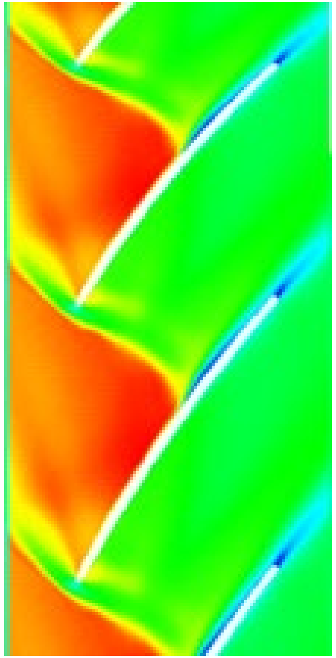
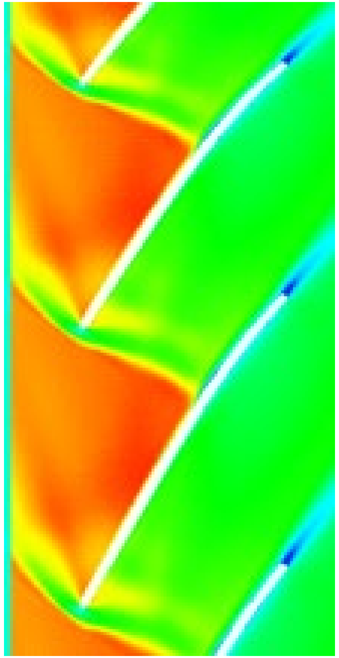
High Fidelity Multi-Disciplinary Optimization of Turbomachinery

Turbine Engine Technology Symposium
September 14, 2022





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Senior Technologist, Aeropropulsion
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Dr. Michael G. List
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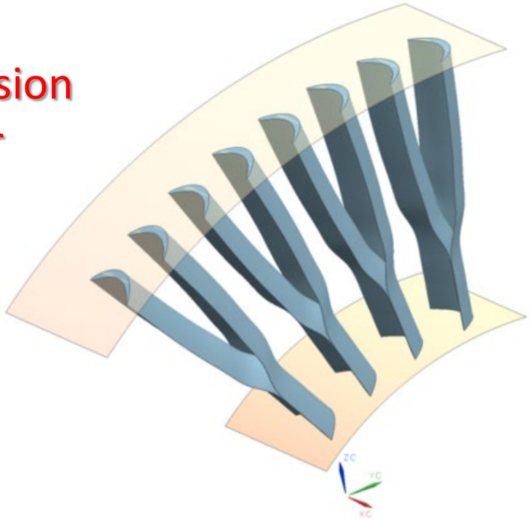
Wright Patterson AFB



Multi-Fidelity

~~High Fidelity~~ Multi-Disciplinary Optimization of Turbomachinery

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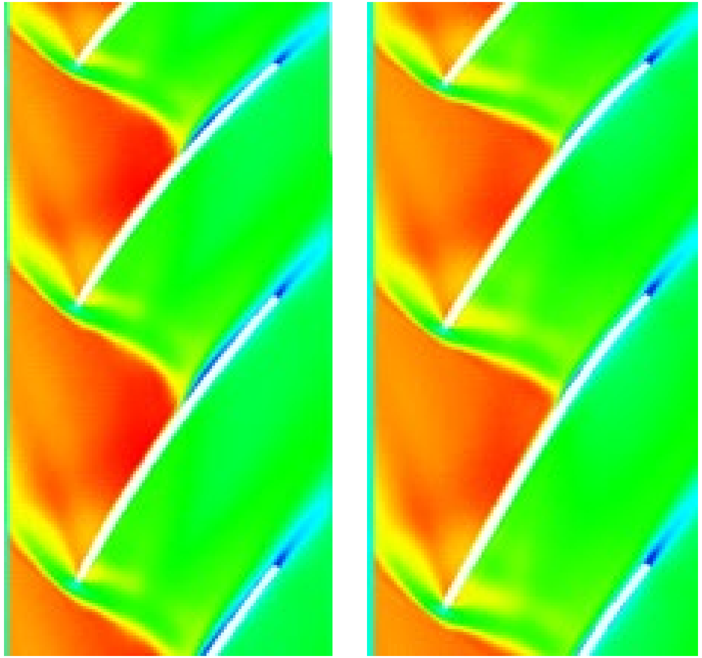

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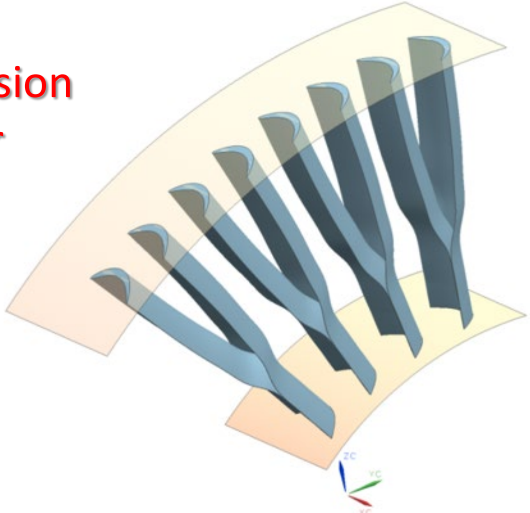


Outline

- Goal
- Design System
- Different Pieces of the Design System
- Details of T-Blade3
- Recent Applications
- Non-Axisymmtric Geometry
- Future Work at NASA
- Conclusions

Goal

- Describe some efforts NASA and AFRL are working on in turbomachinery design and optimization
  - Turbine tool capability at AFRL is excellent, but not yet integrated
- Describe computational tools that NASA and AFRL are working on
- NASA and AFRL are developing and using design and optimization methods for the following reasons:
  - Explore state of the art multi-disciplinary optimization methods
  - Train young engineers about design approaches to improve understanding of the role design and computational methods play in product development by industry
  - Break down silos by integrating disciplines
  - Apply to research projects including novel geometry and integrated ideas

