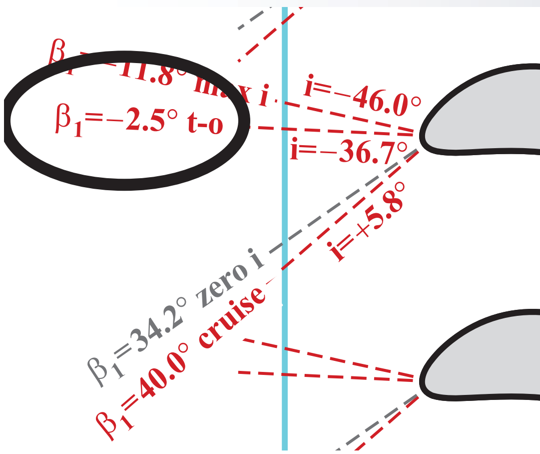


Pressure Distribution, Takeoff, High Tu



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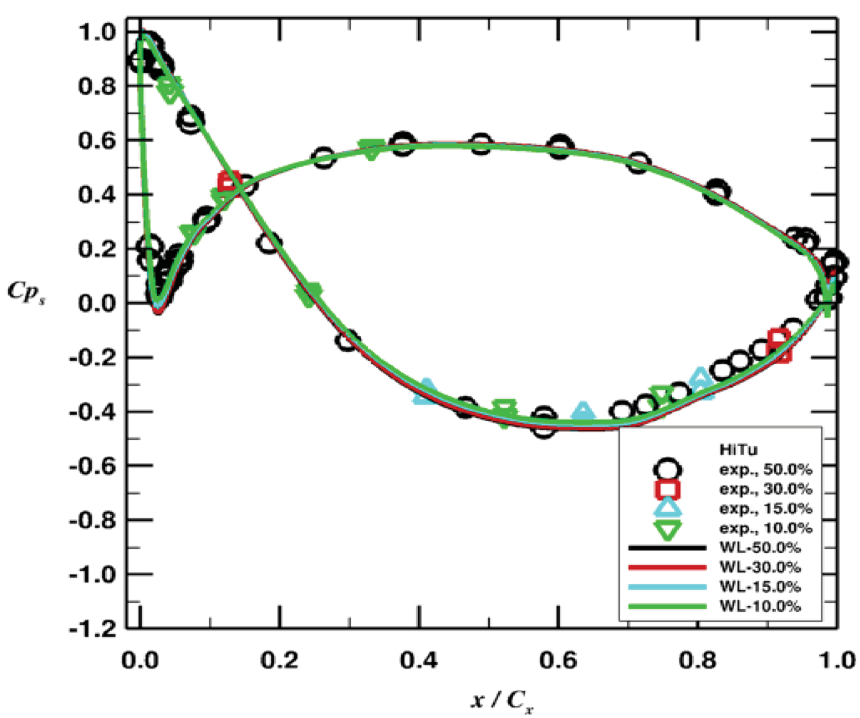
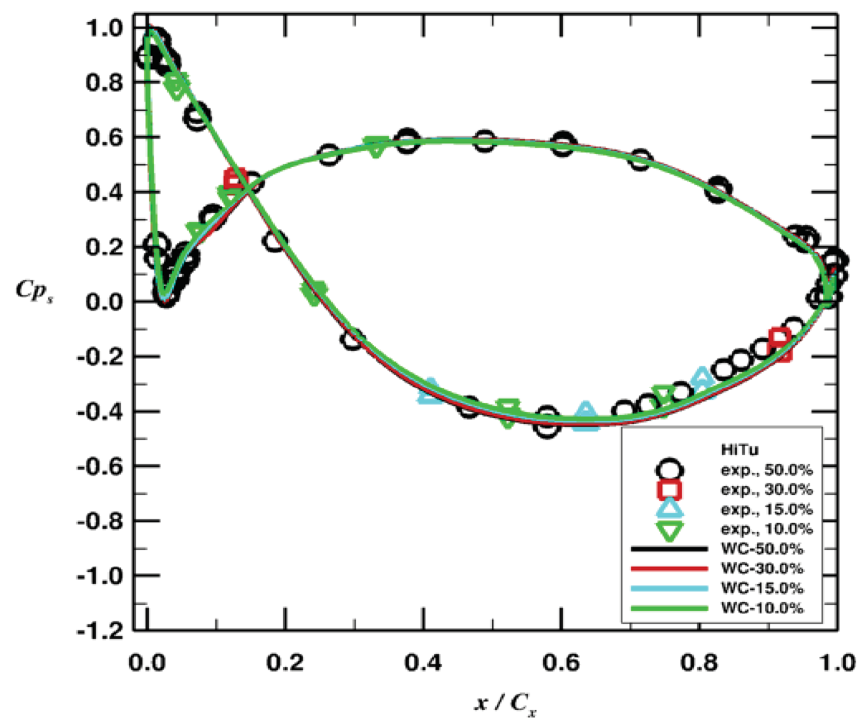
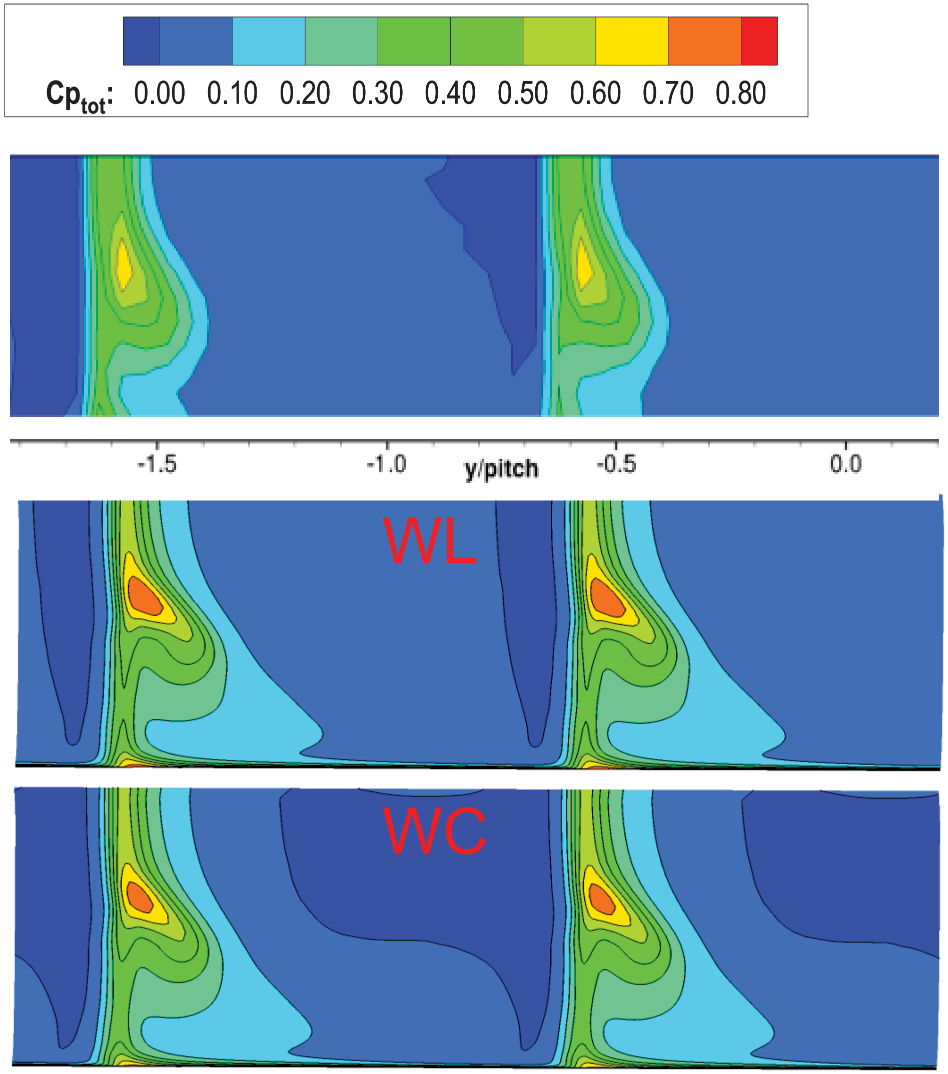




