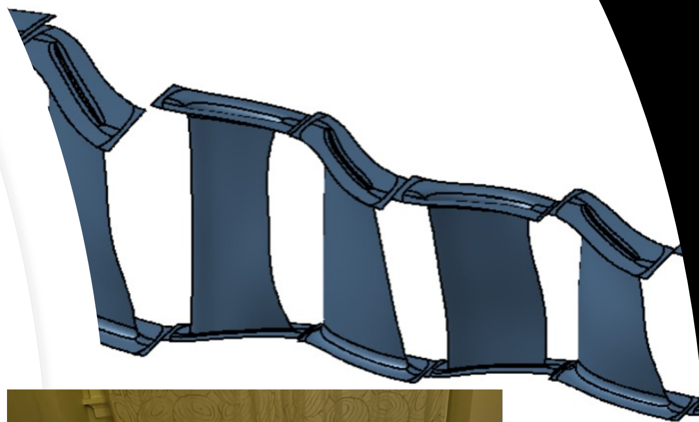
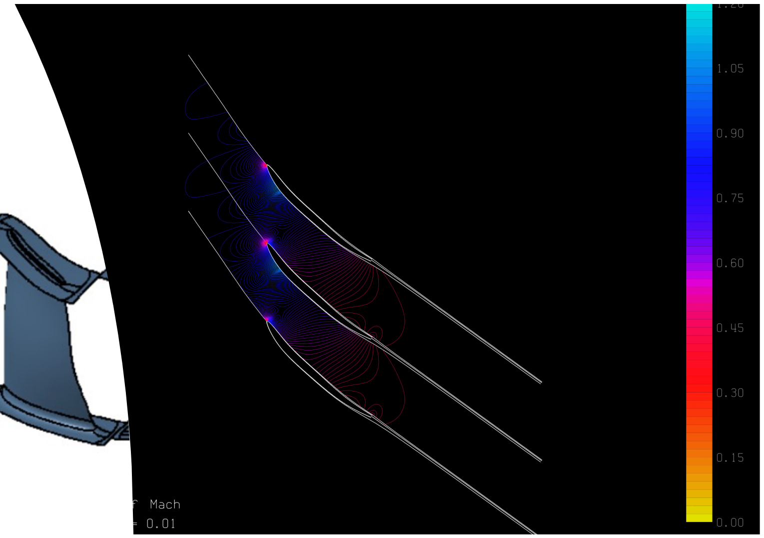
TURBOMACHINERY SIMULATION IMPACT ON DESIGN, UNDERSTANDING, AND OPTIMIZATION





Mark G. Turner

NASA Distinguished Research Associate

2026 TurboExpo

Milan, Italy

June 15, 2026

Outline

Many more optimization cases have been analyzed, but these led to specific lessons learned

- Acknowledgements & Introduction
- CFD Verification and Checklist
- Distortion from Downstream
  - Fan OGVs with Pylon
  - Vane-Strut Interaction
- 3D Isolated Blade Row RANS
- Full Engine Simulation of the GE90
- Unsteady Flows
- Cavity Flows
- Curvature and its role in aerodynamics
- T-Blade3 – 3D blade generator
- Optimization Examples
  - Low Speed Fan with Distortion
  - 3 stage axial S-CO2 compressor
  - Open Rotor Stage
- Conclusions & What's the Future

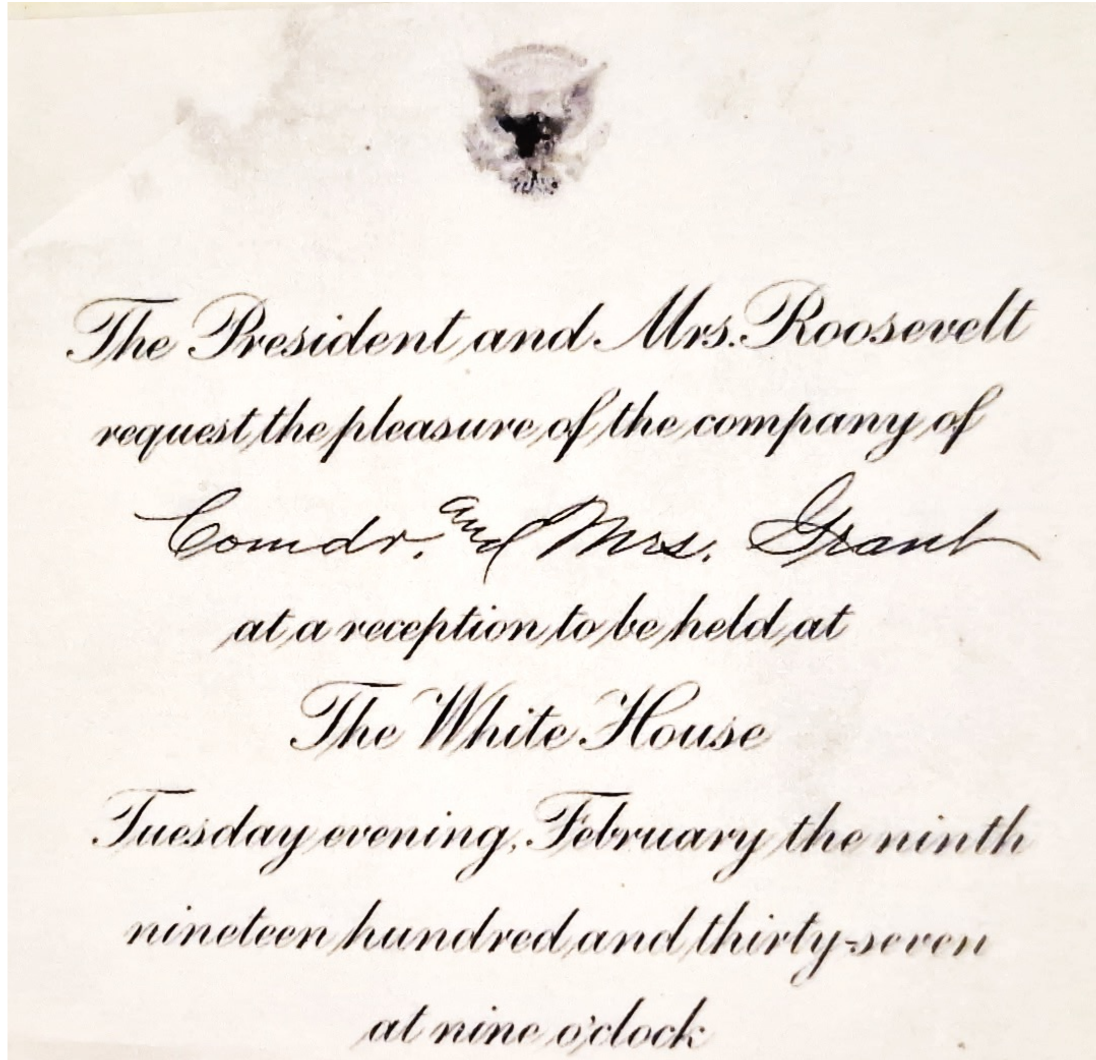
Acknowledgements

- There are hundreds of people to acknowledge and thank for giving me the knowledge, insights, and opportunities throughout my life and career. However, there is not room to thank everyone.

- I thank my wife, Nancy G. Turner, who has put up with my geekiness and not finishing sentences for 45 years. I want to acknowledge my two sons Luke and Graham, and their wives Reina Dickey and Tala Turner. My older brother Cary, who passed away 3 1/2 years ago, his wife, and my other living siblings and their spouses. I want to acknowledge the impact my grandfather, Lucien McKee Grant. He was an admiral in the US Navy, an early Naval Aviator, in the first class of Aeronautical Engineers in the US government and was an active member of the NACA. I want to thank and acknowledge the help Paul Giel has given with this paper. The paper includes more names of people I have personally thanked.

- Thank you to the ASME IGTI Honors and Awards Committee who selected me to be the scholar lecturer and especially the chair, Doug Nagy.

My grandfather crashed his airplane, and my grandmother couldn't go to the reception



The President and Mrs. Roosevelt
request the pleasure of the company of
Comdr. and Mrs. Grant
at a reception to be held at
The White House
Tuesday evening, February the ninth
nineteen hundred and thirty-seven
at nine o'clock

Introduction and Scope of Presentation

- Mark Turner work history: 20 years GE Aerospace, 19 years professor at University of Cincinnati, 5 years at NASA
- Presentation is chronological starting from when I worked at GE
- Lessons learned are presented
- The 2025 paper has Words of Wisdom and Advice I will not present here
- The presentation in Milan will mention the Open Rotor Stage paper that I will present. I will not present that here since that will be shown prior to the conference.

CFD Verification and Checklist

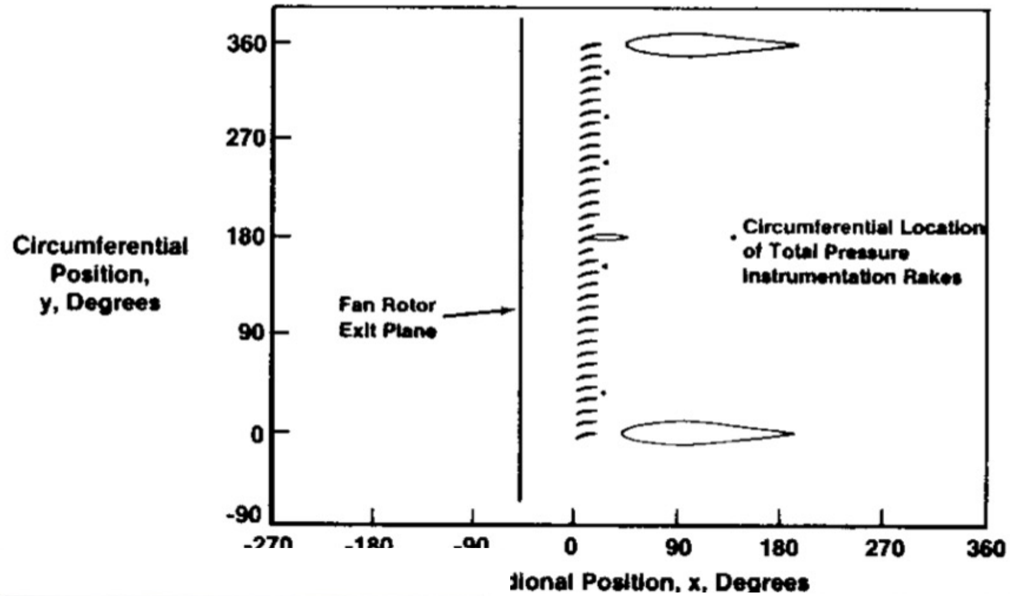
- Verification can be used to check if a CFD code is not correct. It cannot be used to show it is correct
- Check that all boundary conditions are what has been intended
- Check rotation direction is correct for a rotor
- The 2025 paper lists several items in a checklist that should be used when running new cases

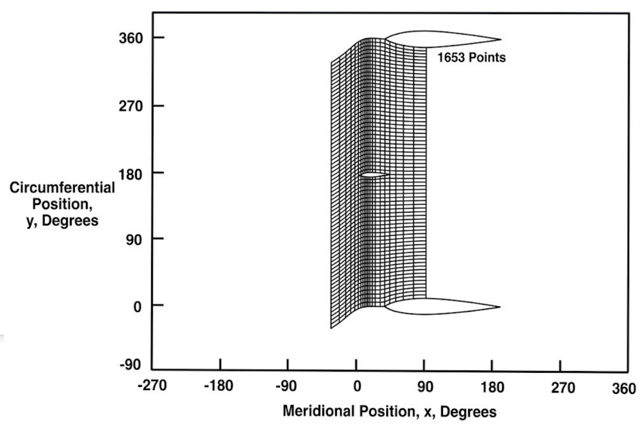
In all cases, better agreement with test data (validation) happens when details of geometry are included: leakage cavities, fillets, hub and casing clearances, cooling holes gridded, etc.

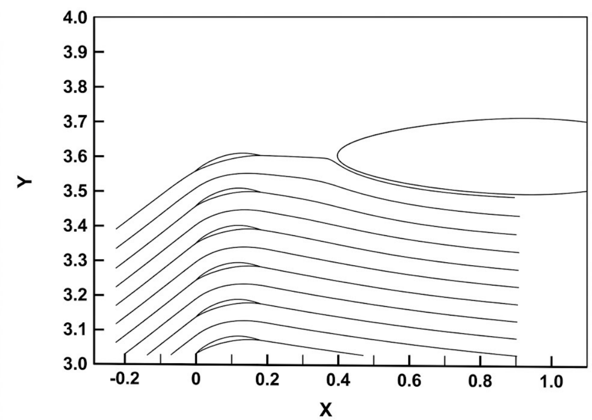
Distortion from Downstream: Fan OGVs with Pylon

- The fan duct in a high bypass ratio fan has a large pylon as a support structure and a smaller strut that carries oil and lube lines.
- These can back pressure the fan
- The Aerodynamic General Implicit Solver (AeGIS) was written to solve this problem in 2D, inviscid. It has high accuracy and needs few grid points.
- The EEE geometry, grid and resulting streamlines are shown.

1985

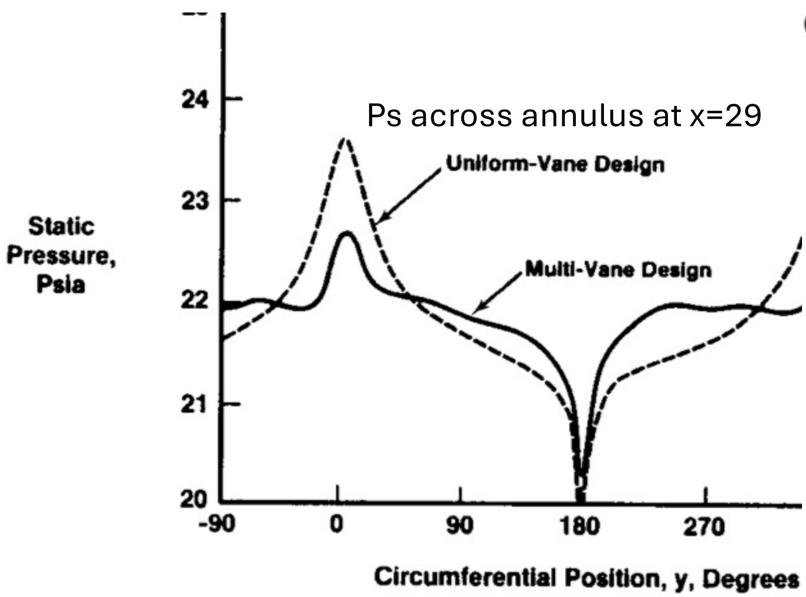


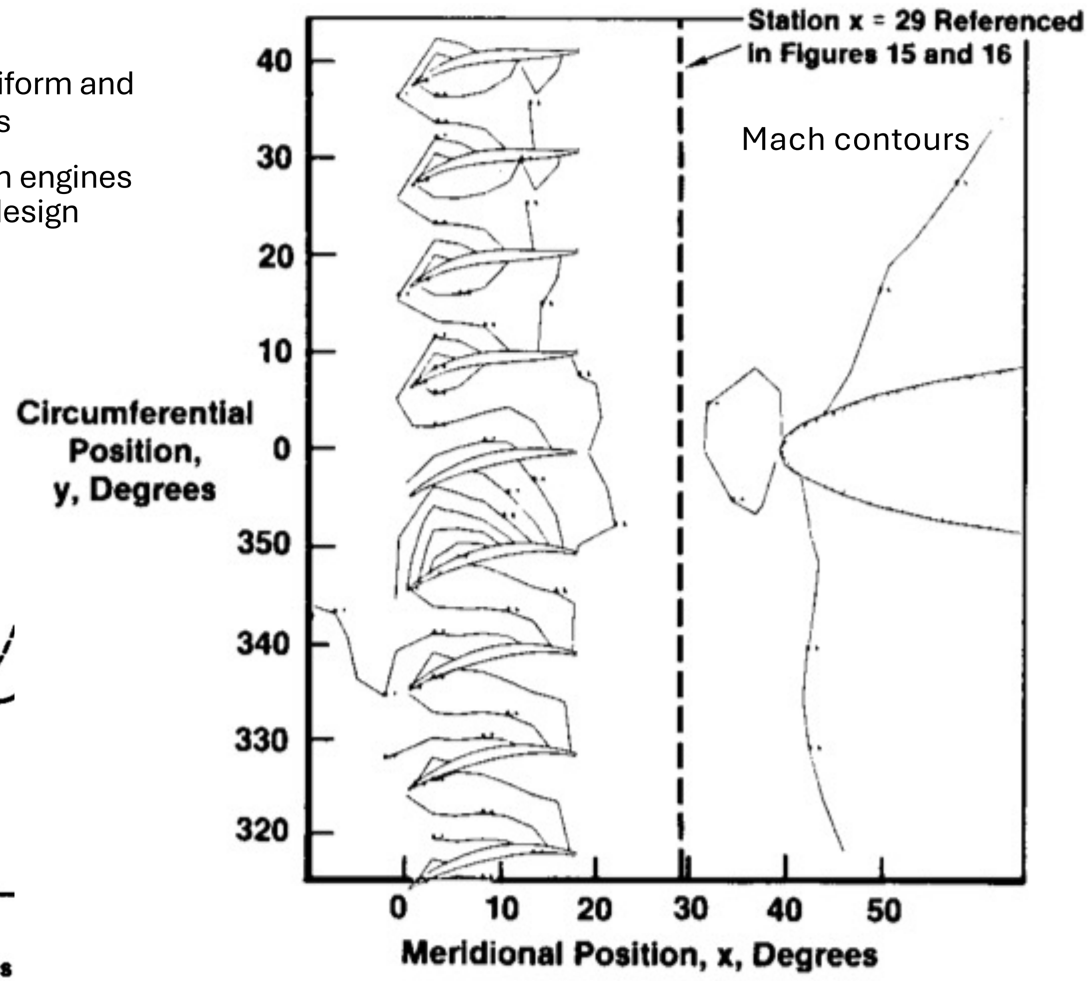




Distortion from Downstream: Fan OGVs with Pylon

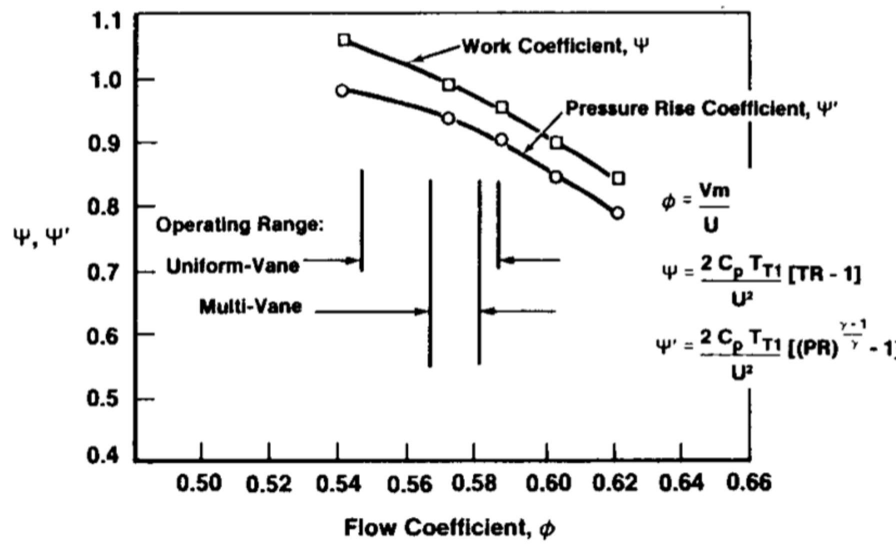
- Comparison of uniform and multi-vane designs
- Almost all turbofan engines use a multi-vane design approach