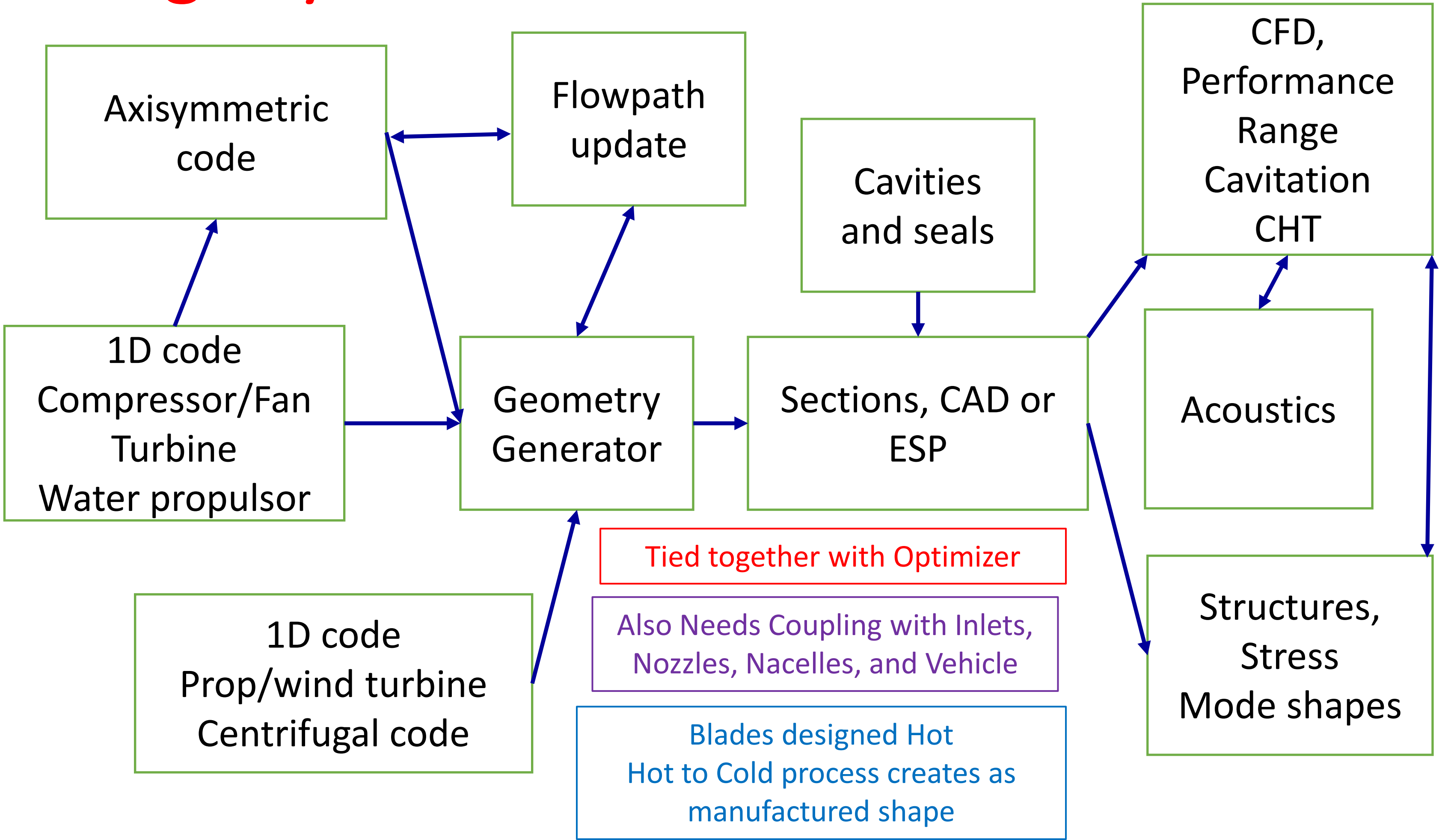
NASA – AFRL Collaboration

- An agreement only at this time to share codes, approaches, and define interfaces
- Nothing Formal
- No plan to have one system
  - Some elements should be plug compatible
  - Some tools make sense to use exclusively
- Makes Common Sense

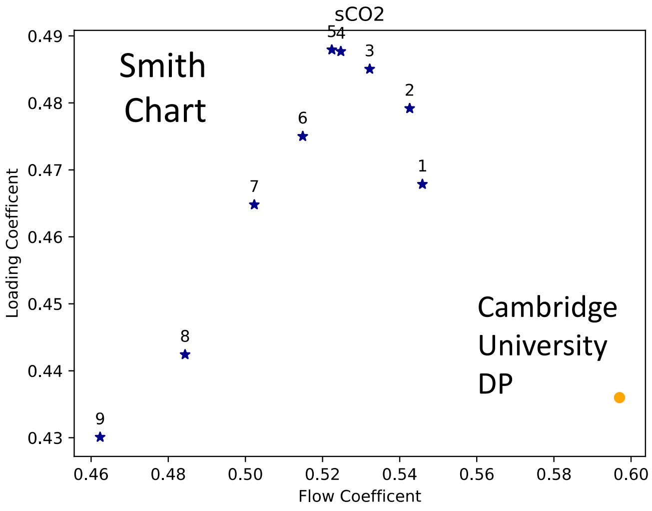
Another TETS Paper

- Tomorrow, Thursday, 15 Sept 2022, 09:30-10:00
- Innovative Propulsion Concepts session
- Darius Sanders presenting
- "Design Overview of the Compression System for the Responsive OpenSource Engine”
- Uses AFRL Compressor Design System

Design System

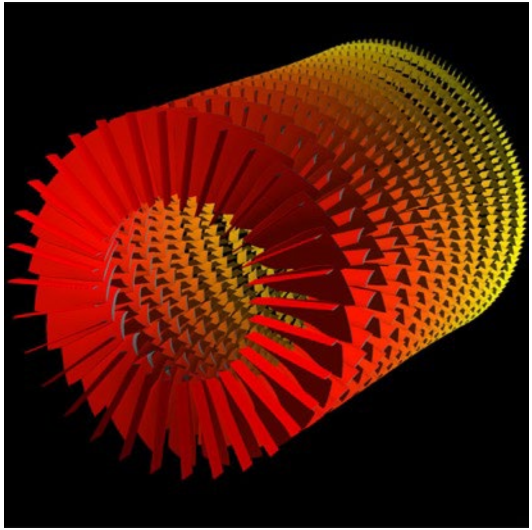


Meanline (1D) Codes



- Many Codes
- AFRL compressor code is called “Meanline” (axial and radial)
- University of Cincinnati Codes (open)
  - TC_Des (Axial Compressor)
  - TT_Des (Axial Turbine)
  - Py-C-Des (on GitHub, in python, different working fluids like S-CO2, air, …)
- NASA
  - OTAC – Uses NPSS as foundation with blade row models and loss

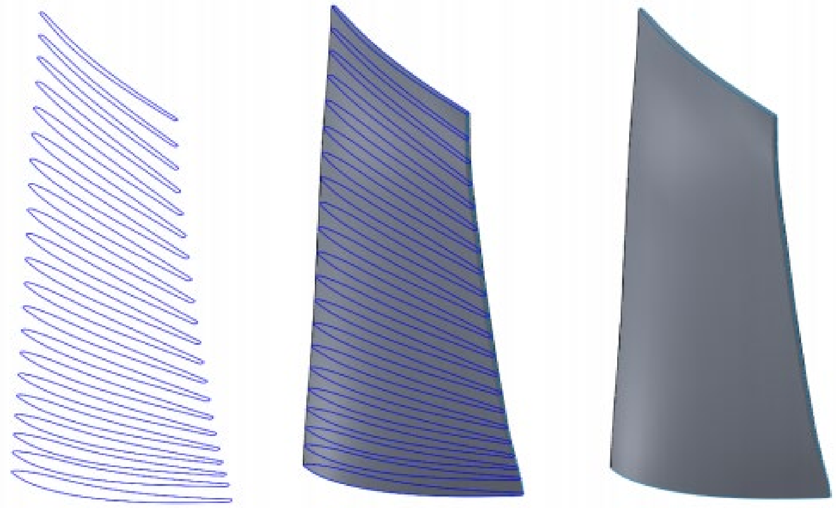
Axisymmetric Codes

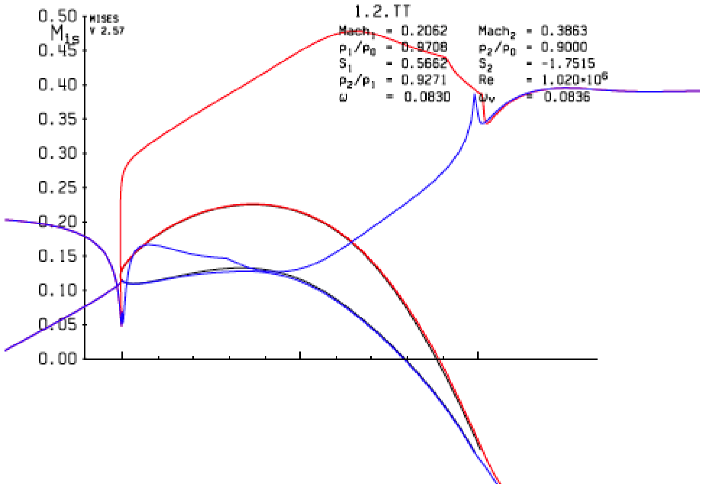


- AFRL code is NewtTS (Newton Thruflow Solver)
  - Modern Streamline Code
  - Includes Compressor Loss Models
  - Generated output for blade shapes directly
  - Design and Analysis Mode
  - Applied for Axial and Radial Compressors only
  - Plan will be for NASA to use and modify for use with T-Blade3 Geometry Generator
  - Plan to enable Turbine Design Capability, but no detailed loss models
- T-Axi
  - Built on Mark Drela's mtflow code
  - Executable available from UC website
  - Will use at NASA until NewtTS is integrated

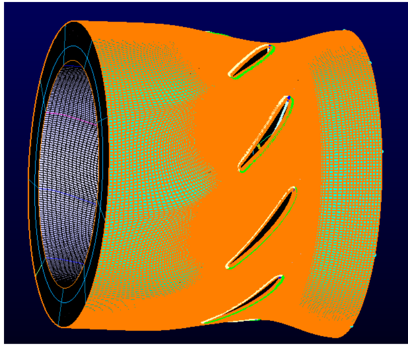
Geometry Generators

- Integrated with NewtTS
  - Meanline – thickness
  - Working for Centrifugal Impeller
- University of Cincinnati T-Blade3
  - Open Source on GitHub
  - Fully Differentiated
  - Integrated with ESP
  - Scripts include OpenMDAO coupling with Mises