C_{pt} for the Cruise incidence, High Tu



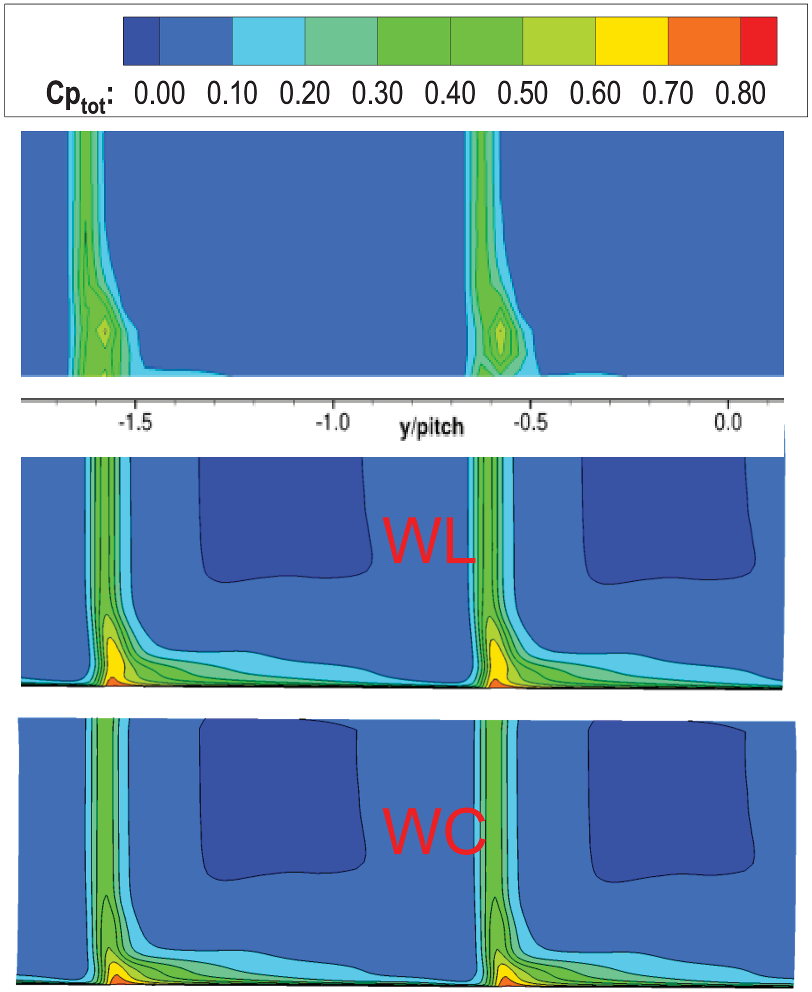
$$C_{pt} = \frac{P_{t1} - P_{t\_x}}{P_{t1} - P_{s2}}$$

Probe Data 7% x=1.07CX

CFD

- The wake total pressure loss coeff. measure C_{pt} over the half-span is conservative.

C_{pt} for the Takeoff incidence, High Tu



$$C_{pt} = \frac{P_{t1} - P_{t\_x}}{P_{t1} - P_{s2}}$$

Probe Data 7% x=1.07CX

CFD

- The wake total pressure loss coeff. measure C_{pt} over the half-span is well predicted.

Summary and Conclusions

- For the VSPT, flow transition/separation has been identified as an important process.
- Large variations in incidence angles require models that can reasonably compute these flows.
- Numerical modeling and validation with companion experimental data of the 3-D flow in a 2-D transonic linear cascade at the two incidence angle conditions corresponding to **Takeoff** and **Cruise** were made.

Summary and Conclusions

- The inlet turbulent length scale, which determines the decay rate of turbulence, was determined from the data.
- At low Tu, WL model missed separation entirely due to early transition while WC model predicted a laminar boundary layer and the subsequent separation as described by the data.
- At higher Tu the two models performed similarly and results were quite satisfactory. At the takeoff condition WC model shows separation on the pressure side while WL model does not.
- Losses are generally better predicted with the WC model.