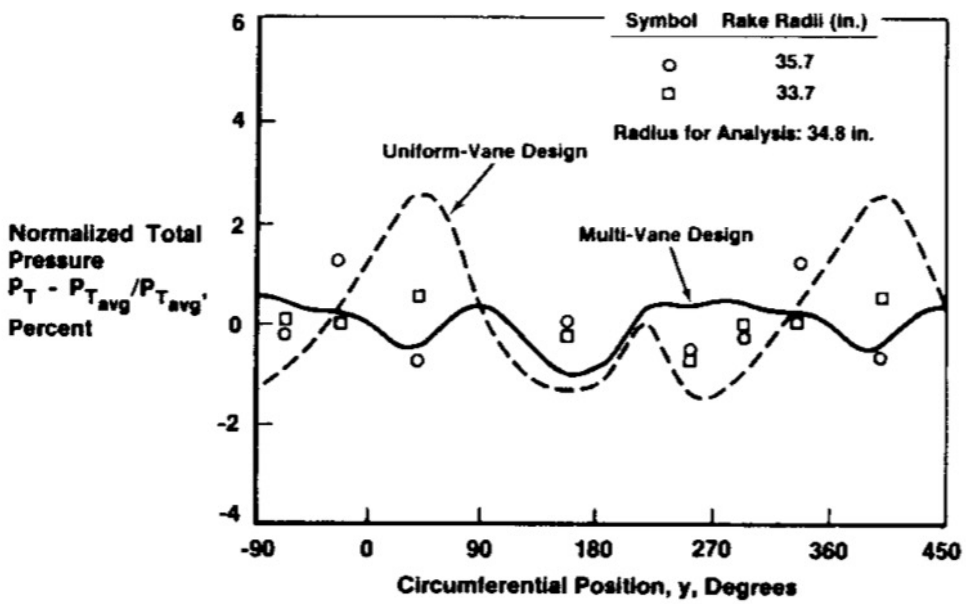


Distortion from Downstream: Fan OGVs with Pylon

- Comparison of test data with multi-vaned design and uniform vane design
- Quasi-steady fan characteristic

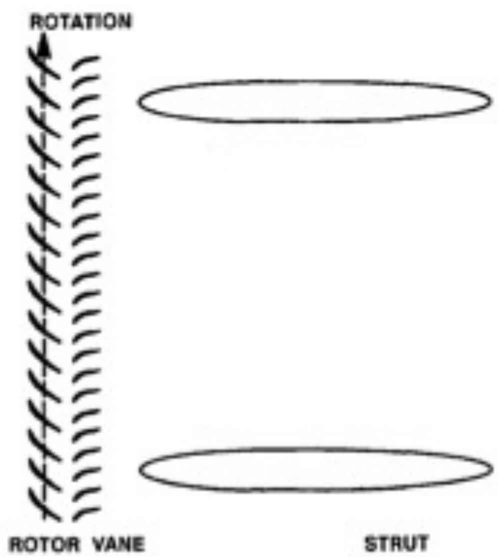


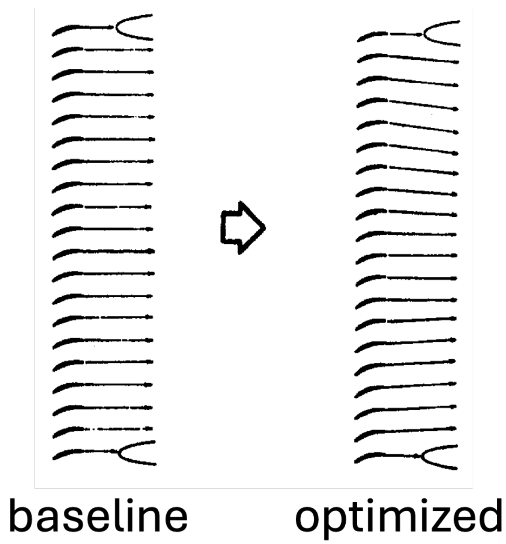
Fan characteristic shows range of flow coefficient for multi-vane design and uniform design

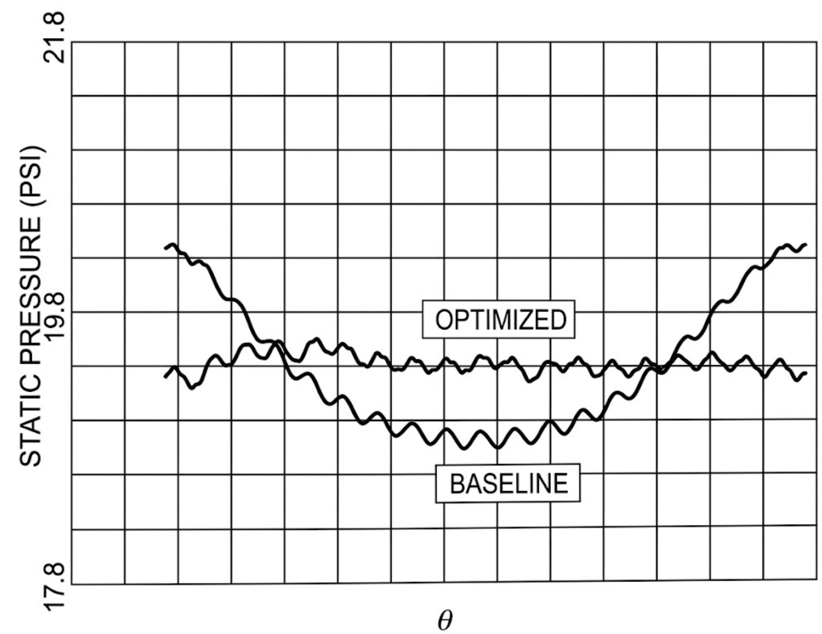


Vane-Strut Interaction

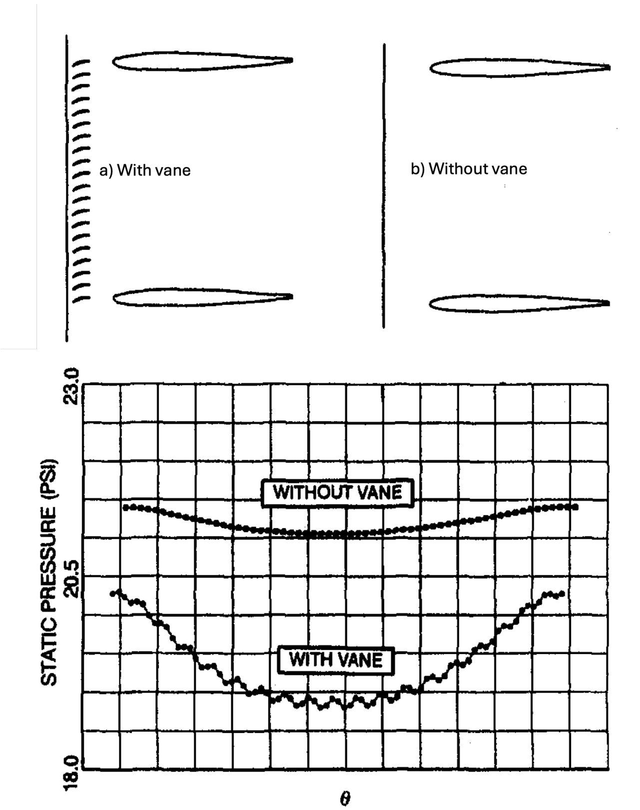
- A small change to an engine family resulted in vibrations in the booster rotor in front of the frame strut
- Custom vanes to guide the flow around the struts can dramatically reduce the pressure distortion upstream of the vane



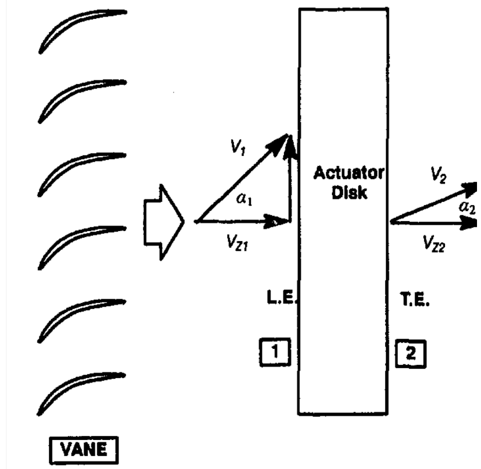




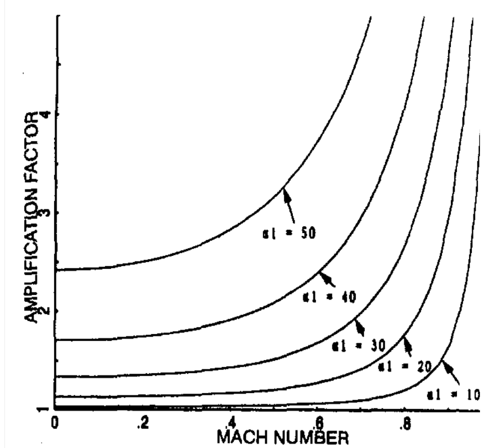
Vane-Strut Interaction



c) Tangential static pressure comparison at the same axial position.



a) Schematic of actuator disk model

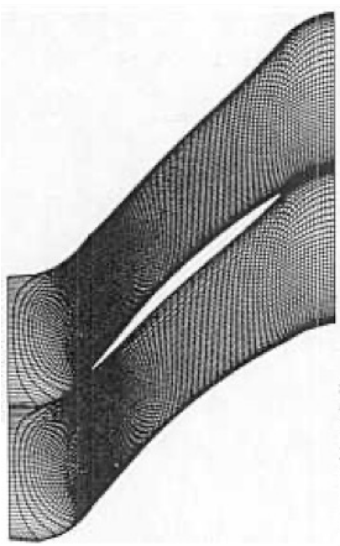


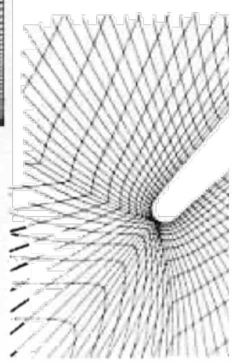
- The vanes amplify the pressure distortion
- A simple actuator disk model was created to understand this
- The amplification is a function of Mach number and vane LE angle
- The new engine had increased the Mach number
- Cut back struts were implemented

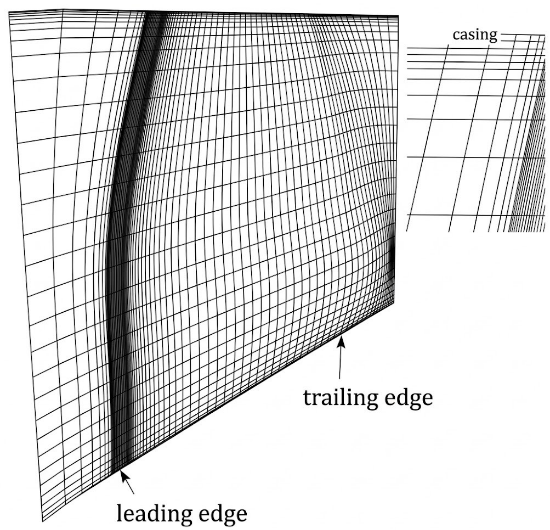
Takeaway: Pylons and struts cause large pressure variations that impact the upstream rotor flowfield or increase the rotor unsteady stresses. A stator magnifies the pressure variation going upstream due to the diffusion of that blade row and the static pressure decreases going upstream. OGVs before a pylon often are designed with different camber and stagger around the annulus to guide the flow around the pylon.

3D Navier-Stokes Solver for Single Blade Row

- Added implicit k-eps solver to 3D Euler Solver
- Validation show is for Wennerstrom Rotor 4
- 3D RANS code for design used for 20 years







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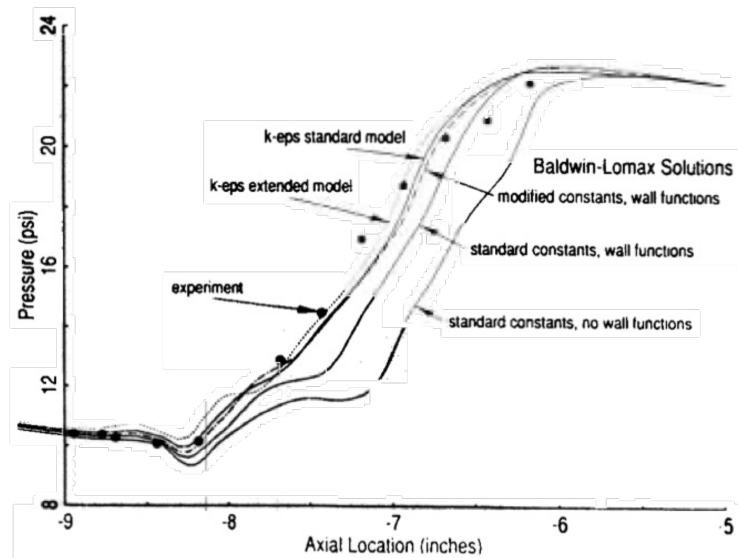
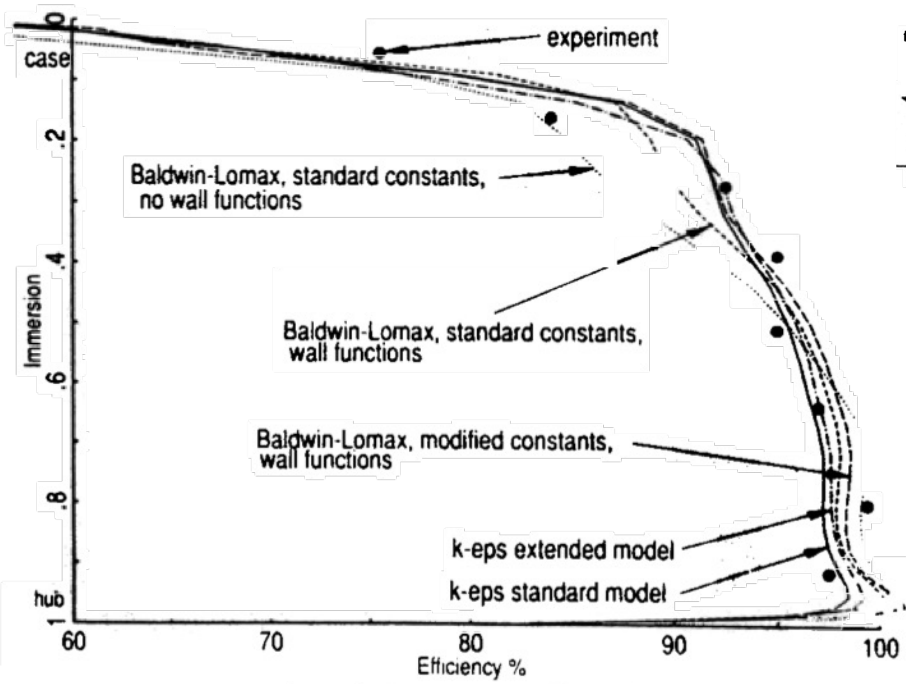
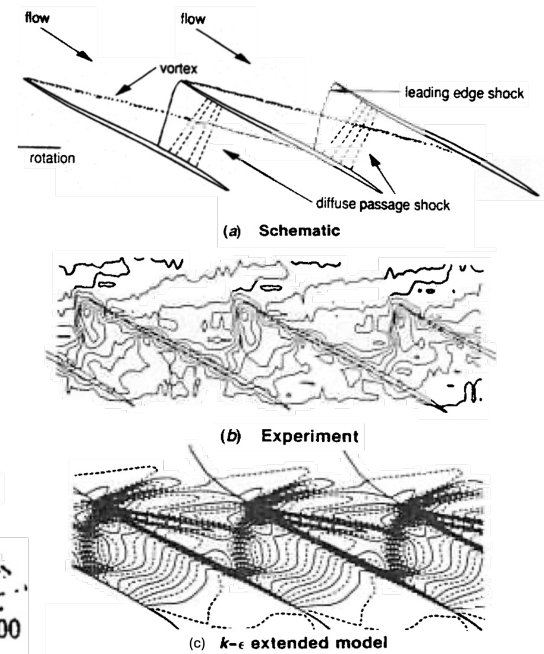


Casing Static Pressure compared to test

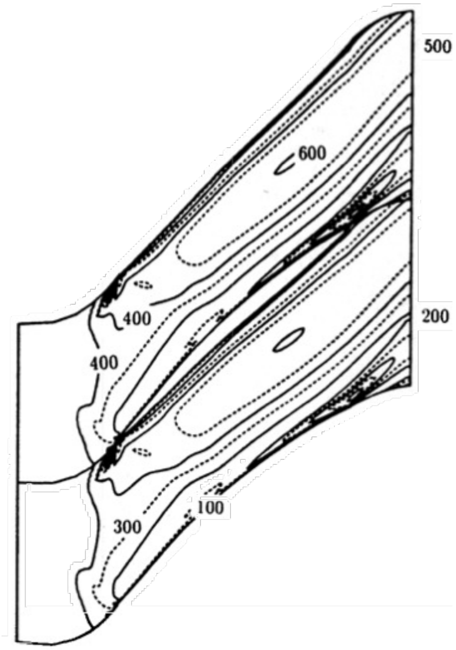
3D Navier-Stokes Solver



Radial Efficiency Profile



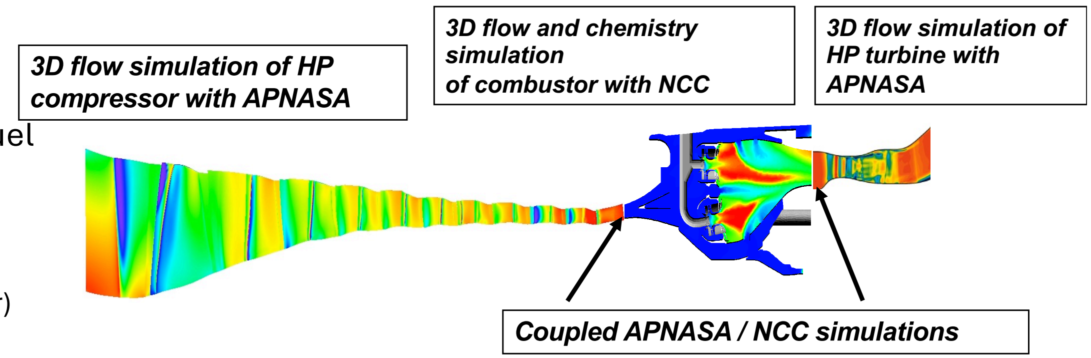
Static Pressure at casing

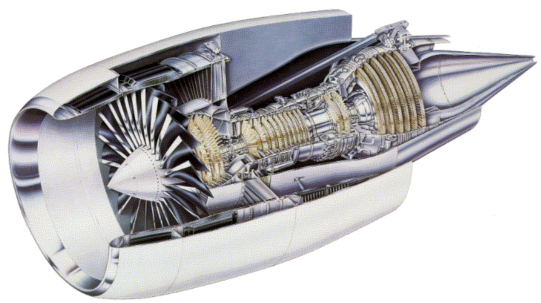


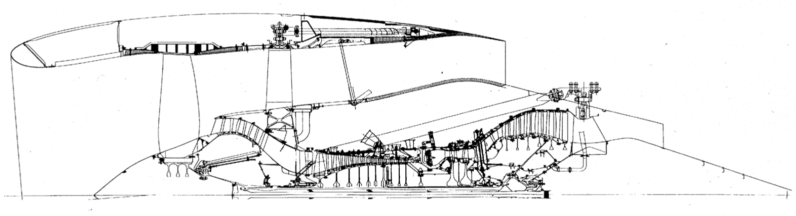
Turbulent to laminar viscosity ratio

Full Engine Simulation of the GE90

- Rigs used for validation of components
- 49 blade rows of turbomachinery
- Dual dome annular combustor with 30 pairs of fuel nozzles
- 0.25 Mach Sea Level Takeoff
- Used Average Passage Code for turbomachinery
  - AP formulation with general grids (described in paper)
  - Rotor Tip clearance
  - Real Gas Model
  - Leakages
  - 4-Stage Runge-Kutta solver
  - Implicit k-eps solver
  - Blade row parallel and MPI
- Used NCC for the combustor
  - Parallel Unstructured
  - Explicit 4-stage Runge-Kutta
  - Gaseous fuel model used