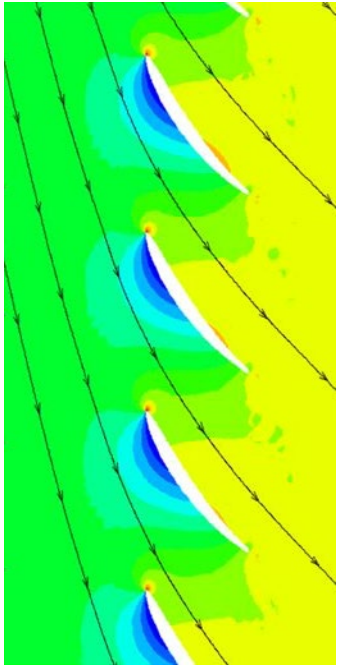




CFD Solvers (includes Mesh Generation)



- At AFRL
  - ADS
  - Star-CCM+
- At NASA
  - APNASA – almost integrated
  - FUN3D
    - Turbomachinery Application Demonstrated (Full Annulus Only) for low speed and transonic two blade row
    - Planned Development for Turbomachinery in FY23
    - Needed for General Geometry
    - Plan to leverage Adjoint Capability and integration with Pointwise and ESP
  - Others Could be used: GlennHT, OpenNCC, Turbo
- At University of Cincinnati
  - Fine/Turbo – Now part of Cadence – Only one license at NASA

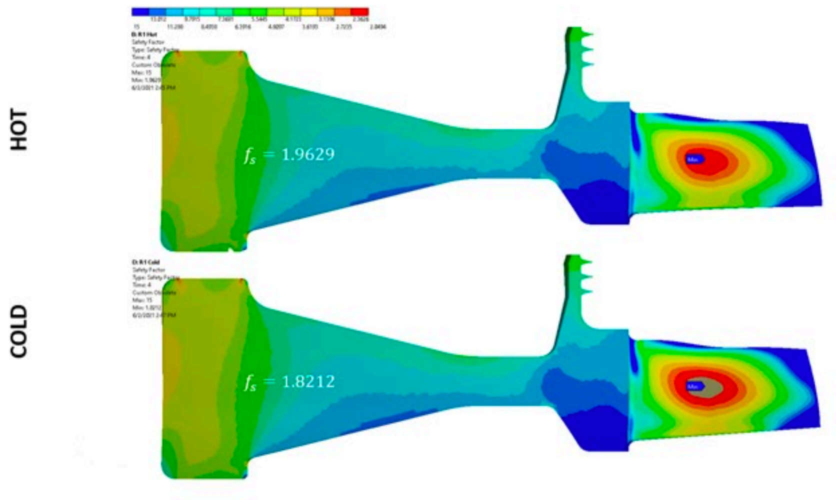


Optimizer

- Needs Automated Design Process
- Used Dakota from DOE in past (pain to compile and get working)
- Currently using OpenMDAO at NASA
  - Available from NASA
  - Python based
  - Gradient Optimization used with Mises
    - Gradients from Finite Difference
  - Genetic Algorithm used with 3D CFD
- Multi-Objective Optimization is Used to incorporate range into design

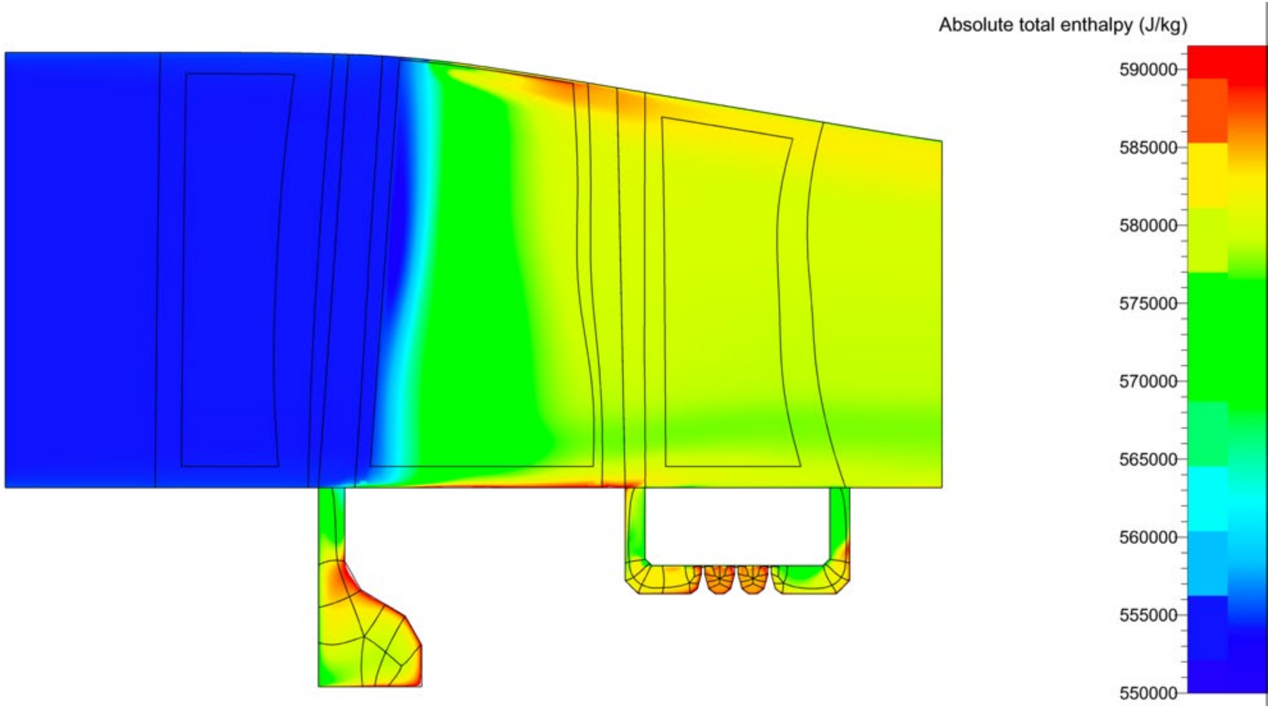
Structural Solver

- Ansys to date
  - Well documented
  - Sometimes difficult to integrate and automate with outside geomtry
- Plan to use NASTRAN
- Plan to also explore open source FEM solvers like TACS (Toolkit for the Analysis of Composite Structures)
- Integral to Hot to Cold process



Other Geometry

- Cavities and Seals
- Casing Treatment
- Novel Geometry
- Flowpath
- Splitters



T-Blade3
Turbomachinery Blade Generator

Contributions by University of Cincinnati Students:

Kiran Siddappaji
Ahmed Nemnem
Syed Moez Hussain Mahmood
Karthik Balasubramanian
Mayank Sharma
Sandeep Kumar
Marshall C. Galbraith
Simon Livingston
and Mark G. Turner

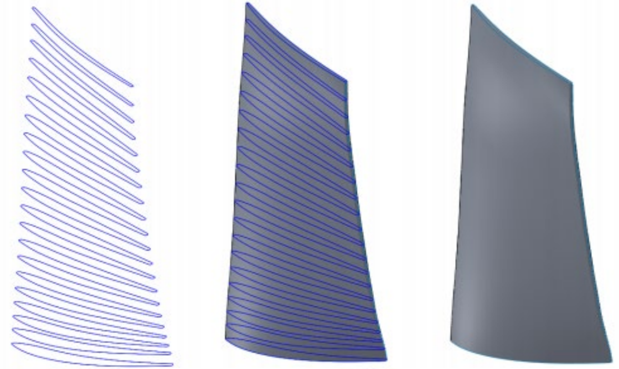
Is now in use at NASA

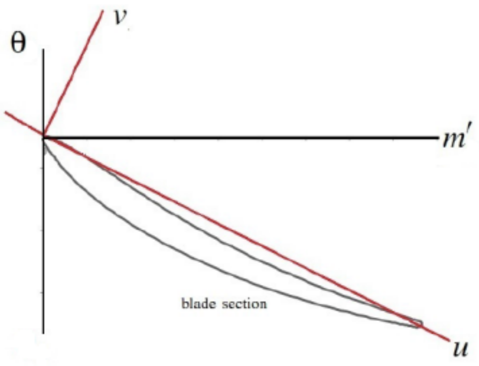
My background is Aero - What I’ve Learned is:

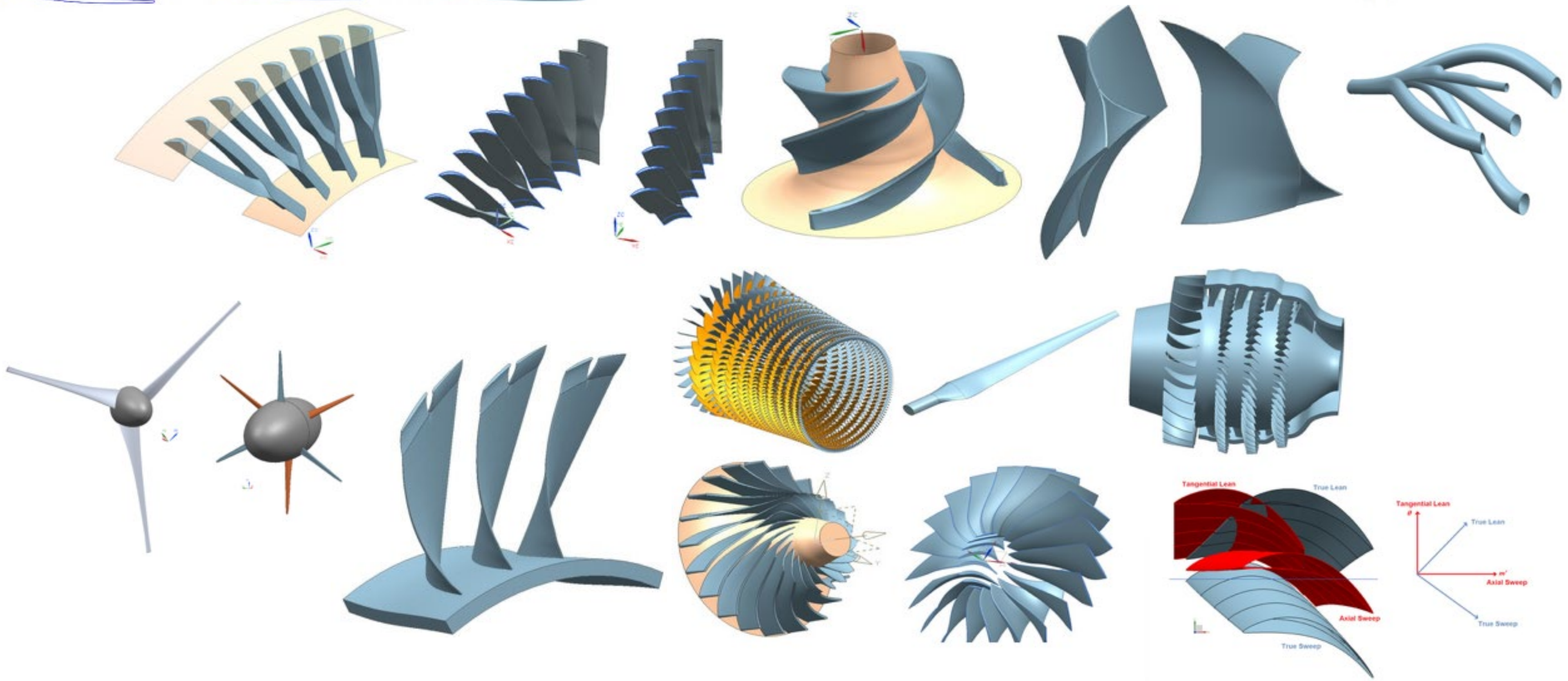
- Structures is more important than aero performance
  - If it breaks, it’s not useful
  - Integrate with MDAO
  - Need to have real features such as fillets, shrouds, and disks
  - Need Campbell Diagram early
  - Need an automatic way to get CAD
- Multi-Discipline is critical (structures, aero, heat transfer, acoustics, aeromechanics, operability, controls, …)
- Optimizing for off-design is essential
  - For 2D, include off-design incidence loss parameter as part of an objective function or an additional objective function
  - For 3D, include design point and near-stall point efficiencies as two separate objective functions
- Define the Right Objective Function
  - Include expected mixing loss in BLI applications to create a modified efficiency
- Need a Gradient Based Optimization Capability in 3D -> Adjoint
- Apply the Correct Boundary Conditions
  - Exit Mach Number
  - CHT or specified Temperature at Walls – Turbomachinery is not adiabatic
- Most Optimized Compressor Blades have a Curvature Inflection

Break Down the Silos!

T-BLADE 3
(open source)

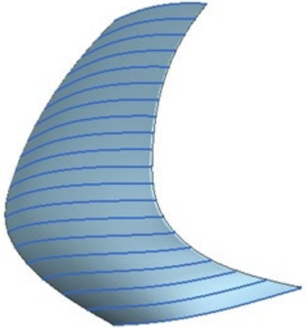




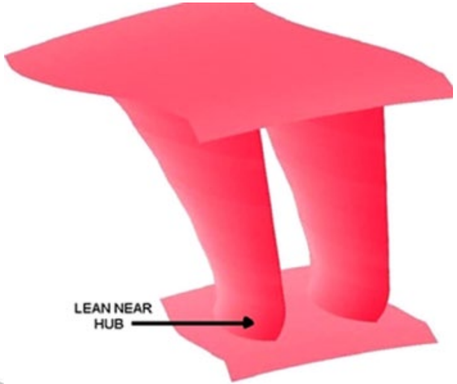


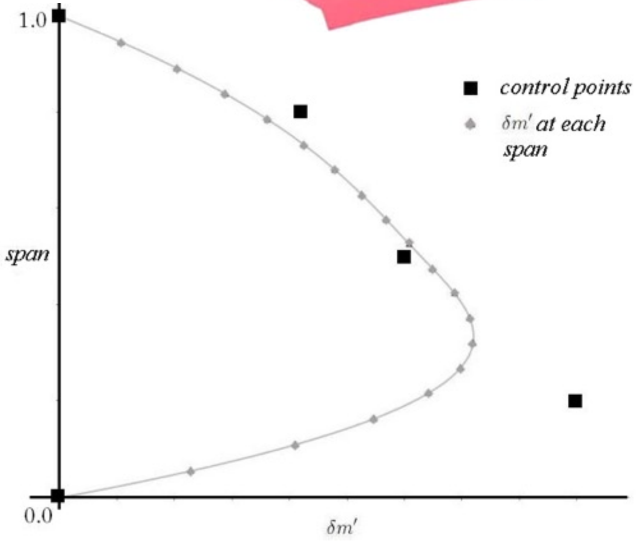
B-spline defined Sweep and Lean with options