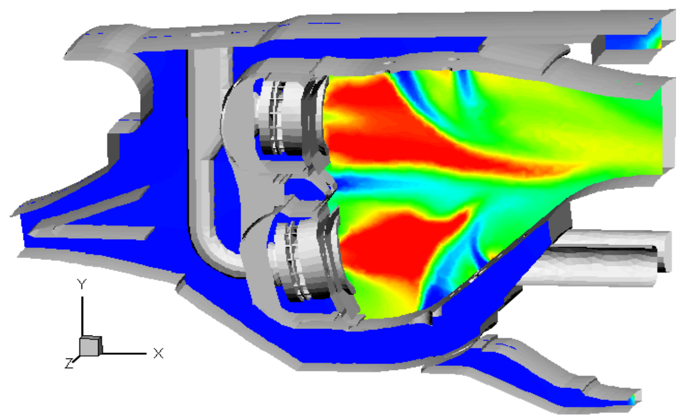
2000

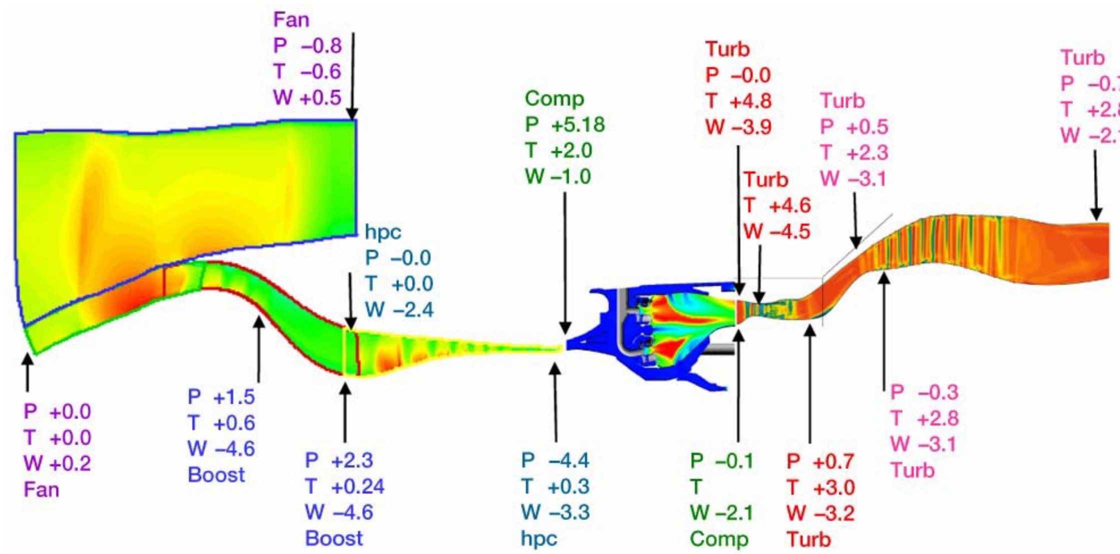
Full Engine Simulation of the GE90

- GE90 Cycle compared to Simulation Cycle
  - SFC -0.99%
  - BPR +0.63%
  - OPR -1.10%
  - Thrust 0.99%
- Engine to engine variation
  - SFC 0.25%, Thrust 0.5%

Takeaway: The full engine simulation of the GE90 proved that such a large and complicated simulation could be done in 3D. It paved the way for other full engine simulations and more component coupling. It was critical that the GE90 was an active engine development project at the time, so geometry and test data were readily available.

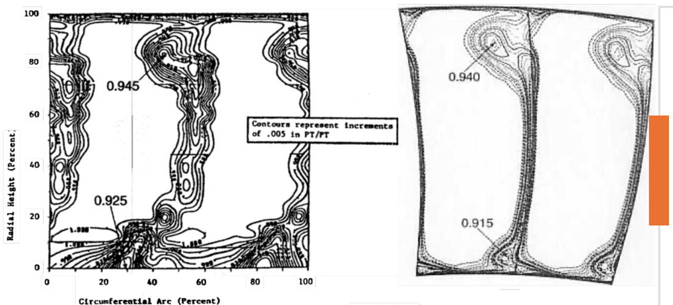
Total Temperature





Unsteady Flow Example in the EEE LPT Rig

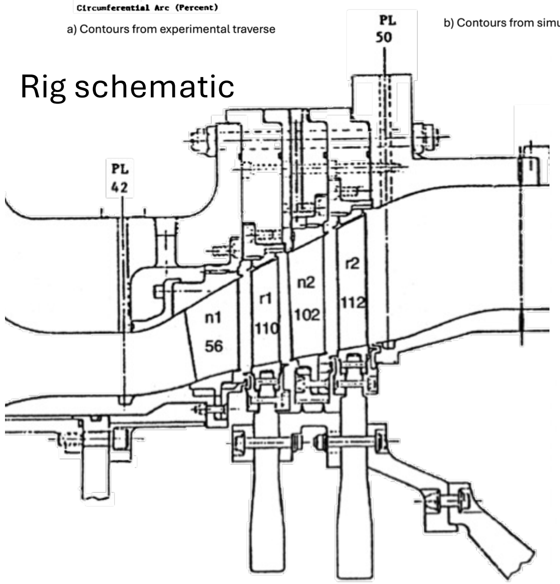
- Used MSU-Turbo by J.P. Chen
- Start with Average Passage
- Flow has a lot of spanwise variation due to unsteadiness



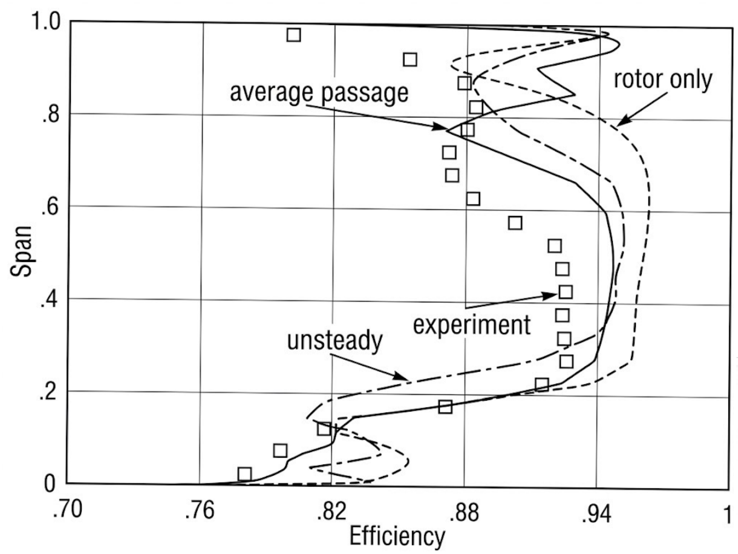
a) Contours from experimental traverse

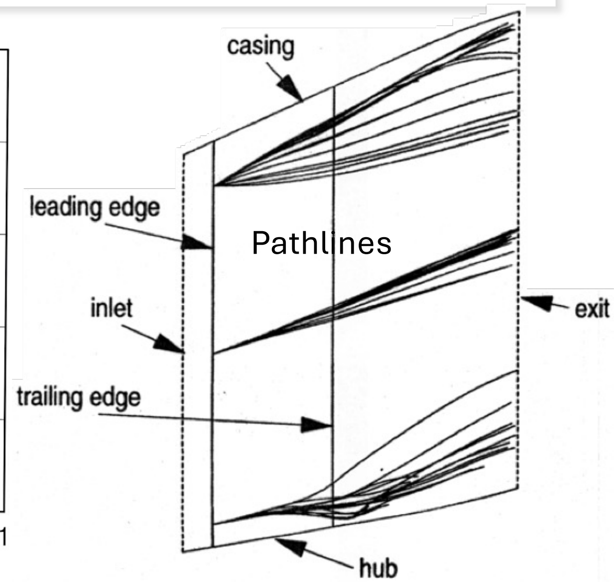
b) Contours from simulation

Rig schematic



Profile of Rotor Efficiency

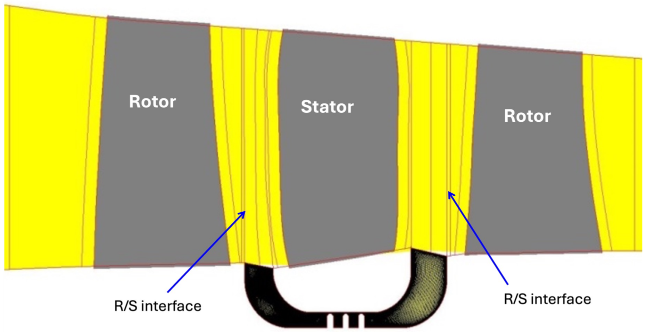


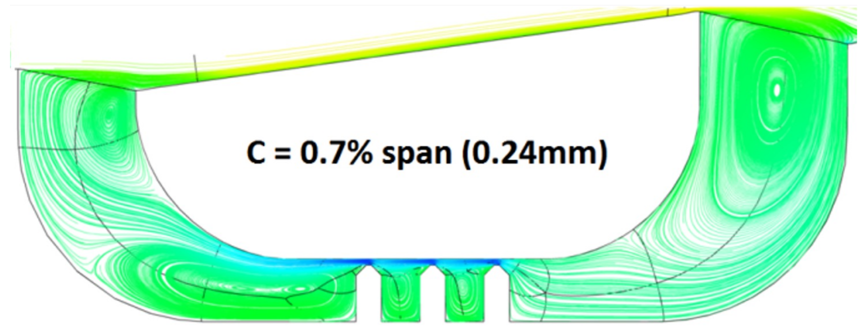


High endwall slope of the casing of a low-pressure turbine vane can be used to increase the radius and raise the rotation velocity. However, this high slope means that low momentum fluid may not stay attached to the endwall. It then appears to be a deficit in total pressure at a lower span.

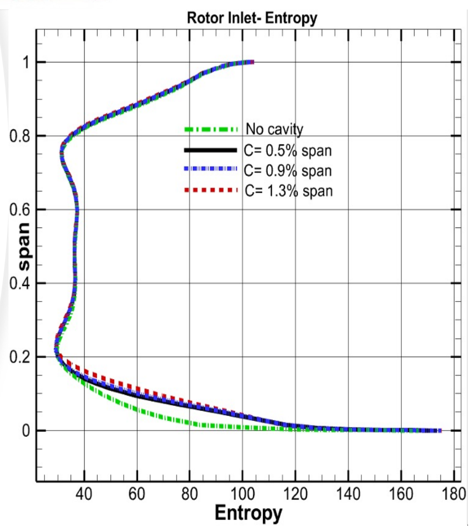
1996

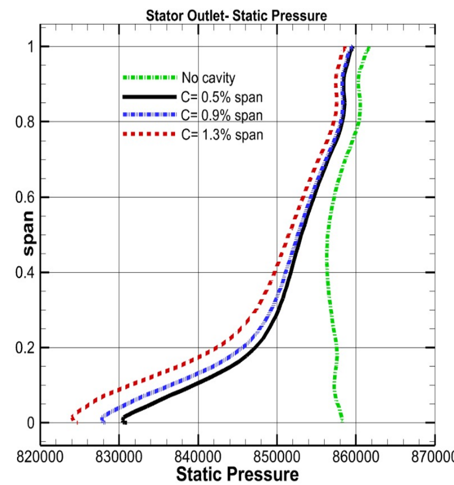
Cavity Flows





- Based on EEE HPC rotors 6&7plus stator 6
- Fine-Turbo with NLH
- Understand hub clearance gap sensitivities
- Shear work model developed

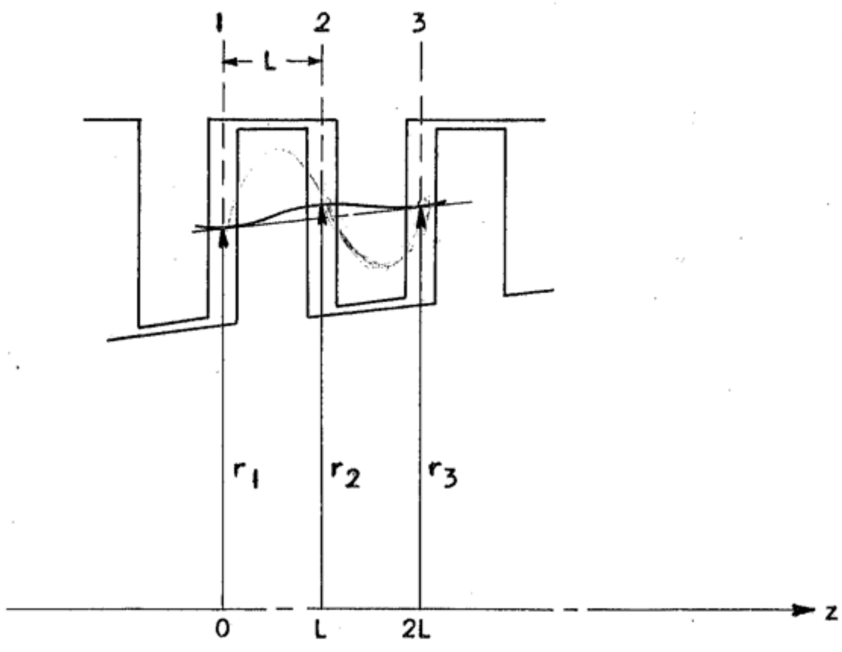




Due to the static pressure change across a compressor stator, the flow goes through the seal teeth from downstream to upstream. Tighter clearances reduce the mass flow through the cavities and seal teeth. However, the Total Temperature rise across the seal teeth will be greater for the tighter clearance.

2017

Radial Equilibrium paper by Wu, 1949



Tapered passage.

Figure shows the stations and streamline displacement

The paper explains how the radial pressure gradient can be related to flow quantities

The displacement equations essentially relate to the streamline curvature

Not explicit in formulation

Wu, Chung-Hua and Lincoln Wolfenstein, "Application of Radial-Equilibrium Condition to Axial-flow Compressor and Turbine Design," NACA Tech Note 1796, Lewis Flight Propulsion Laboratory, Cleveland, Ohio, January, 1949.

Streamline Curvature used in Axisymmetric Flow Solution Method

Smith and Novak published separate papers in 1966 on Radial Equilibrium or SLC methods

The meridional angle is:

$$\emptyset = \tan^{-1} {V_r}/{V_z}$$

Curvature is:

$$C = 1/r_m = 1/r_c = -\partial\emptyset \,/\, \partial m$$

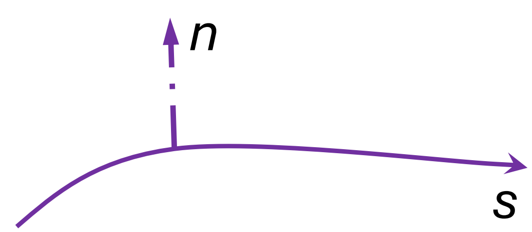
also

$$C = {y''}/{(1 + y'^2)^{3/2}}$$

Pressure Gradient in 2D

n is normal to the streamline

$$\partial p \,/\, \partial n = \rho C V^2$$

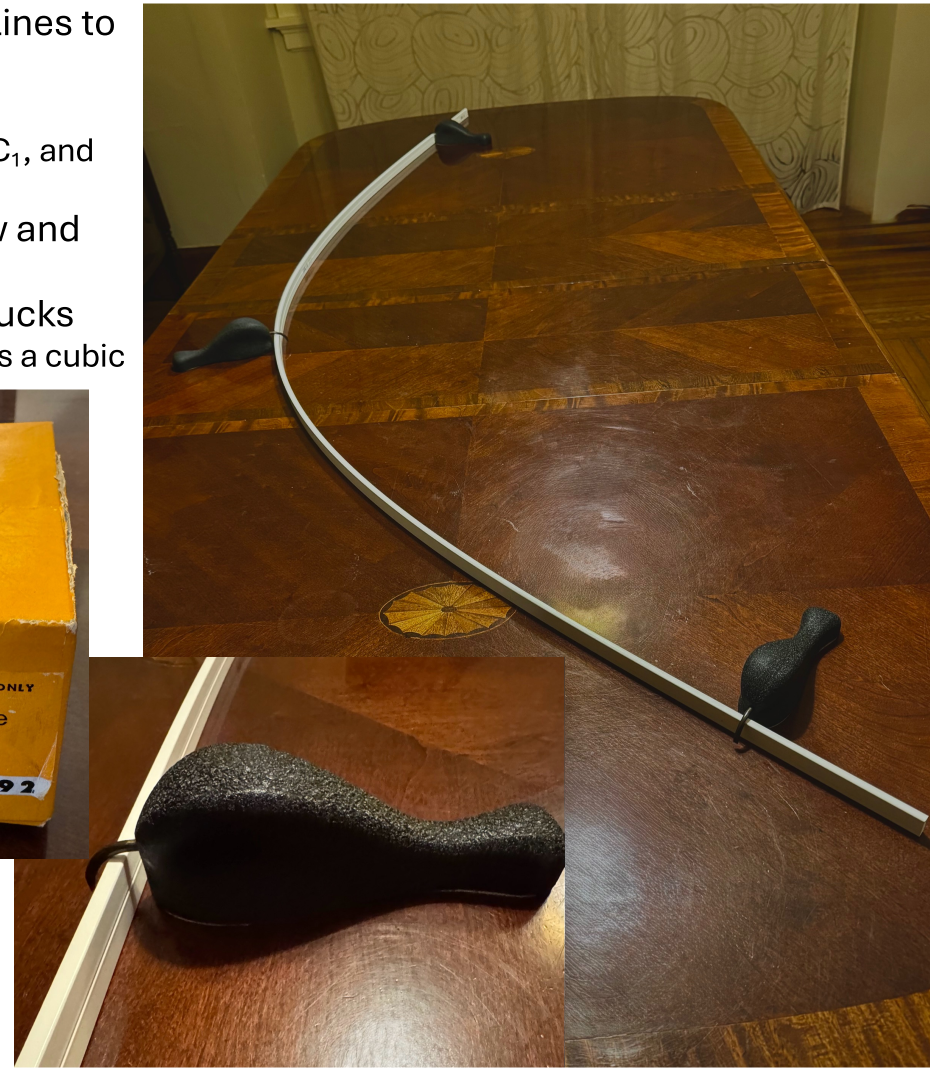


These equations show why Curvature is used rather than radius of curvature. A flat plate (cylindrical endwalls). It has an infinite radius of curvature which would be difficult to handle numerically.