FORWARD SWEEP

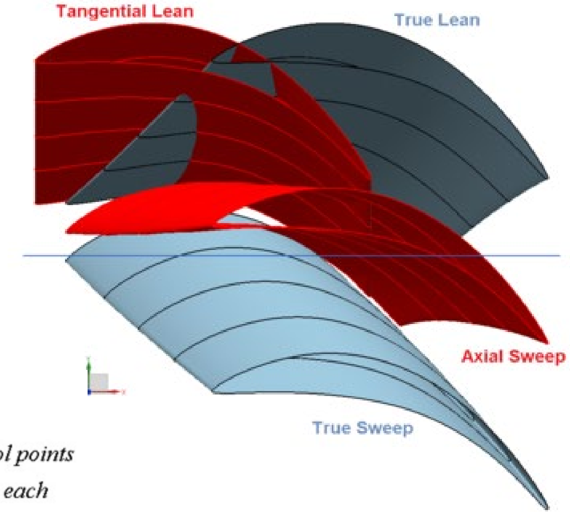


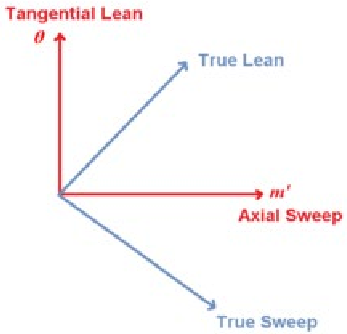
BACKWARD SWEEP

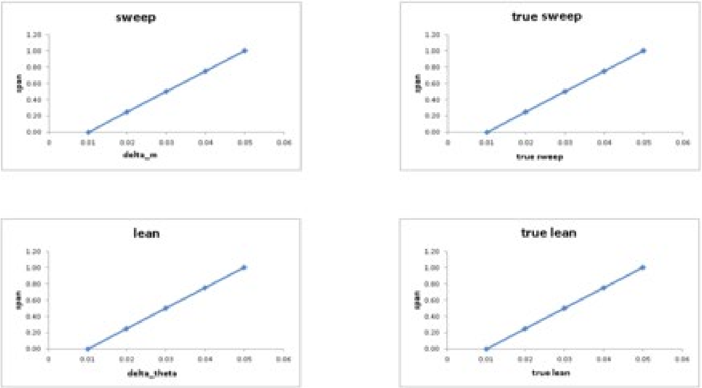




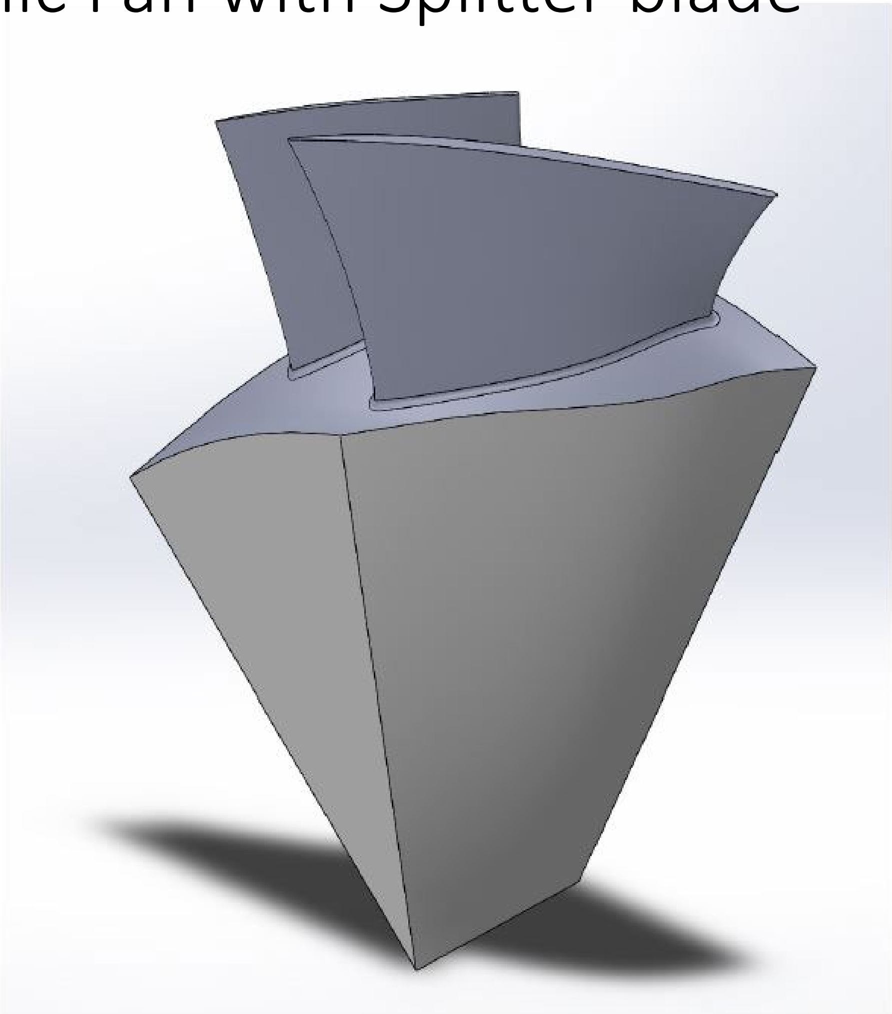
Spanwise Sweep Perturbation

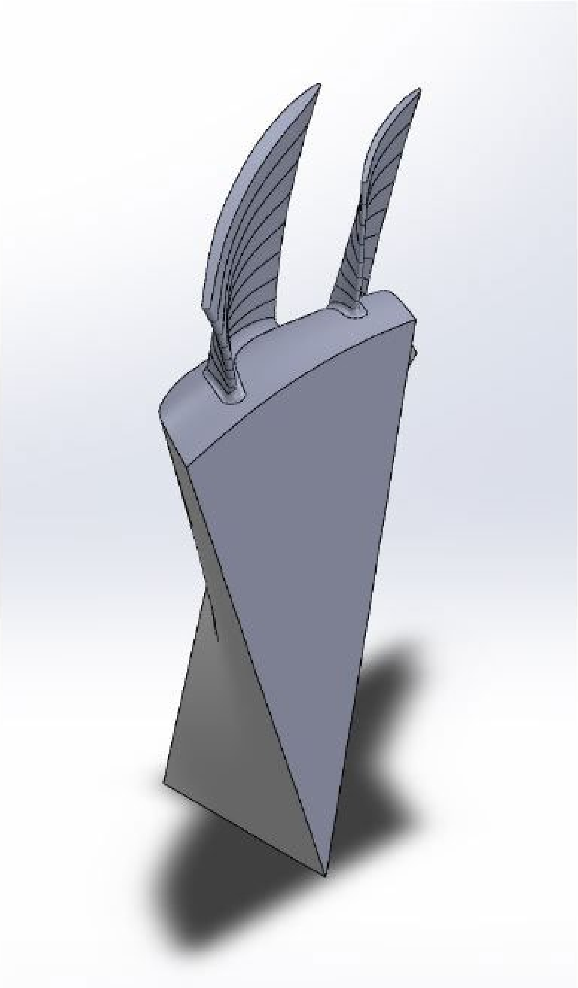




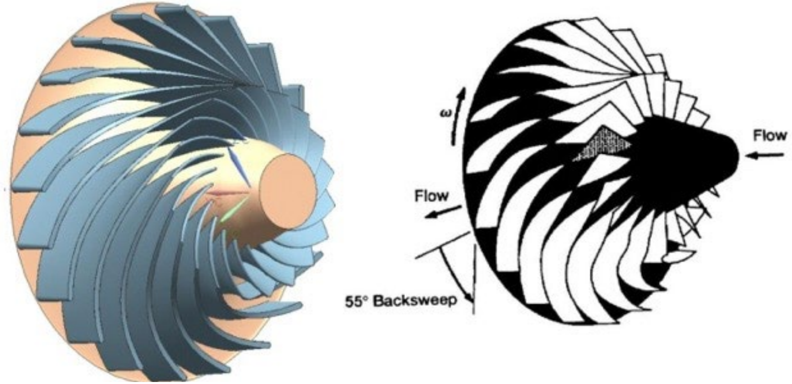


Transonic Fan with Splitter blade

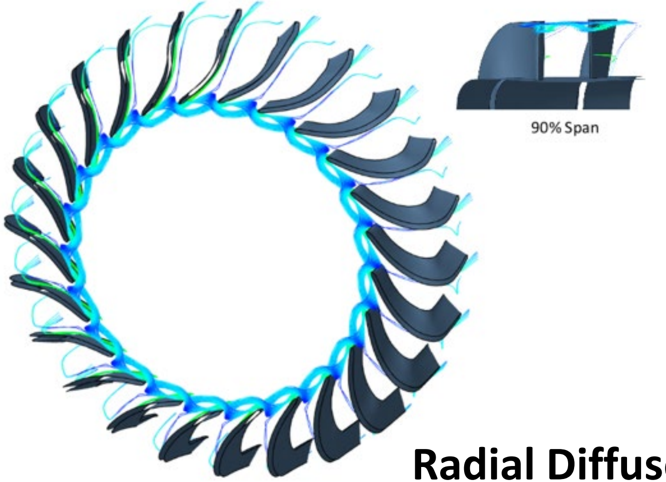




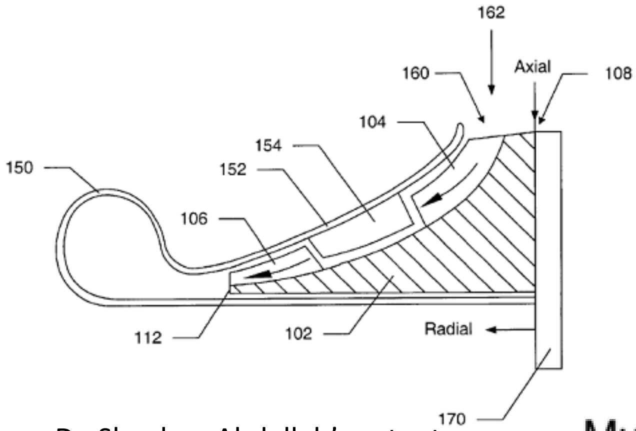
Radial Machines



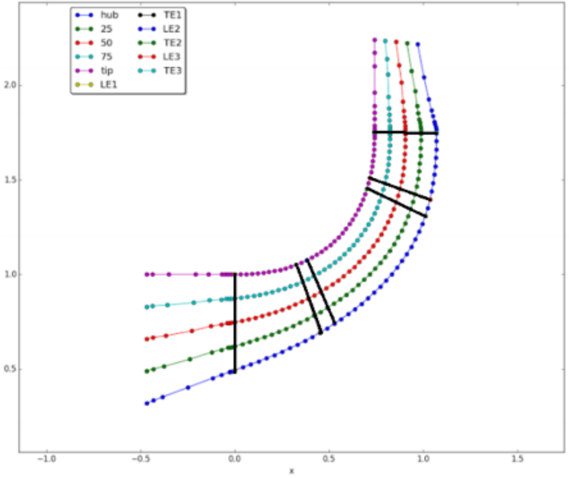
Radial compressor model compared with NASA LSCC



Radial Diffuser

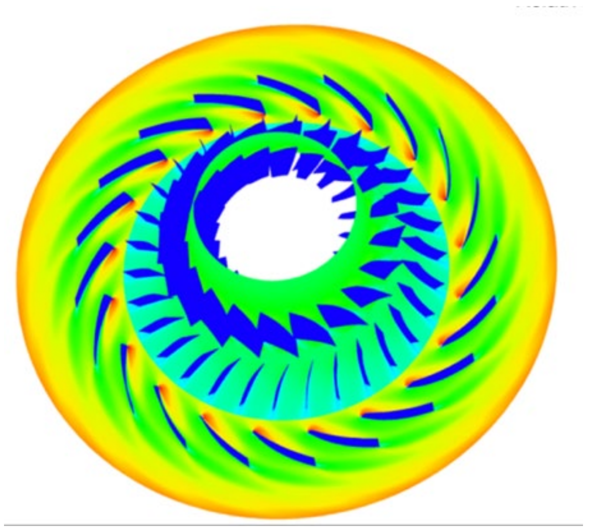


Dr. Shaaban Abdallah's patent

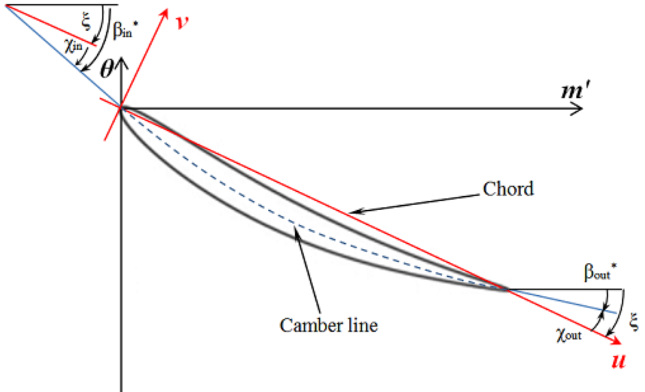


Flow path of Multistage compressor.

Multistage Compressor Geometry.

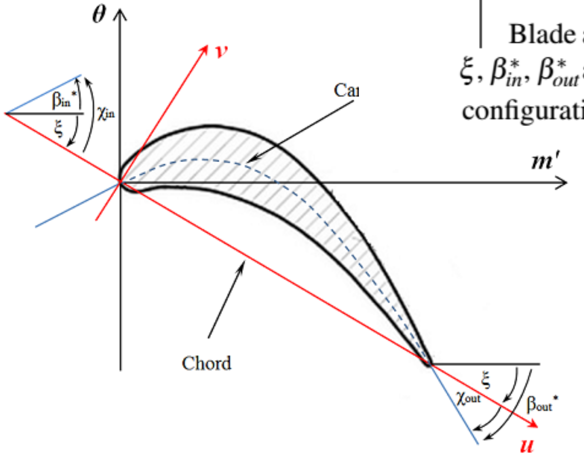


B-spline defined Curvature distribution of meanline



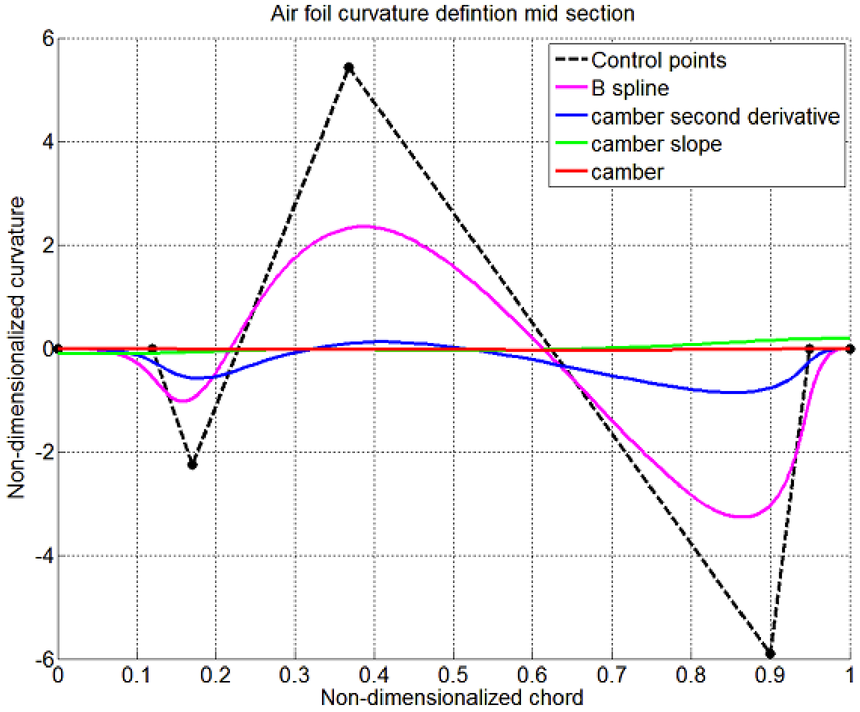
Blade angles for a compressor blade.

ξ, β^*_{in}, β^*_{out} and χ_{in} are negative in sign for this configuration (χ_{out} is positive).

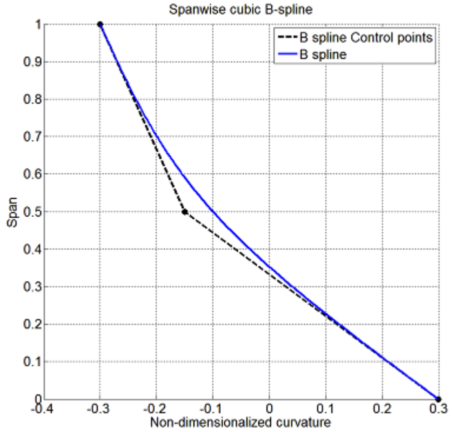


Blade angles for a turbine blade.

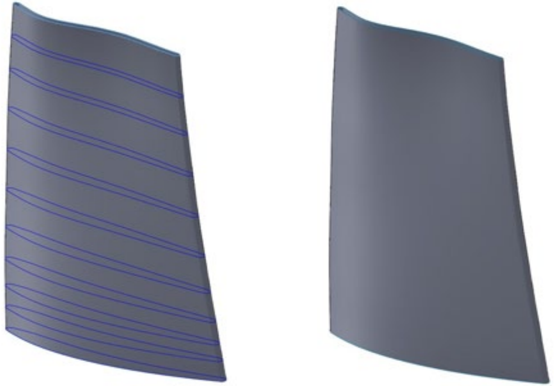
For this configuration, β^*_{in}, χ_{in} and χ_{out} are positive in sign and ξ and β^*_{out} are negative.