I had the privilege to work under Roy Smith and for Dick Novak

Cubic Spline

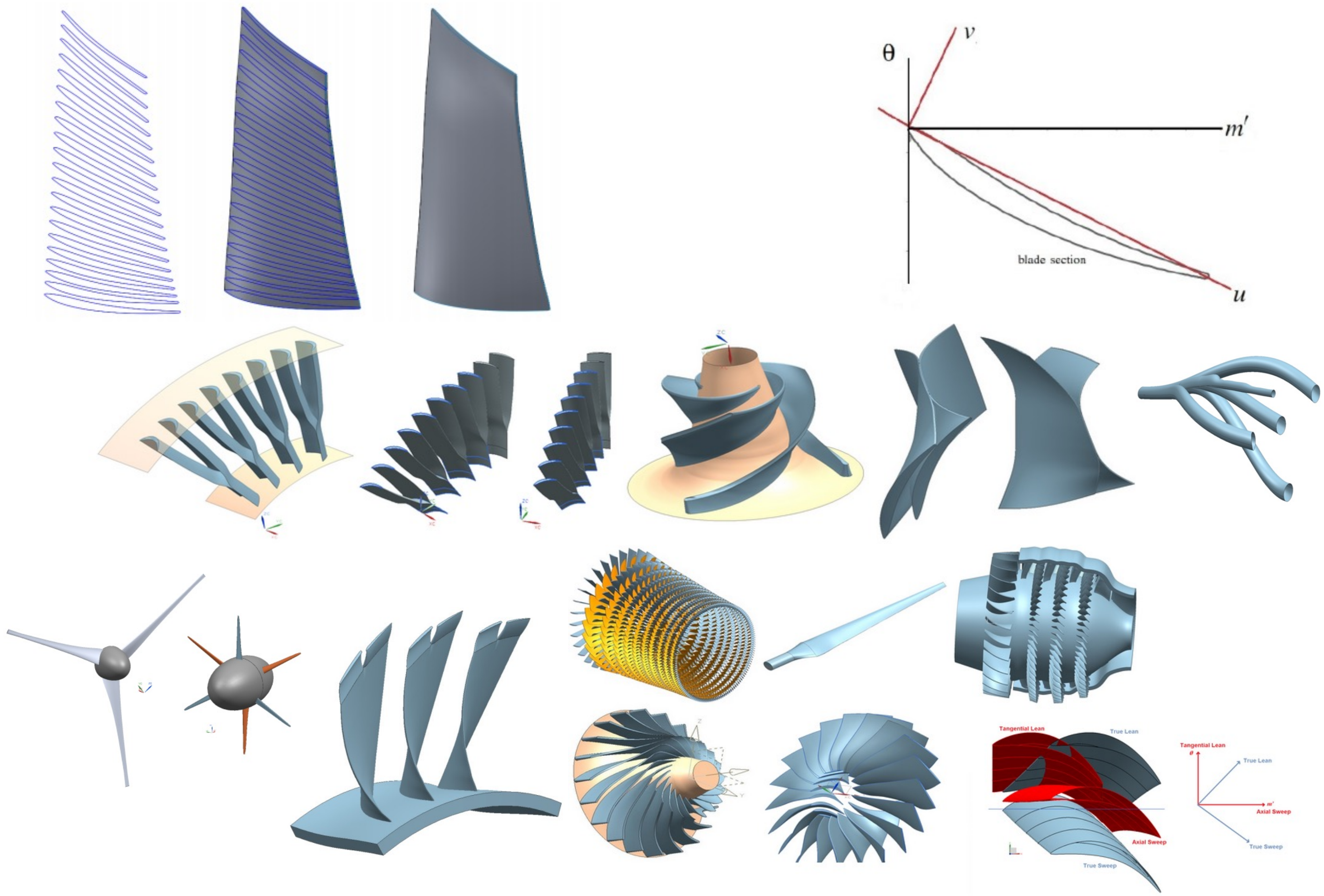
- Many Streamline Codes use Cubic Splines to get the Curvature
- 3rd order polynomial between knots
  - Continuous in value, C_0, 1st derivative, C_1, and 2nd derivative C_2
- Special care is taken for transonic flow and extent of stencil
- Similar to drafting spline with lofting ducks
  - Thin beam theory shows displacement is a cubic between knots



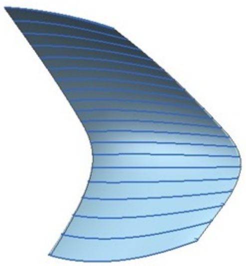
Physical splines used for boat layout and turbine blades

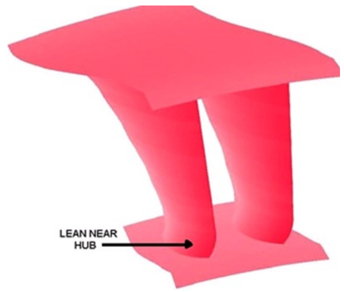
Use Curvature Concept as Basic Parameters for Blade Design

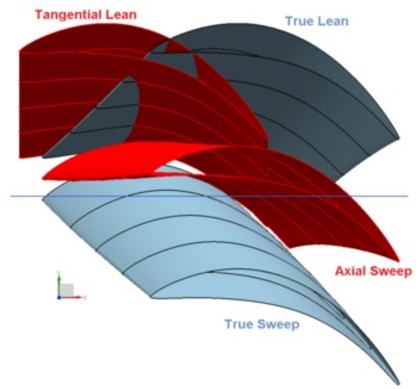
T-BLADE 3 Turbomachinery Blade Generator

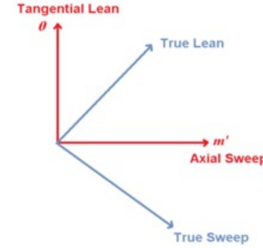


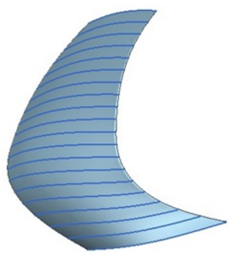
B-spline defined Sweep and Lean with options

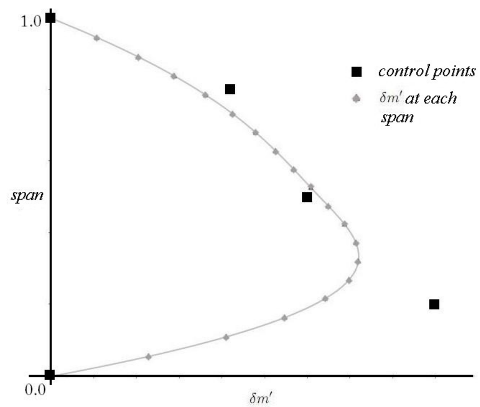




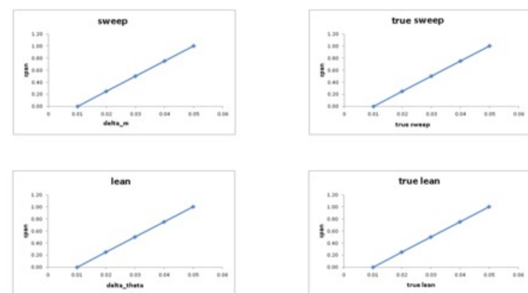








Spanwise Sweep Perturbation



Radial variation of lean, sweep. LE angle and TE angle using B-splines introduce by Kiran Siddappaji

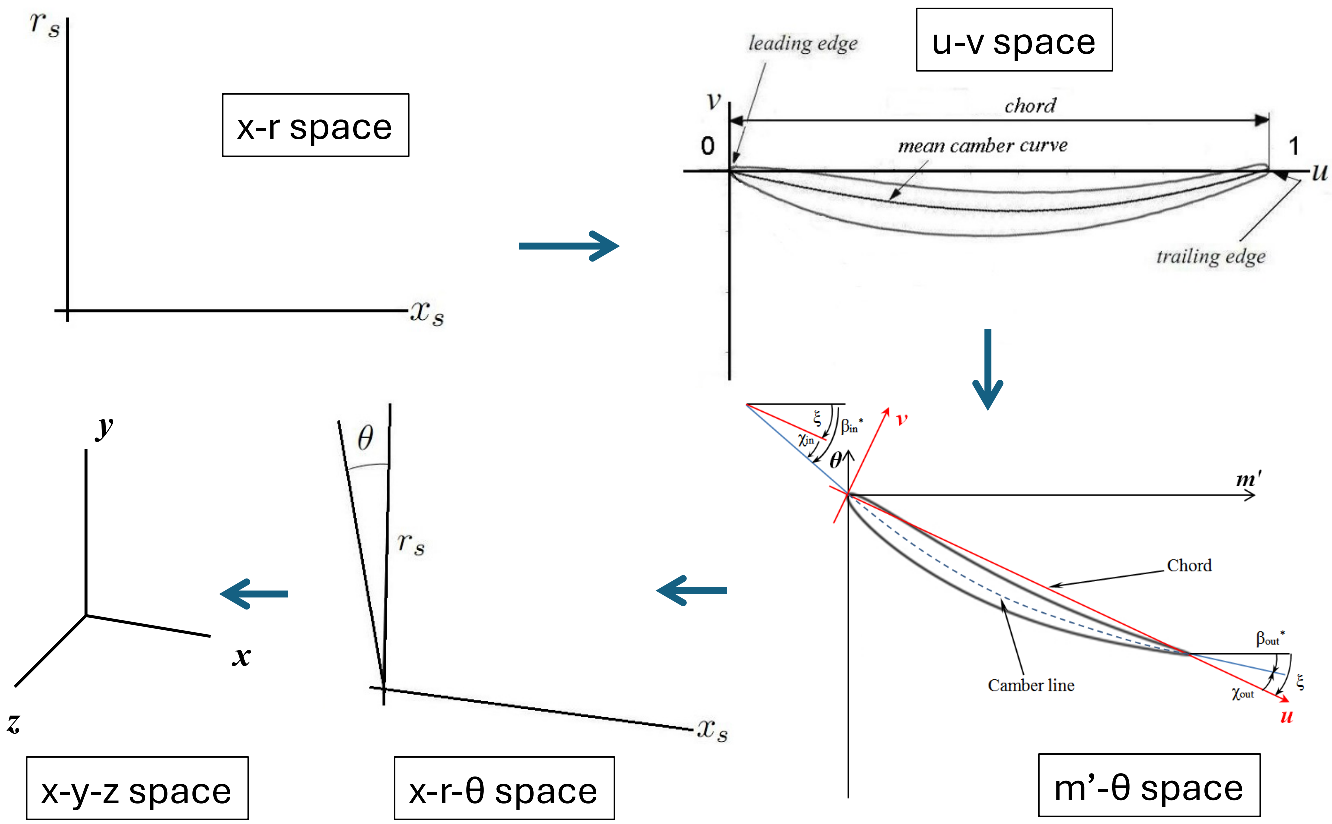
Optimization

- Needs parametric (variables) geometry generator – T-Blade3
- Needs a grid generator and solver
  - MISES
    - 2D or quasi-3D blade to blade solver
    - solves for streamlines and a coupled boundary layer
    - Newton Solver allows convergence to machine zero in about 10 iterations
  - XFOIL – airfoil design and analysis code with similar coupled boundary layer as MISES
  - MTFLOW
    - Axisymmetric version of Mises
    - A version with loss models is T-Axi
  - Fine/Turbo and Autogrid
    - Developed by Numeca, now Cadence
    - Autogrid reads sections of blade geometry
    - Many turbulence unsteady options
    - Convergence is typically not to machine zero
- Define one or more objective functions: loss, stress
- Optimizer
  - Gradient based for MISES
  - Genetic Algorithm for 3D
  - OpenMDAO and SciPy directly, have been used
- Scripts to tie things together (now written in python)

Future optimization will use SciPy other optimization tools

Coordinate System

Blade constructed in u-v space



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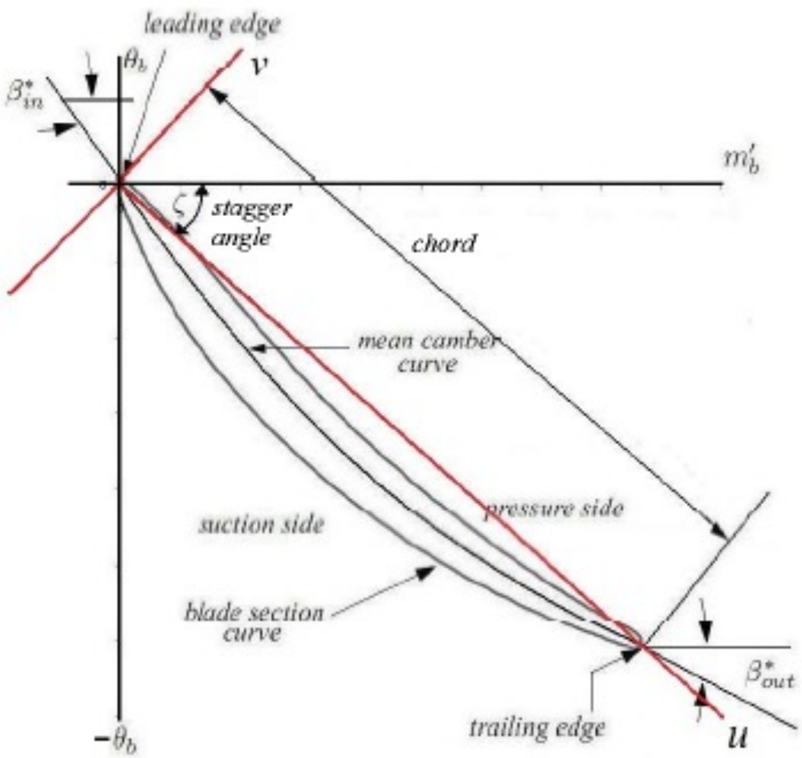
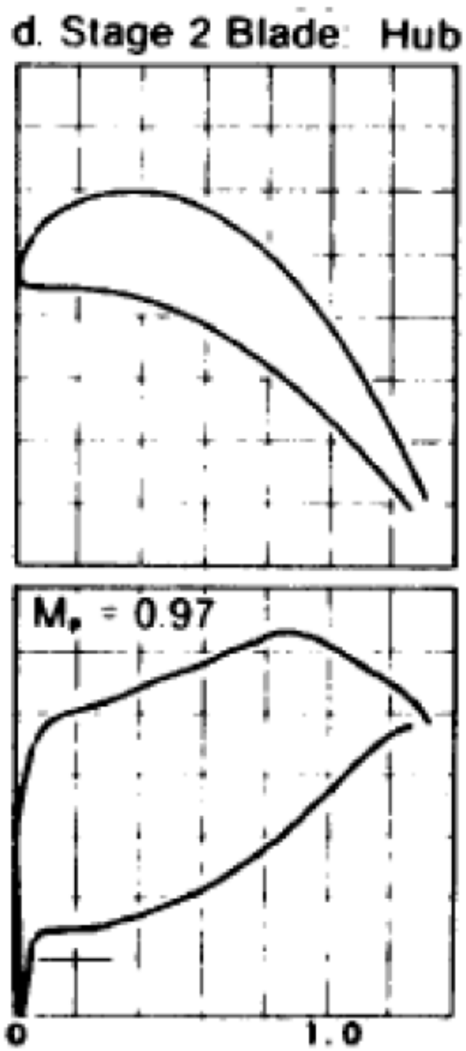
Airfoil parameters



- β is the relative flow angle
- β* is the blade angle
- Incidence Angle: if β_{in} greater than zero then $i = \beta_{in} - \beta*_{in}$ and if $\beta*_{in}$ is less than zero then $i = \beta*_{out} - \beta_{out}$.
  - Angle between the chord and a reference line around the fuselage
  - Fixed and cannot be varied during flight
  - Not to be confused with angle of attack
- Deviation Angle: if camber is negative then $\delta = \beta_{out} - \beta*_{out}$ and if camber is positive then $\delta = \beta*_{out} - \beta_{out}$
- Stagger Angle: angle between the chord line and m'_b axis

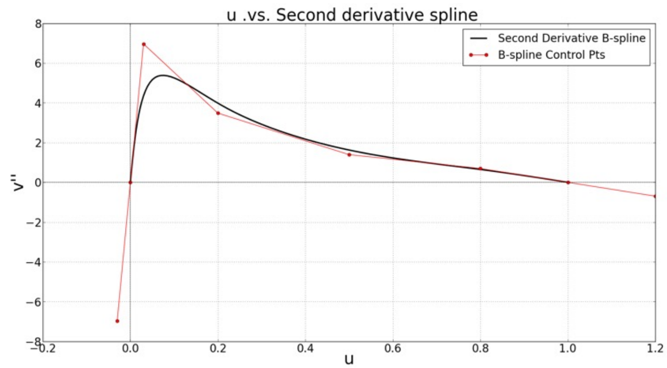


EEE HPT Rotor 2 Hub Example

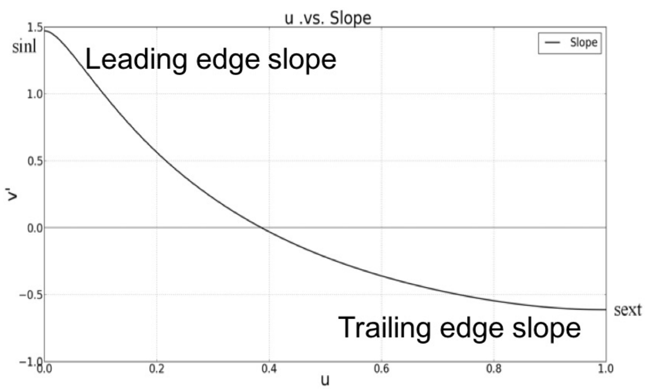
Rotor second stage hub section data	
Number of blades	70
Rotor inlet relative flow angle	31.5^o
Rotor exit relative flow angle	59.9^o
Rotor inlet relative Mach No.	0.339
Rotor exit relative Mach No.	0.724
Hub radius	31.115 cm
Trailing edge thickness	0.1575 cm
Axial width	3.353 cm

Timko, L. P., 1990. Energy efficient engine high pressure turbine component test performance report. Tech. Rep. NASA CR - 168289, National Aeronautics and Space Administration, September.

Use Second Derivative (Curvature) to define Meanline



B-Spline used



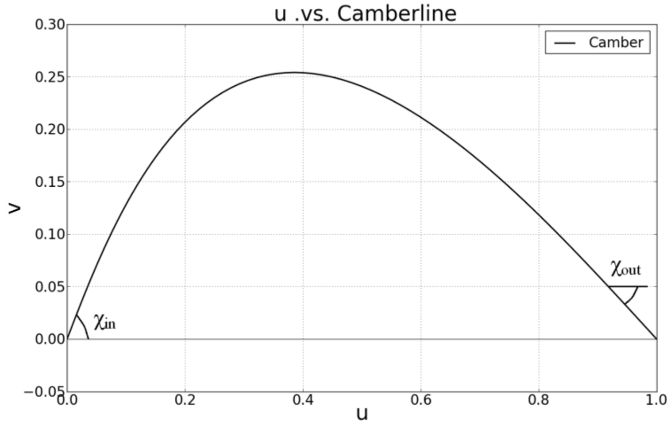
Integrate to Get Slope

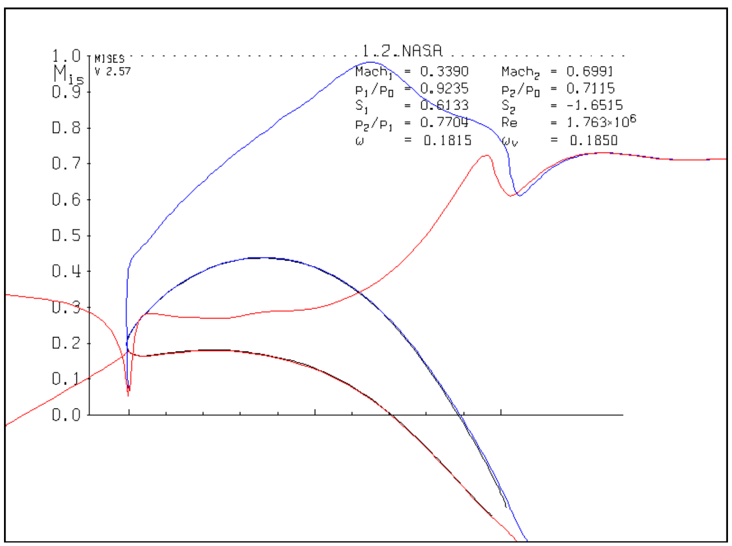
$$v'(u) = \int k\left(v''(u)\right) du + tan\left(\chi_{in}\right)$$

Constant to get v(1)=0

Inlet angle in u-v space

Get Meanline, Add thickness, Apply Stagger





Integrate to Get Meanline

$$v(u) = \int v'(u)du$$

$$v(0) = 0$$

$$v(1) = 0$$

le and te metal angles in m'-theta

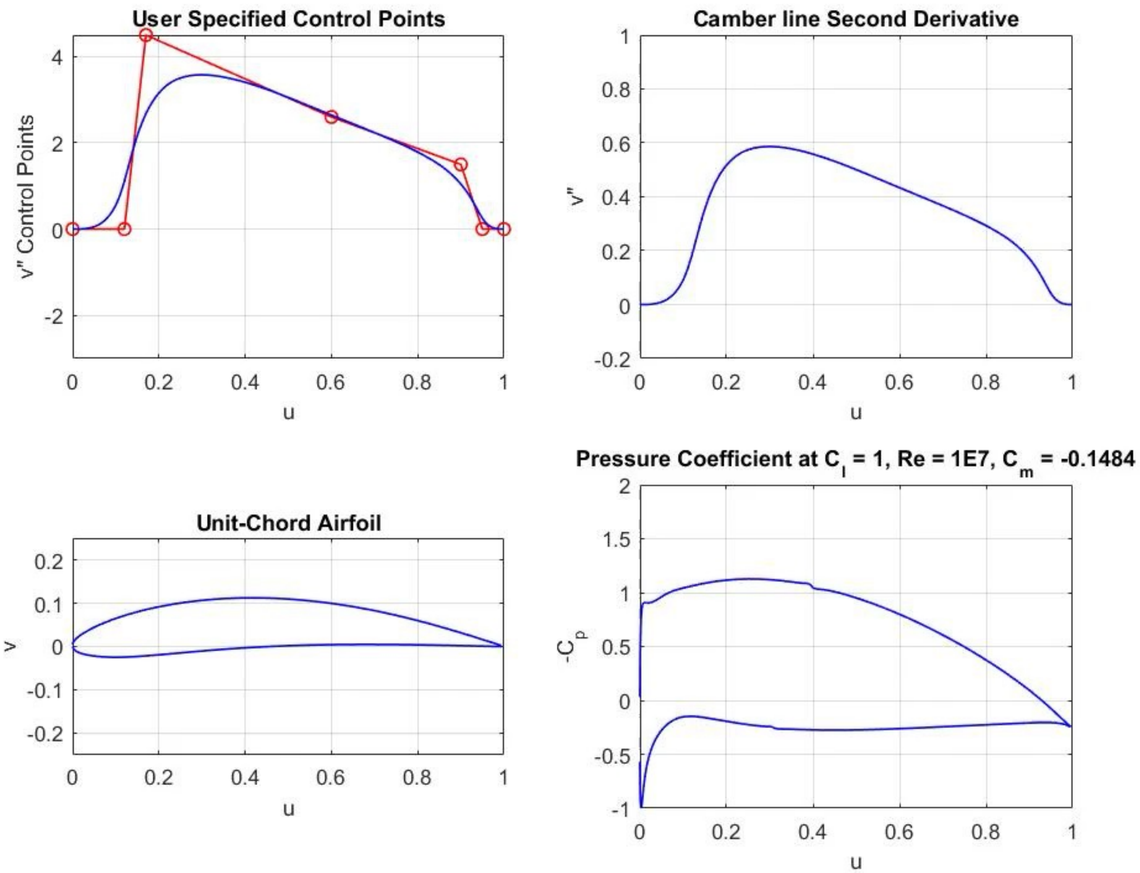
output

$$\xi = \left(\frac{\beta^*_{in} + \beta^*_{out}}{2}\right) - \left(\frac{\chi_{in} + \chi_{out}}{2}\right)$$

is stagger

Mises Solution for blade similar to EEE HPT R2

Geometry and Aerodynamics Manipulation



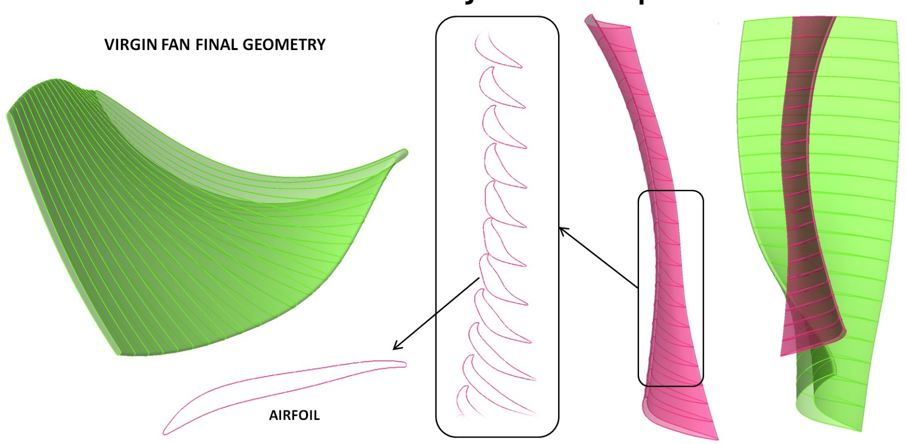
Low Speed Fan Design Process and Properties

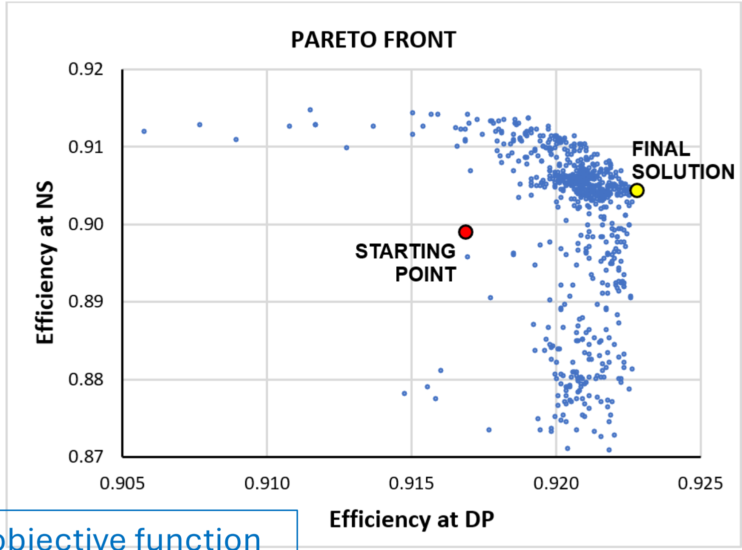
- Requirements, assumptions and limitations:
  - load coefficient = 0.47 and flow coefficient = 0.50
  - rotor hub-to-tip ratio = 0.30-0.33
  - limited number of motor options on the market
  - maximization of stage efficiency for axisymmetric flow while maintaining the adequate stall margin (at least 12%)

Fan diameter [m]	0.58
Rotor tip Mach number	0.223
Rotor inlet hub/tip radius ratio	0.31
Running tip clearance (% span)	0.35
Number of rotor/stator blades	15/31
Rotational speed (RPM)	2500

Fan Design Process and Properties

- Design steps:
  - simple one-dimensional analysis to establish the basic parameters of the fan and find a satisfactory operating point of the motor and the fan
  - initial three-dimensional blade design using open-source software (TCDES and T-AXI, developed by the GTSL at University of Cincinnati)
  - a series of manual modifications to the initial geometry - based on the literature or preliminary CFD results (blades parametrization in T-Blade3)
  - an automatic multi-objective optimization

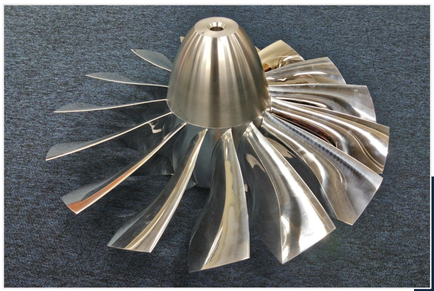


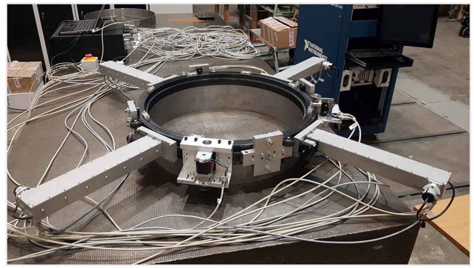


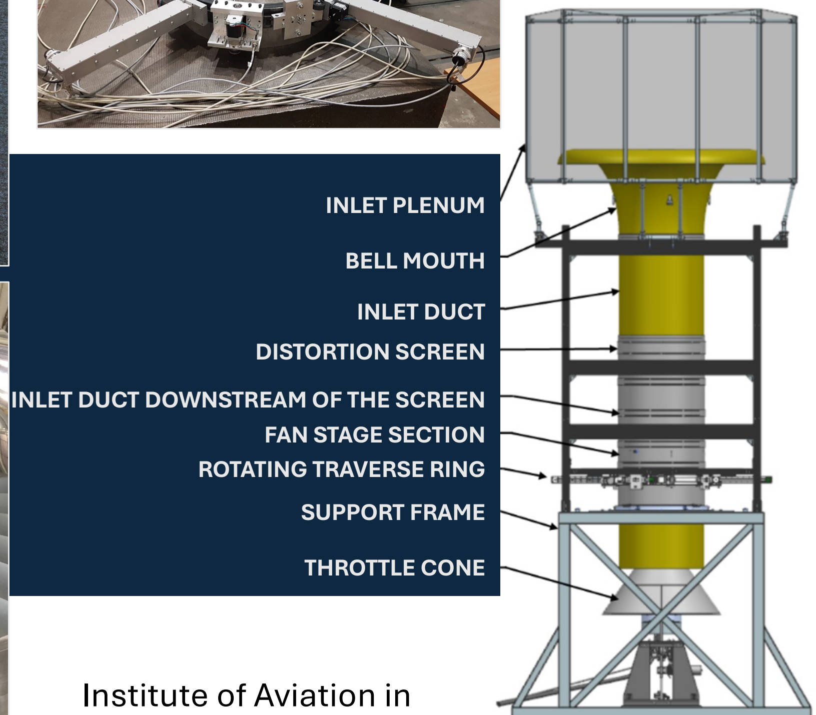
Both design point efficiency and a point closer to stall are added for the objective function

Experimental Test Rig

- Inlet - mass flow rate estimation in real-time
- Other sections designed to work with a dedicated rotating traverse system:
    - 4 different probes
    - radial and circumferential traversing (180°)
    - fully automated and precise cross-sectional measurements



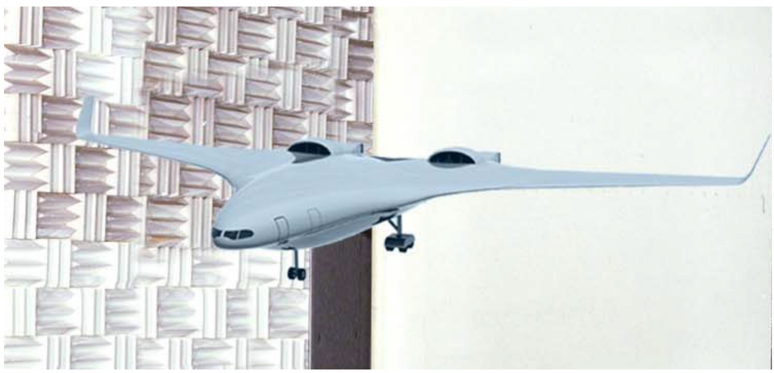


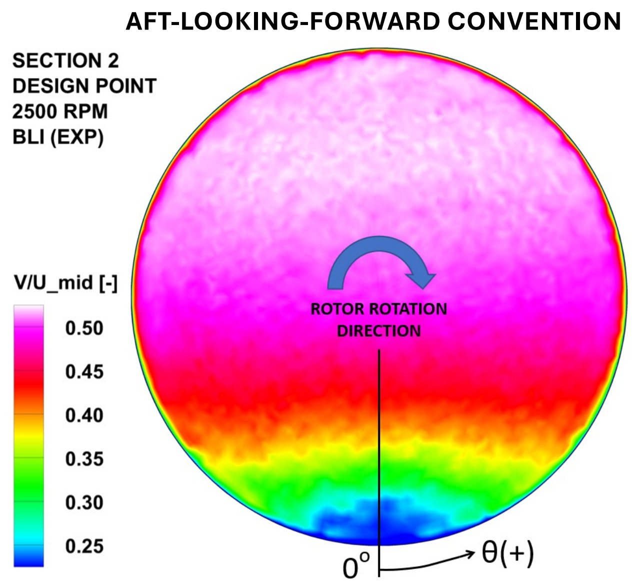


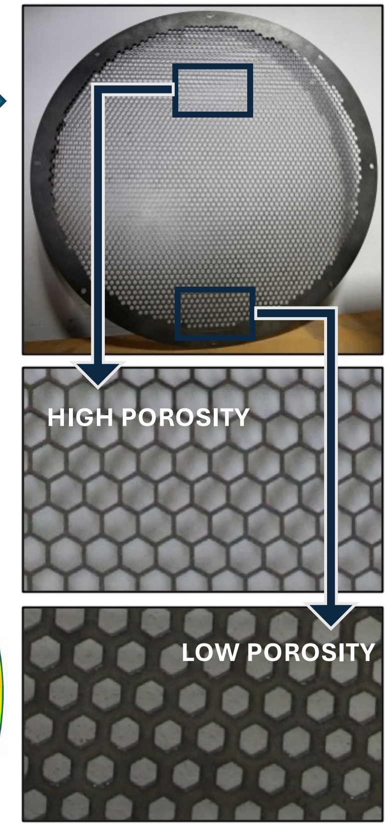
Institute of Aviation in Warsaw, Poland

Inlet Distortion Characterization

- Inlet distortion on the test rig introduced by a variable porosity screen
- Inlet distorted velocity profile based on the profile obtained in Cambridge-MIT Silent Aircraft Project (SAX-40)





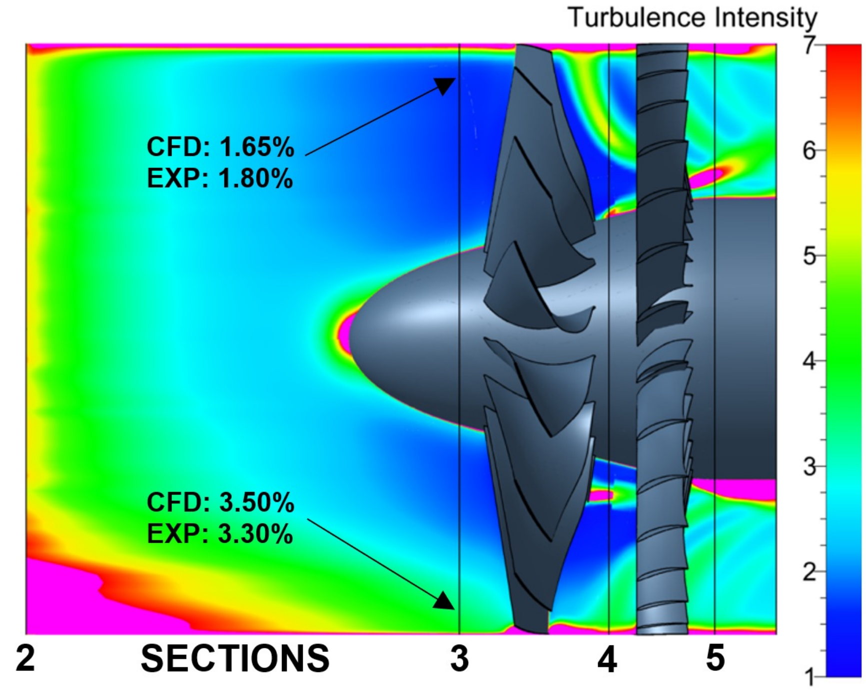


Numerical Modeling

- Numerical Setup
  - full-annulus time-marching RANS simulations (FINE/Turbo solver)
  - k-ω SST turbulence model with AGS algebraic transition model
  - gas model - compressible (Air Perfect Gas)
  - spatial discretization – central scheme
  - temporal discretization – explicit four stage Runge-Kutta scheme and dual time stepping technique

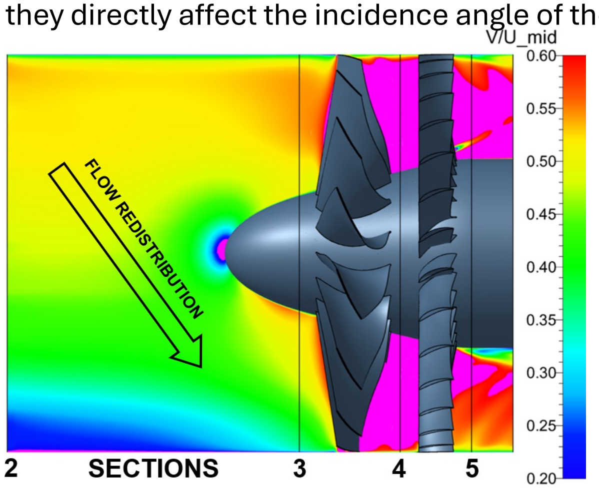
Boundary Conditions

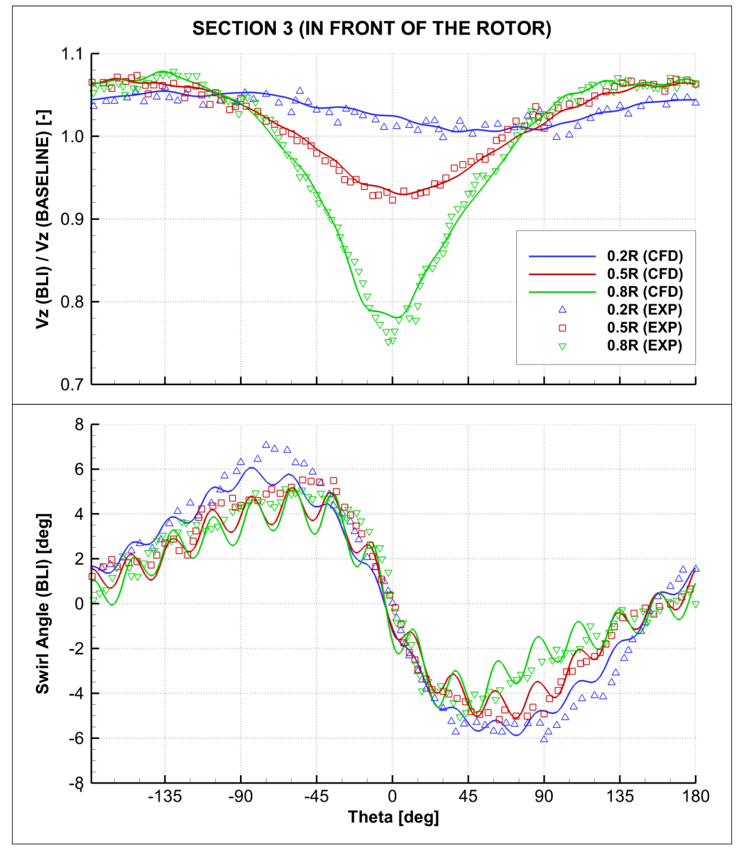
- inlet BC (section 2) – experimentally measured total pressure and turbulence intensity profiles, estimated turbulence length scale profile
- outlet BC – static pressure adjusted to maintain the specified MFR value



Unsteady Rotor Loads

- Flow Redistribution Upstream of the Rotor
  - Fluid migration from the upper half of the annulus towards the bottom:
    - reduction of the difference in <u>axial velocity value</u>
    - the appearance of the <u>circumferential (swirl)</u> and radial components of the velocity vector
  - Changes in <u>underlined quantities</u> are particularly important because they directly affect the incidence angle of the rotor blades.