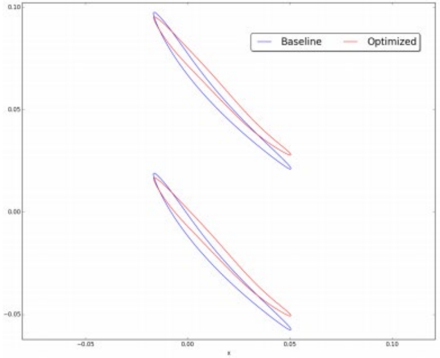


B-spline defined Smooth Spanwise Variation

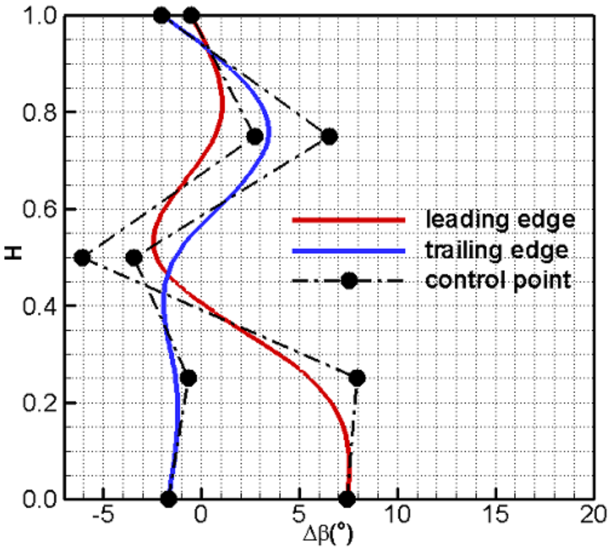


Spanwise curvature variation to obtain blade shape

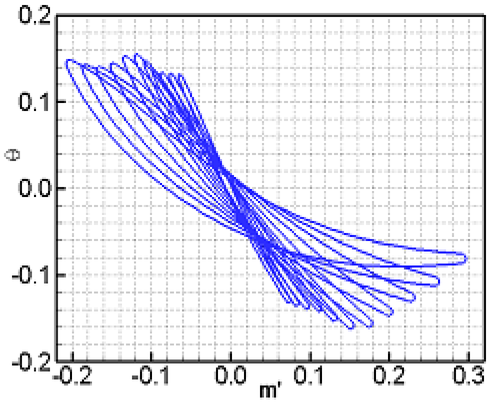




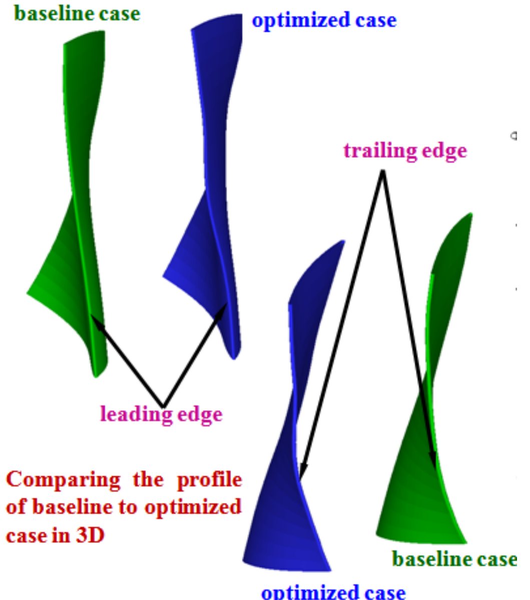
(b) Mid section curvature.



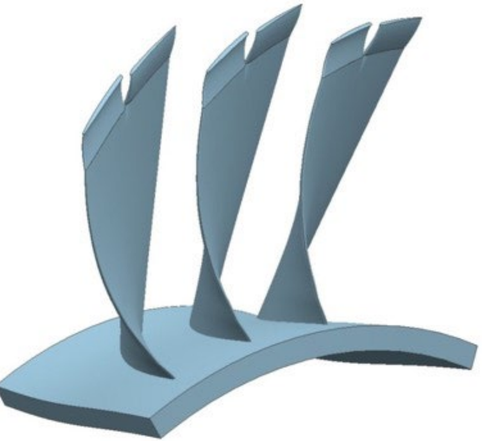
Flow angle adders at rotor LE and TE.



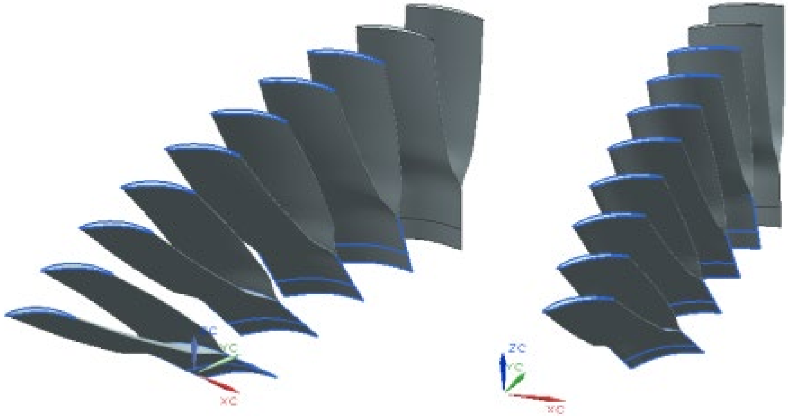
Stacking airfoil on the centroid for optimum rotor



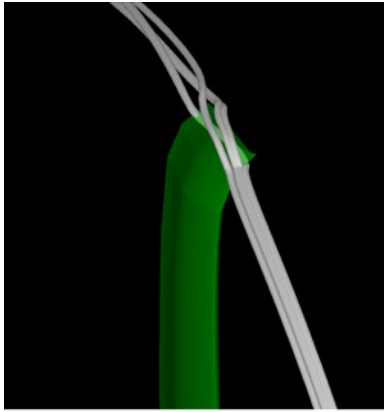
Novel Geometry Designs



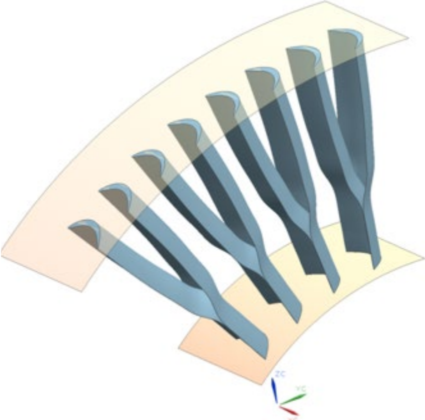
Combine T-Blade3 with CAD to enable Turbomachinery Innovation!

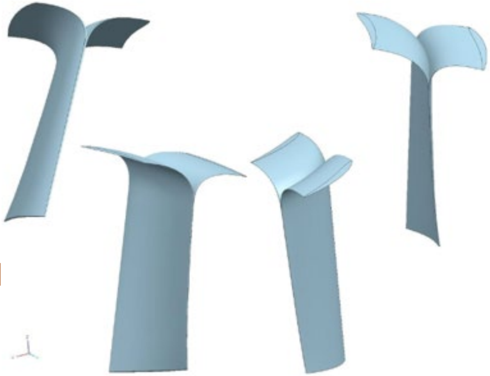


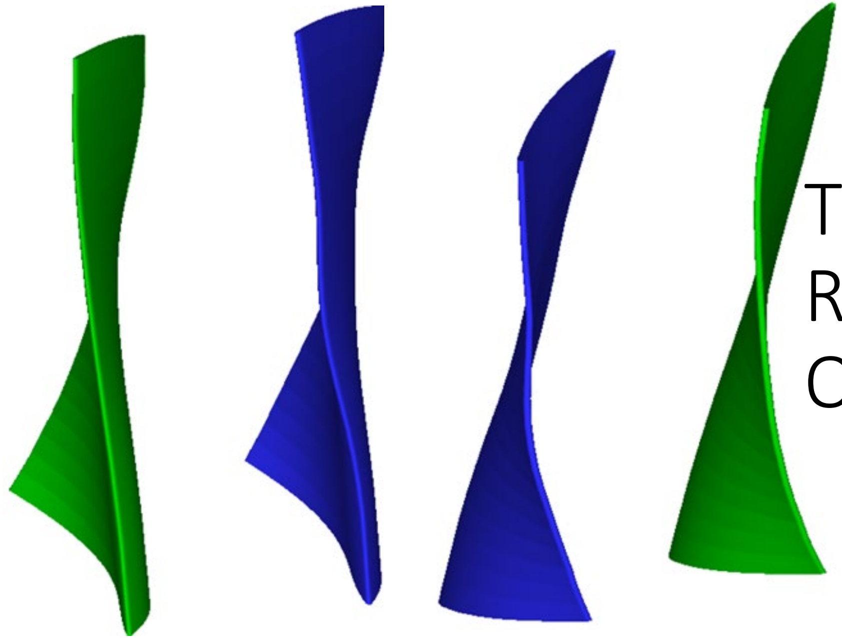
Outlet Guide Vane (variable solidity)



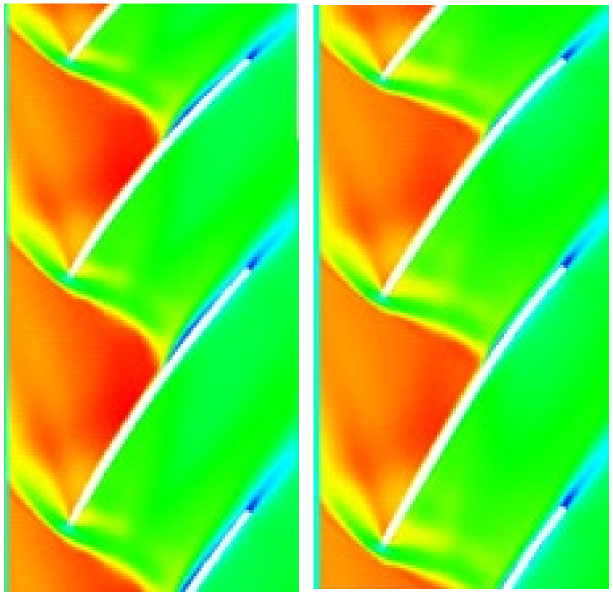
NREL-Winglet tip streamtubes.