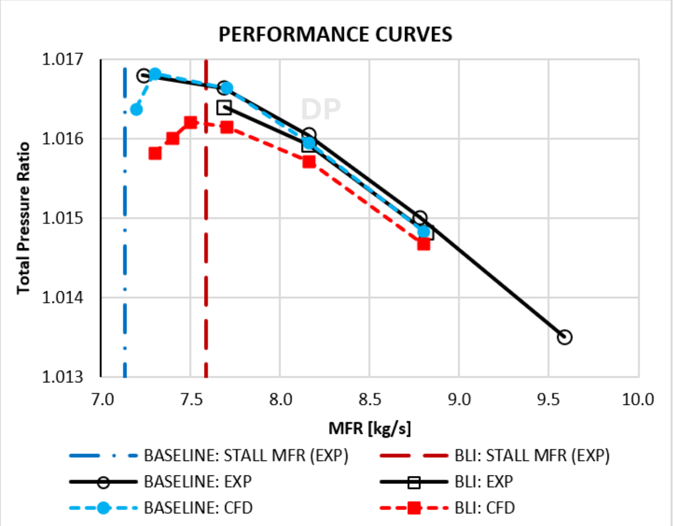


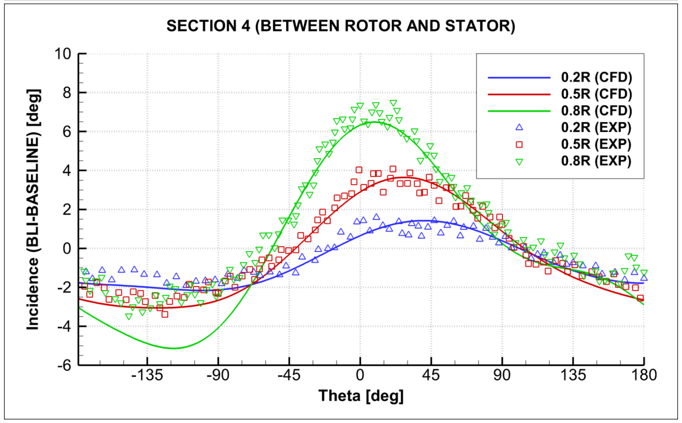
Performance Curves

- Stall Margin Reduction
  - Stall condition determination criterion used:
    - EXP: noise and MFR stability criterion
    - CFD: maximum PR criterion
- Stall Margin definition used: $SM = \frac{PR_{NS}}{PR_{DP}} \cdot \frac{MFR_{DP}}{MFR_{NS}} - 1$

Stall Margin			
	BASELINE	**BLI**	**REDUCTION**
EXP (noise level)	14.4%	7.5%	48%
CFD (max. PR)	~12.0%	~8.9%	~26%

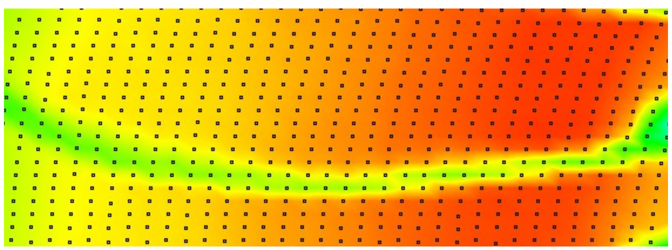
- Off-design work conditions of the stator blades → reduction of the stall margin
  - Variation of the stator incidence is higher than rotor incidence:
    - rotor incidence: (-3; 5) degree
    - stator incidence: (-4; 8) degree



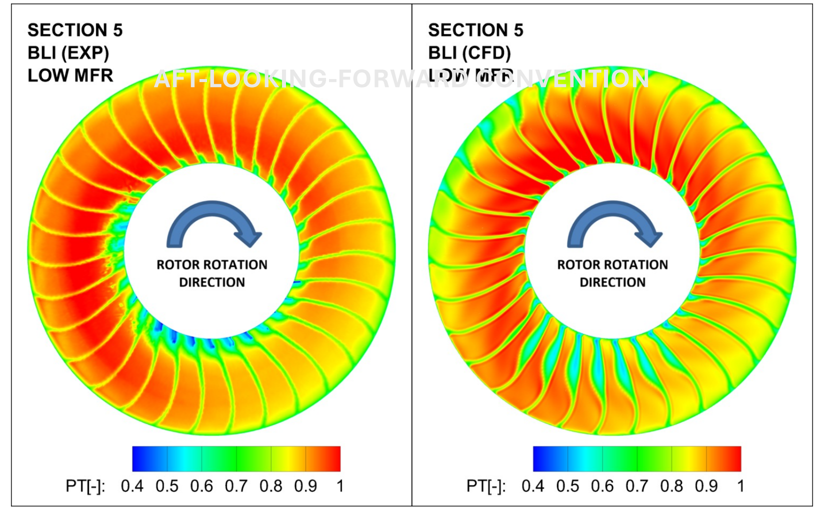


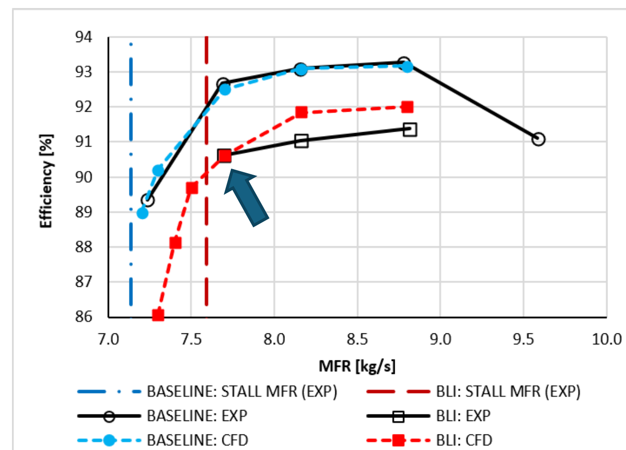
Stage outlet results discussion

- EXP vs CFD data – simulations validation
  - The greatest discrepancy for the lowest MFR – two regions of additional losses in CFD:
    - in the bottom part of annulus
    - near the casing
  - Insufficient resolution of the measuring point maps - overestimated total pressure ratio and efficiency in EXP?



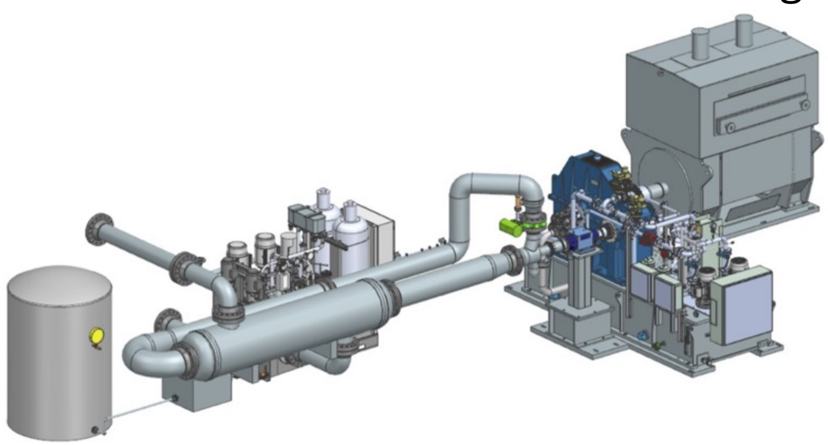
  - In section 5:
    - 9360 measurement points 18 hours of measurement time





The SCO_2 Axial compressor

- Echogen Pumped Thermal Energy Storage System (PTES) defines compressor requirements
- 9 stage 100 MW SCO_2 compressor design
- Scaled 10 MW first 3-stages of the compressor designed/optimized by UC and to be tested in NDTL's 10MW test cell
- Size: 0.25m in diameter and 15 cm in length



2021

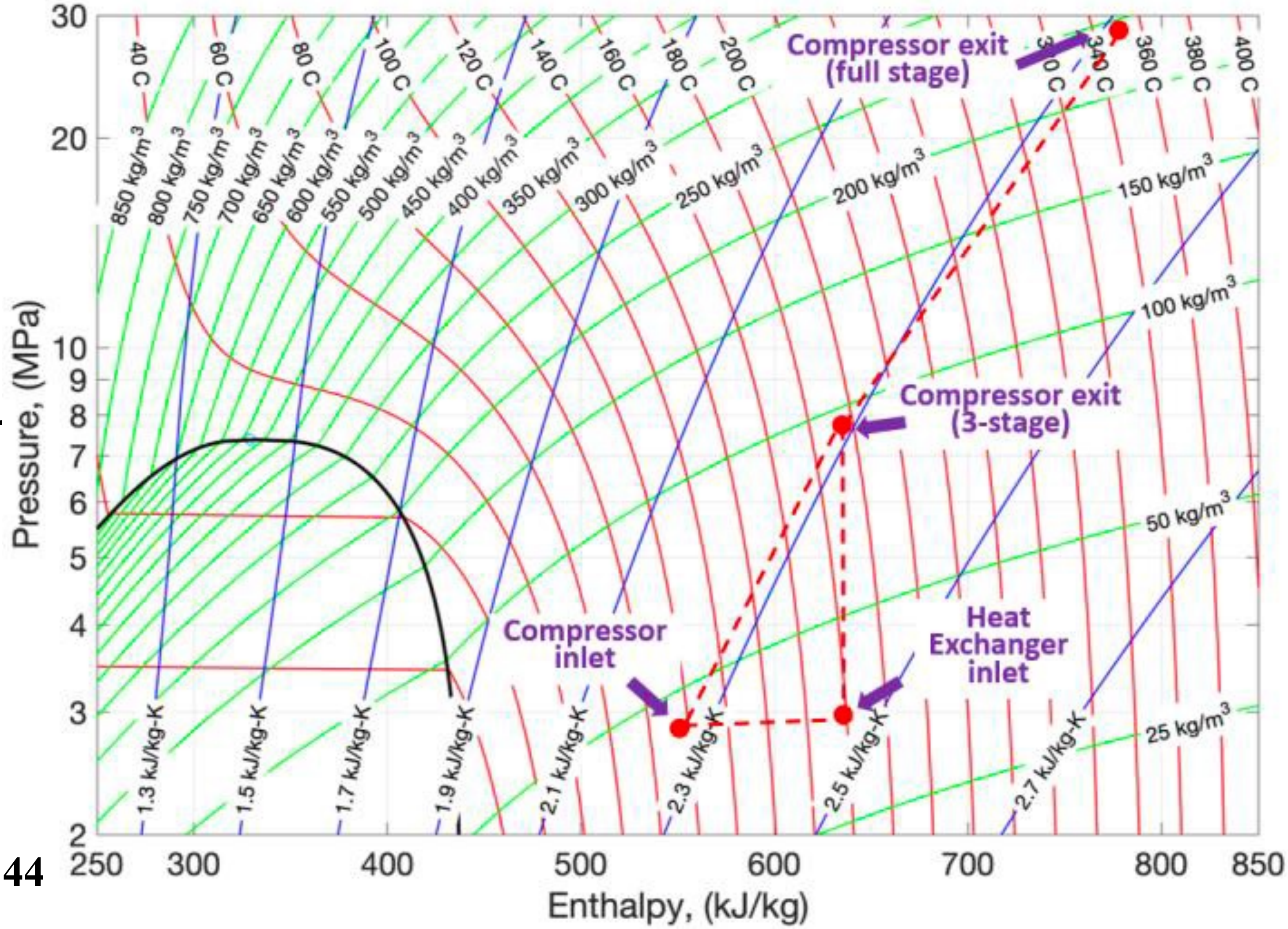
NDTL Supercritical CO_2 Compressor Test Facility

SCO_2

- High thermal efficiency
- Compact physical footprint
- Operational flexibility
- Abundant, low cost, non-toxic

- First Stage tested first with limit on mass flow due to S-CO2 supply system
- Three Stage tested next

Three Stage Design Conditions or p-h diagram



from **2021-sCO2.eu-144**

Axial Compressor Design/Optimization System

- Similar to traditional approach of using meanline – axisymmetric – 3D CFD – static FEM – Campbell diagrams
- Second and Third stage designs completed before first stage test

Details of Design System are Unique and Revolutionary

Axial Compressor Design

CO_2 Application

- Design team is one professor*, 4 graduate students, & 2 undergrads
- Open Source meanline code Py-C-Des using CO_2 properties in tables from Refprop
- 3D geometry from T-Blade3
  - Parametric
  - Creates sections on surfaces of revolution
  - 2nd derivative of blade meanline plus NACA thickness
  - Lean and Sweep
  - Creates solid model by connecting with ESP

Traditional

- Design teams usually in an aero group and separate structures group with information sent in files by hand
- Proprietary meanline code
- Very Simple geometry or proprietary geometry generator
  - Connections to CAD are proprietary or cumbersome

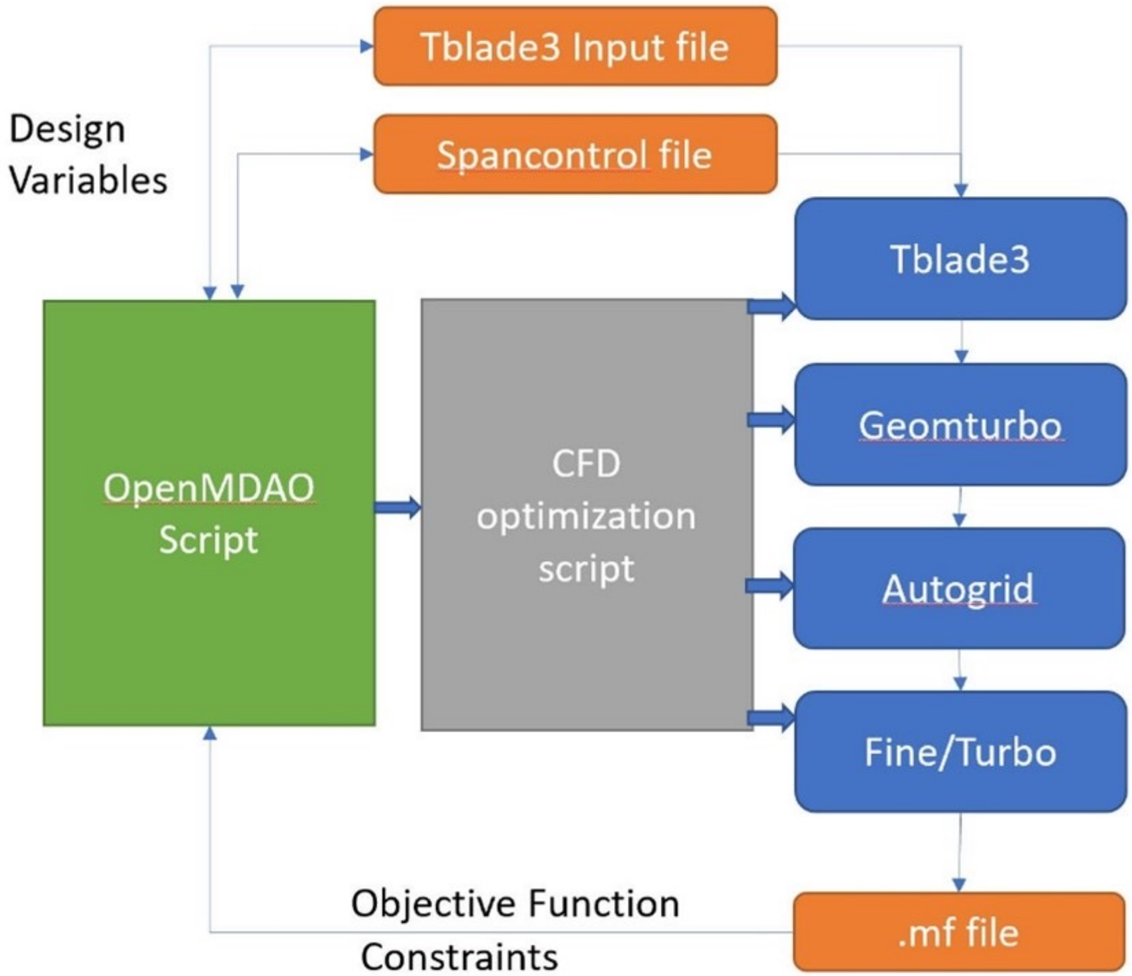
Axial Compressor Design

CO_2 Application

- No empirical base to start from – design from first principles
- Axisymmetric Solver from MIT mtflow (limited because fixed gamma)
- Builds in Off-Design Range & Operability
- Blade-to-Blade Optimization
  - design inlet angle and 7-deg incidence
  - Constrains exit angle
  - Solidity is a parameter (chord)
  - Uses OpenMDAO and Mises
- Parametric Optimization in 3D
- Solid model from ESP is used for FEM: Static stresses, Campbell Diagram, Automated hot-to-cold

Traditional

- Evolutionary step from a prior design
- Proprietary axisymmetric solver
- Operability improvements from design point changes
- Solidity comes from past experience
- Uses expert designer for blade-to-blade design or simple optimization
- Expert designer makes geometry changes by hand with hand running of simulation
- Solid models from geometry built in CAD by hand or specialized scripts
- Hot to Cold process is proprietary

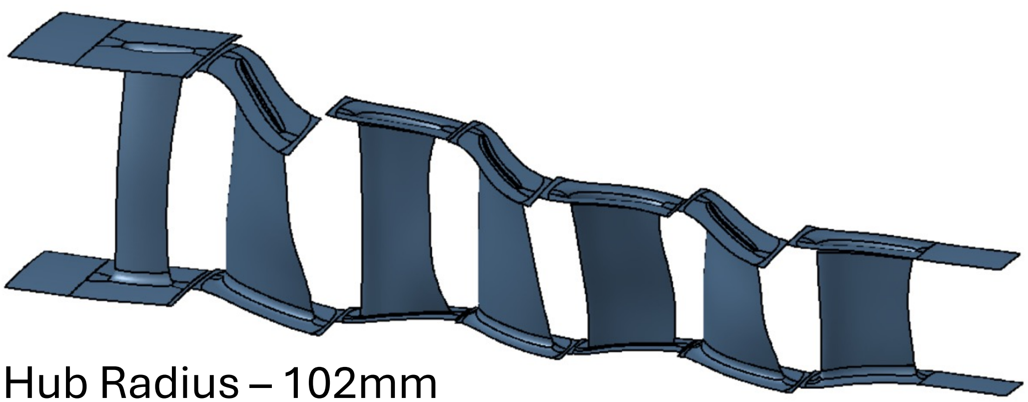


3D Optimization Flow Chart

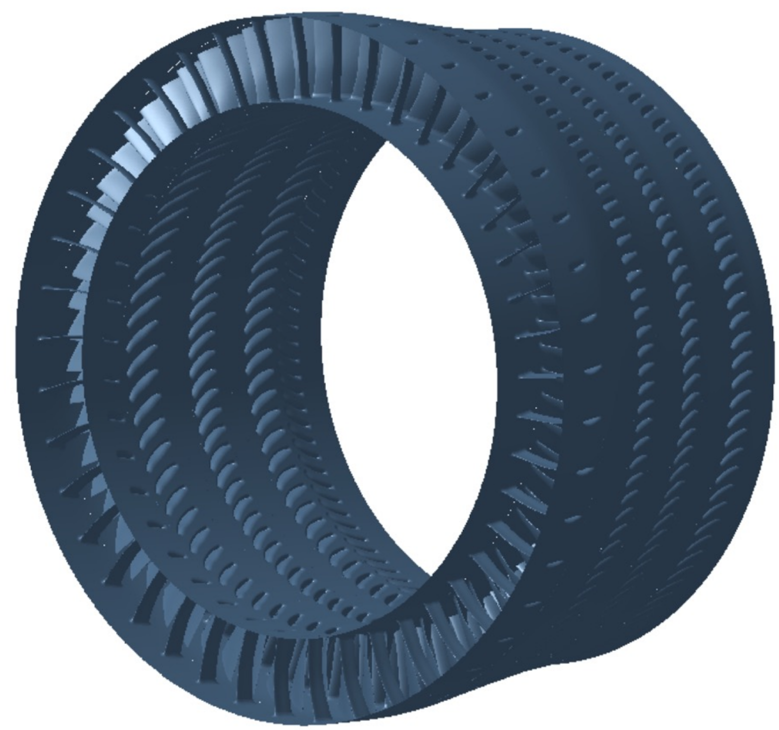
No constraints used for this application

Three Stage Design

Row	Tip Radius_LE (mm)	Hub Fillet (mm)	Tip Gap (mm)	Tip Fillet (mm)	Blade Count
IGV	134.79	1.6	-	1.6	43
R1	134.22	1.6	0.201	-	69
S1	131.56	1.6	-	1.6	114
R2	128.62	1.6	0.192	-	88
S2	126.24	1.6	-	1.6	112
R3	123.59	1.6	0.186	-	83
S3	122.09	1.6	-	1.6	101



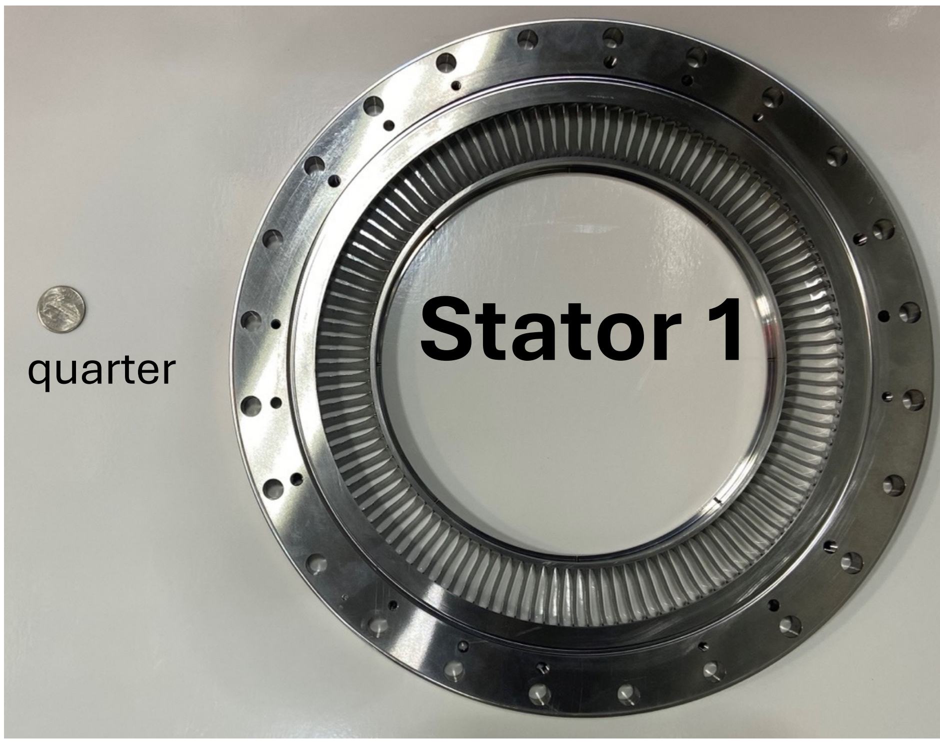
Hub Radius – 102mm



Three Stage Hardware

Rotor 1

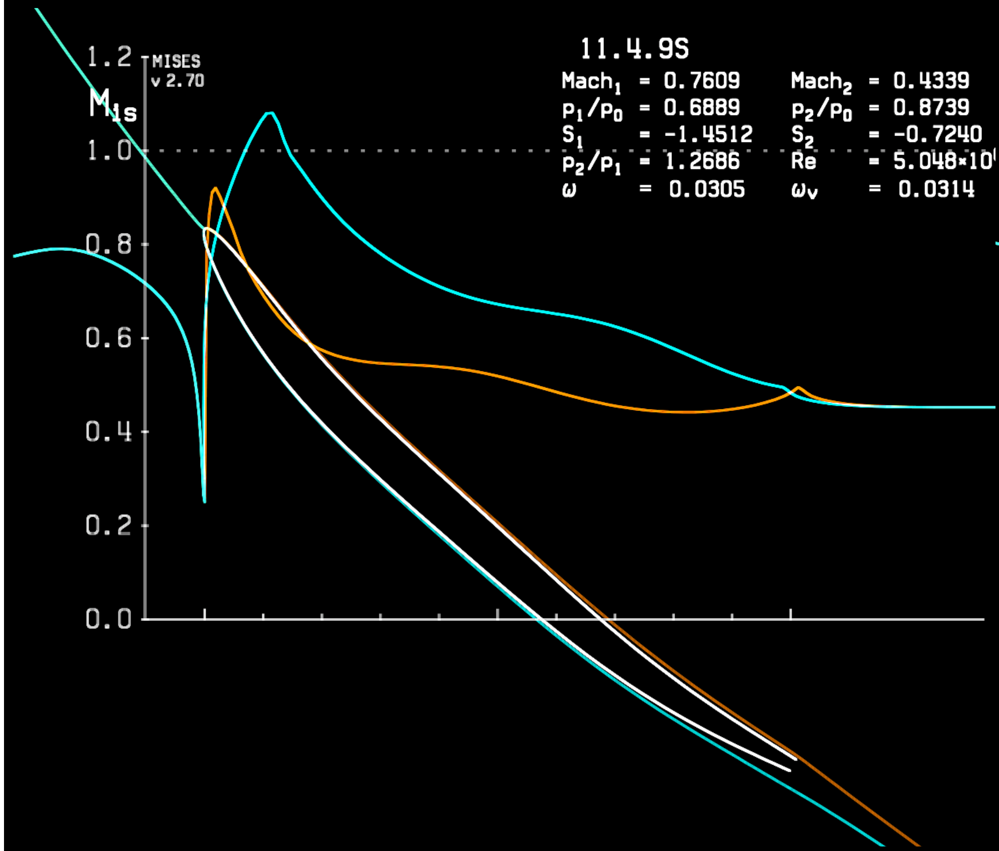
Hardware

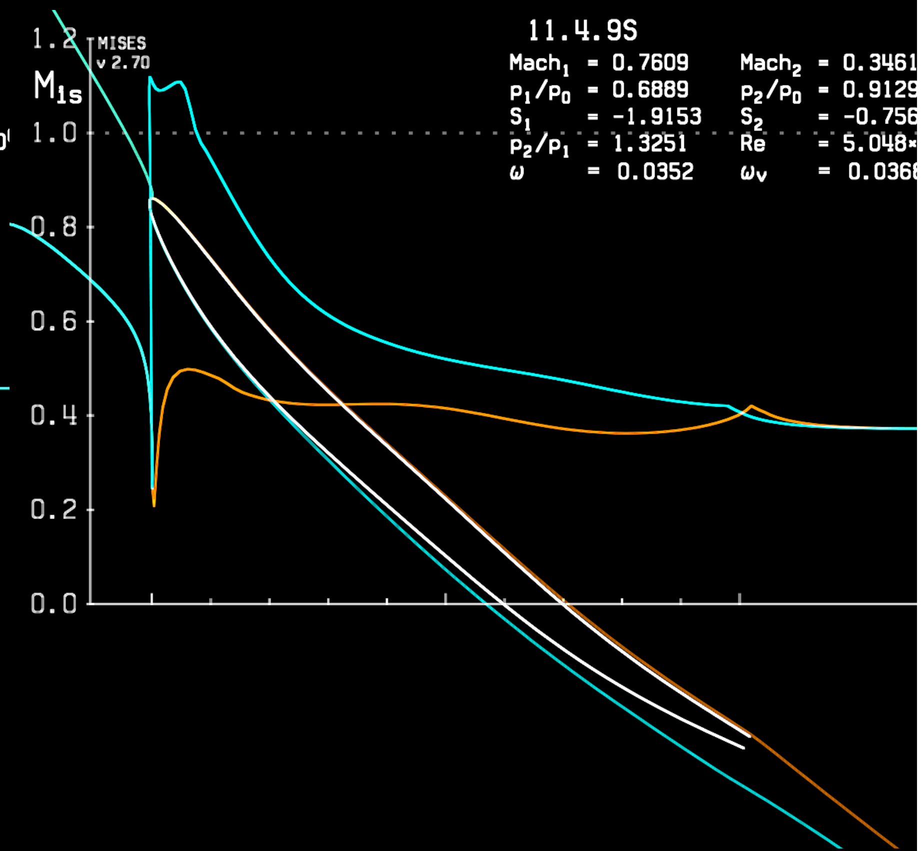


Rotor 2

Rotor 3

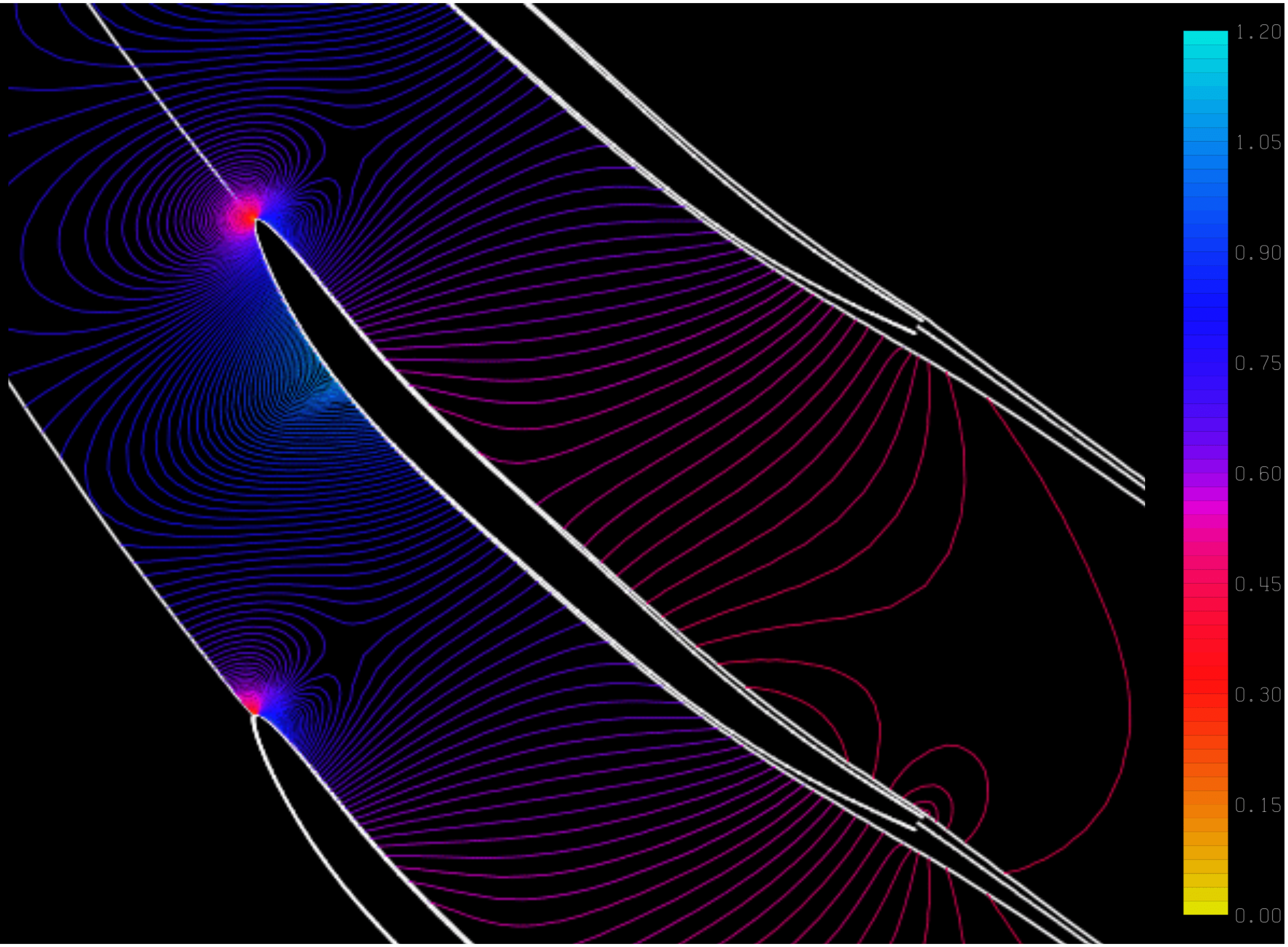
MISES (Quasi-3D Optimized Results)



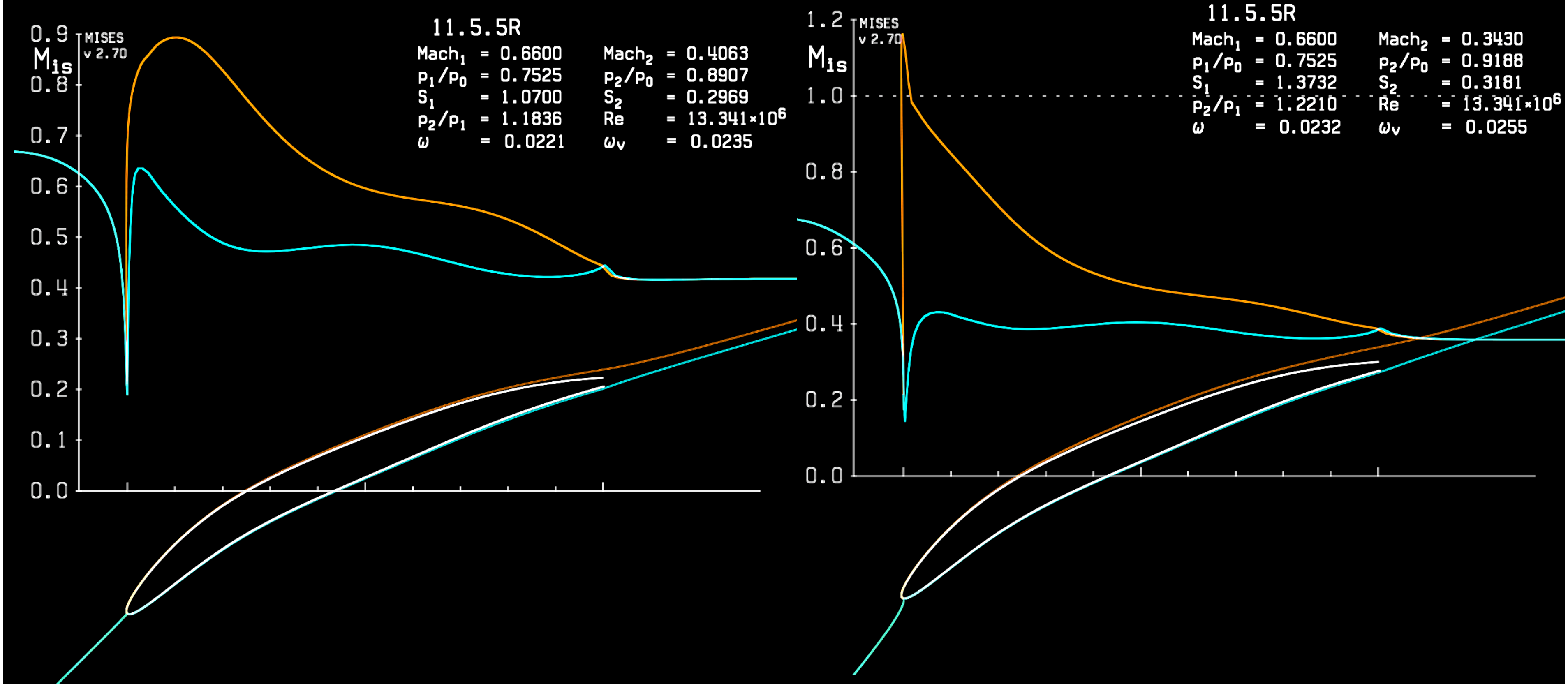


Design Incidence (left) and 7-deg incidence (right) rotor 2 blade (MISES)

Rotor 2 Mach Contours at Design Incidence



MISES (Quasi-3D Optimized Results)



Design Point (left) and 7-deg incidence right) Stator 2 (midspan)
Constrain to exit flow angle at the design incidence

CFD Details

Solver : Fine/Turbo

BC's inlet : PT at inlet, TT = 371.15K

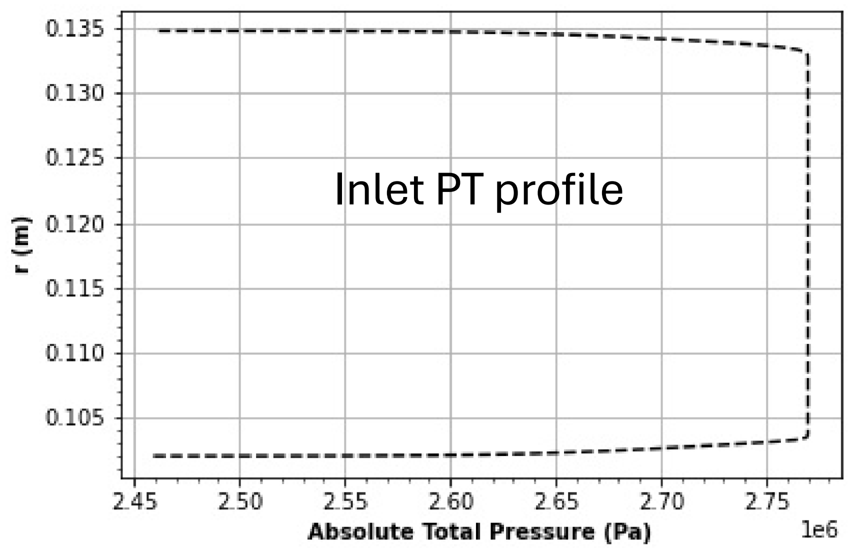
BC's outlet: Ps at exit, M = 0.47

Turbulence : Spalart-Allmaras (SA)

Mixing Plane

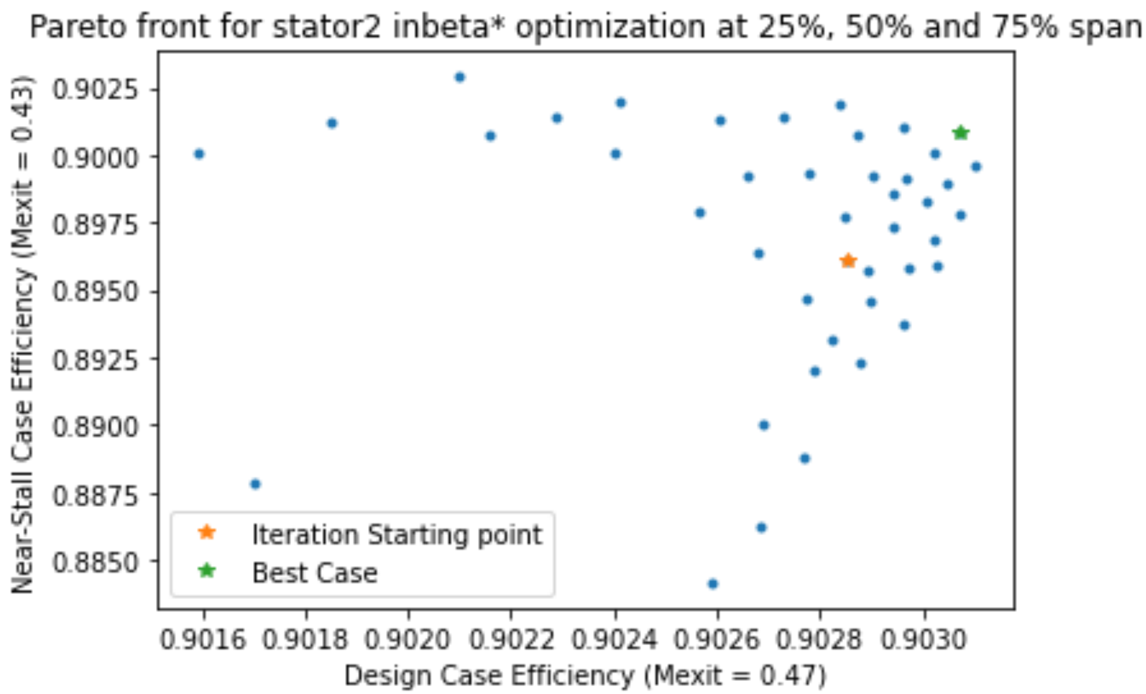
RPM = 19800

Row	Spanwise Points	No. of Grid Points
IGV	193	3.82 million
R1	289	9.9 million
S1	193	8.6 million
R2	305	11 million
S2	193	8 million
R3	305	10 million
S3	193	8 million
Total Grid Points		60 million
First Cell Width		1.2×10^{-7} m



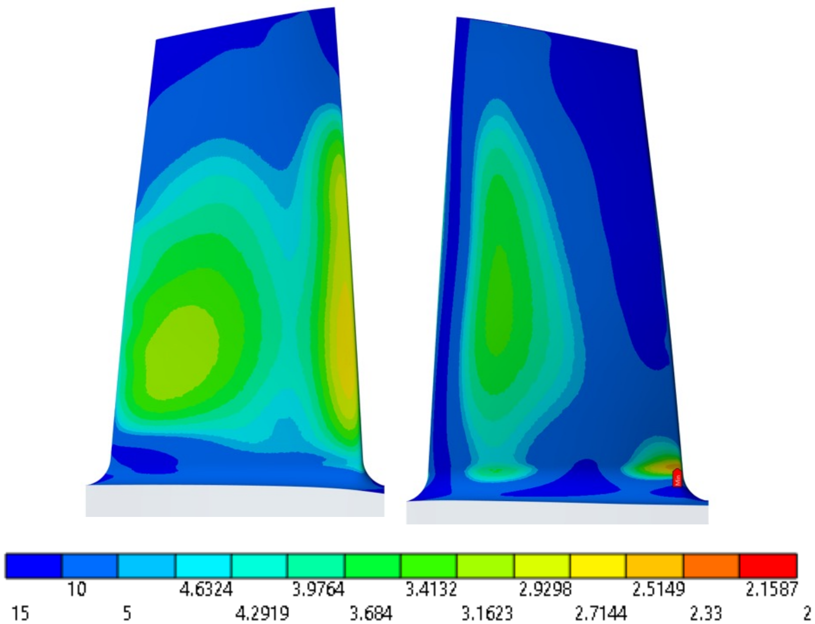
3D Optimization

- Driver – Genetic (OpenMDAO)
- Population size – 50
- Crossover – 0.1
- Mutation – 0.01

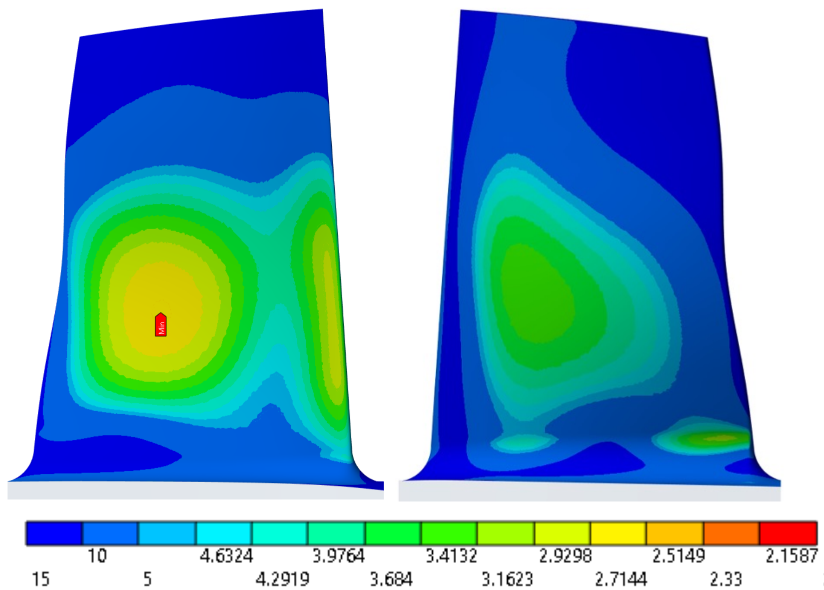


Objective Functions are a Design Point Efficiency and an Off Design Efficiency (closer to stall)

Safety Factor Contours

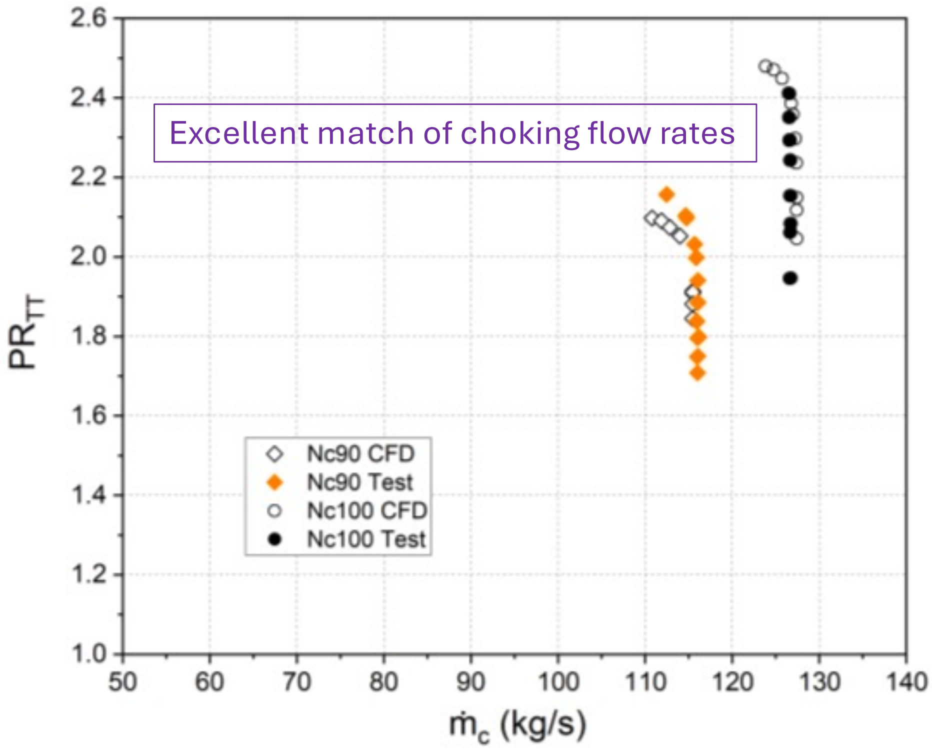


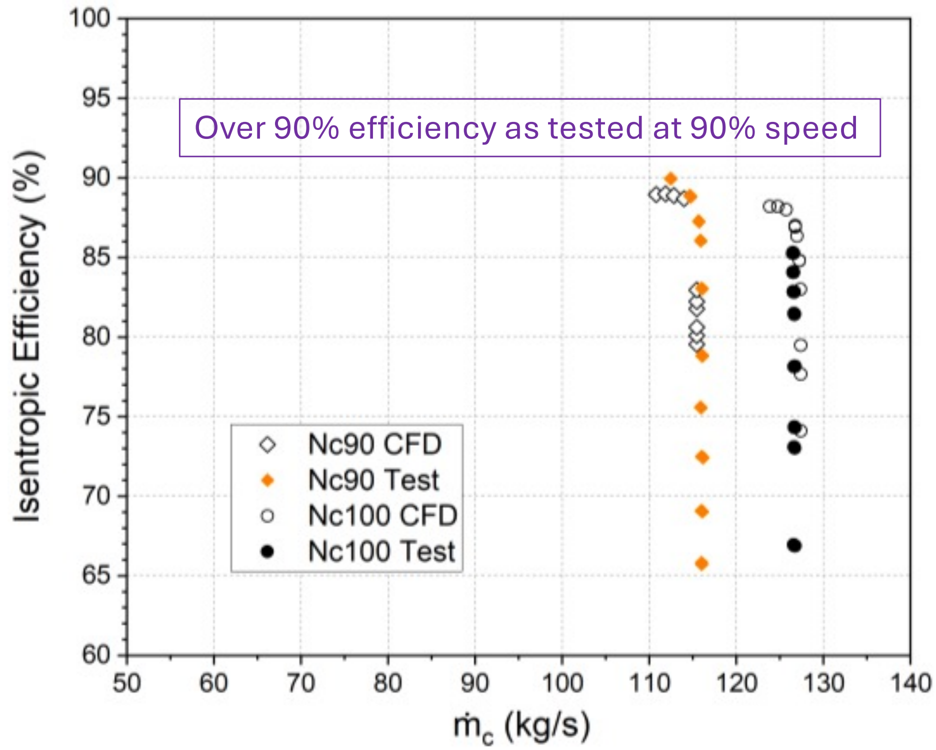
R2 safety factor contour on pressure side (left) and suction side (right).



R3 safety factor contour on pressure side (left) and suction side (right).

Performance Characteristics comparing CFD and Test





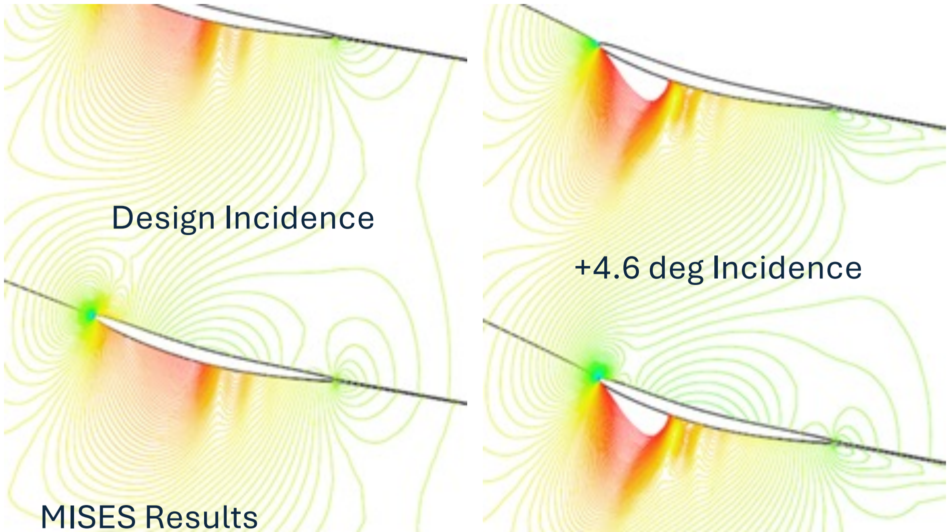
At 60% and 70% speed the measured peak isentropic efficiency over **91%**

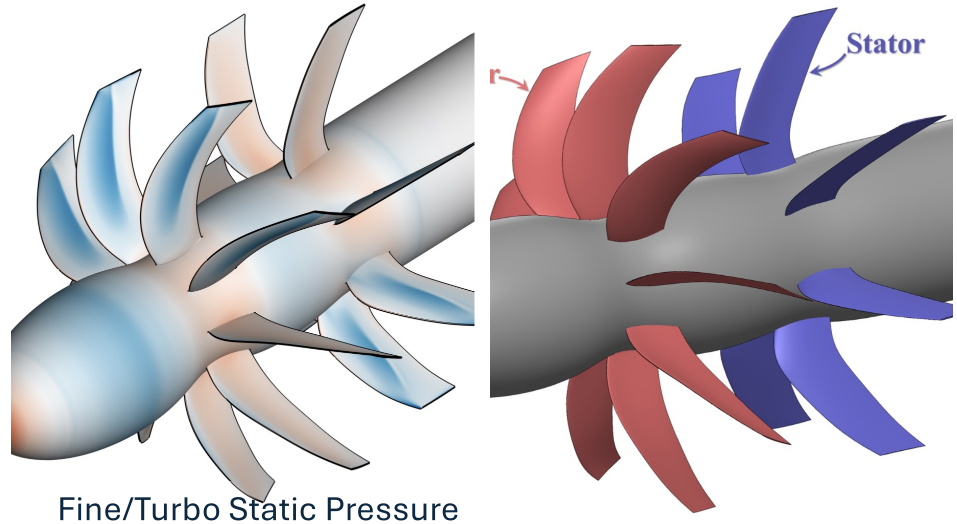
Mean tested clearances were used in CFD simulations.

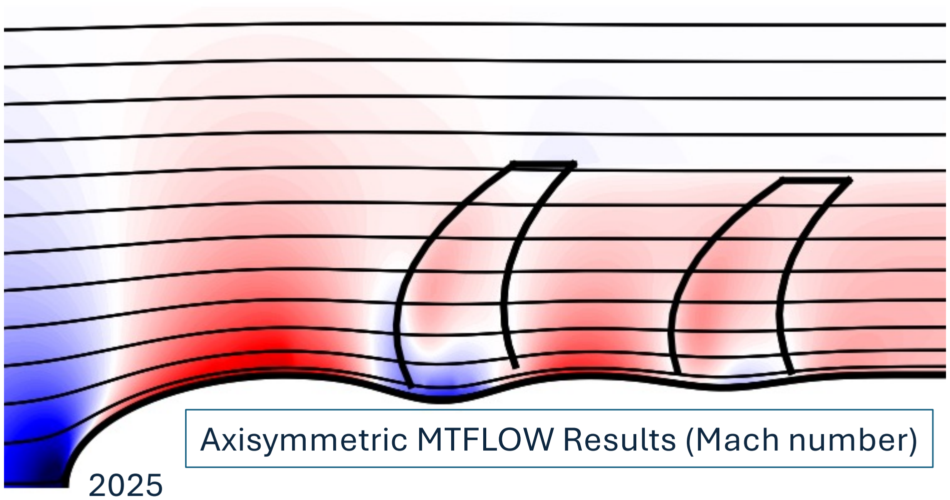
Power for Final Design

At 100% speed, and design inlet PT, the power is 9.52 MW (not including lost power with bearings and motor efficiency)

At 100% speed, design point efficiency is 89.85%, PT ratio of 2.61, and mass-flow rate of 125.86 kg/sec







OpenRotor Stage

- NASA designed Open Rotor Stage
- For Mach 0.785 and structurally sound
- 84.7% net efficiency based on simulation
- Paper GT2026-178157 presented later in conference with full details
- 1.7% of net efficiency due to transition

Conclusions

- I have presented my contributions to supporting design and optimization of turbomachinery and aircraft engines for the past 47 years
- Many of the simulations have led to greatly improved understanding of flow physics and mechanisms

What's in the Future?

- Propulsion Airframe Integration: Simulation and Design of Airframe and Open Rotor Stage
- The back pressure caused by the pylon and wings on the OGV of the Open Rotor Stage are the same physics, except more 3D, that I worked on with fan OGV designs back in 1982
- Aeroacoustics in the Optimization Process (likely as a constraint)
- Faster Computers, more LES, AI, more data that needs to be understood