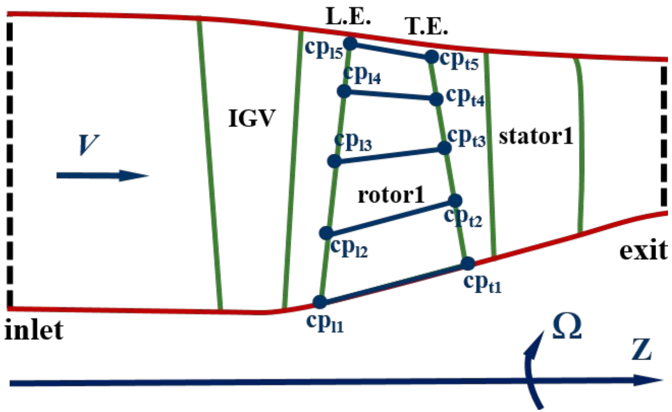


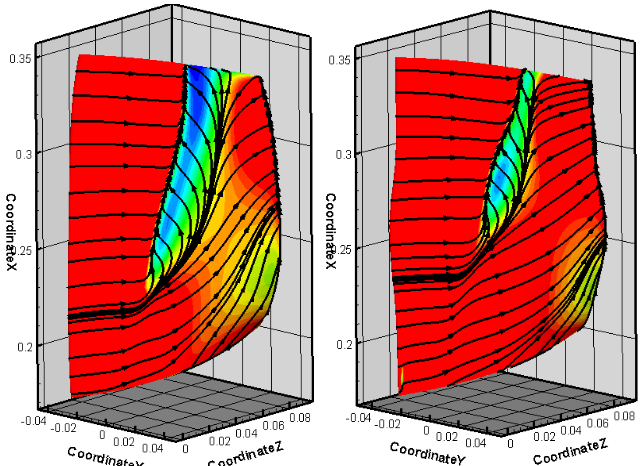




Transonic Rotor Optimization







Left baseline

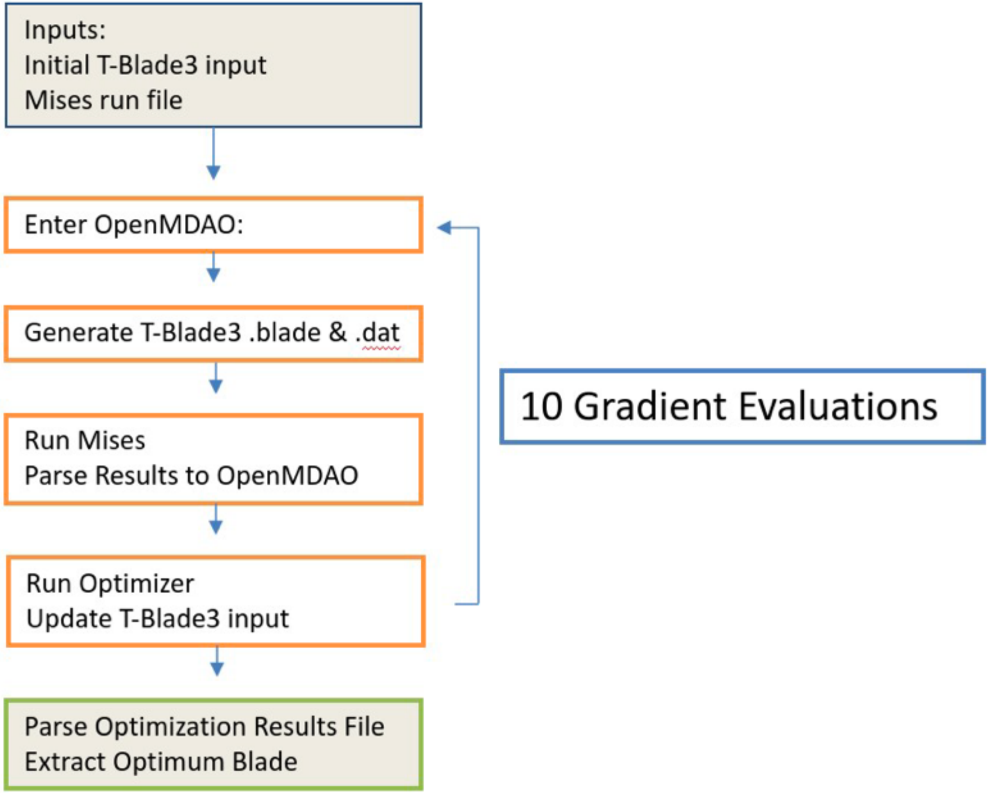
Right optimum

Blade Section Optimization with MISES

<u>Contributors:</u>
Tom Viars
Matt Ha
Abby Scorsone
Rokas Ogorodnikas

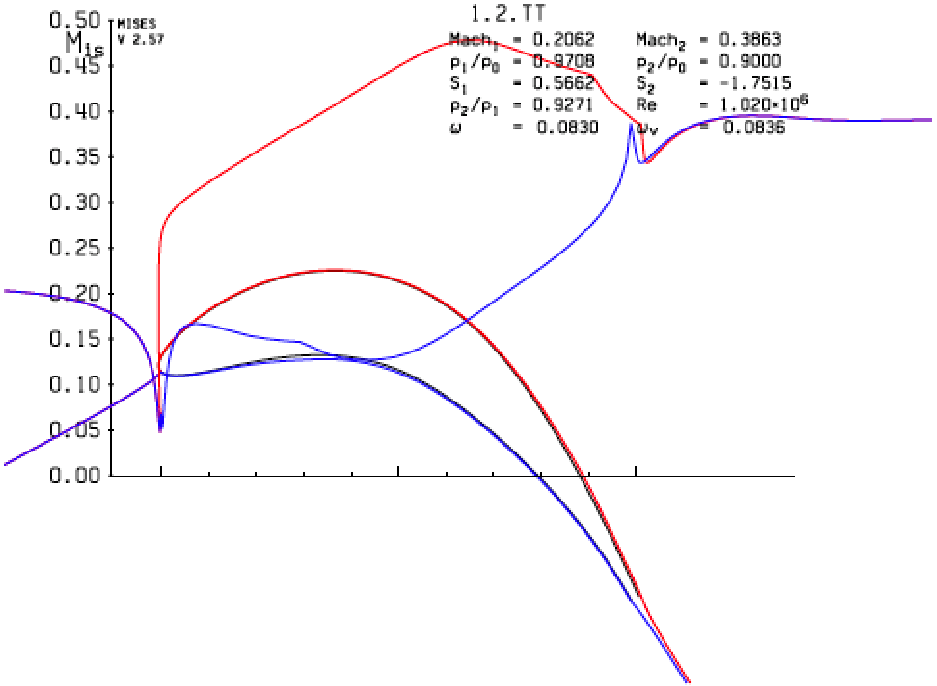
Uses OpenMDAO from NASA GRC

Download T-Blade3 including python MISES optimization scripts from github
Download OpenMDAO from NASA
Get MISES from MIT (free to US government)



Turbine section Constrained Optimization

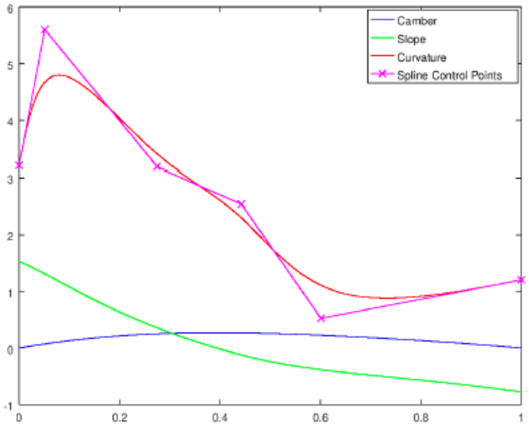
Inc	-0.82415	c4	0.436817
Dev	-5.75608	c5	0.090227
c1	0.55105	c6	0.206527
c2	0.961792	dydxTE	-0.05394
c3	0.54742	u_tmax	0.282473

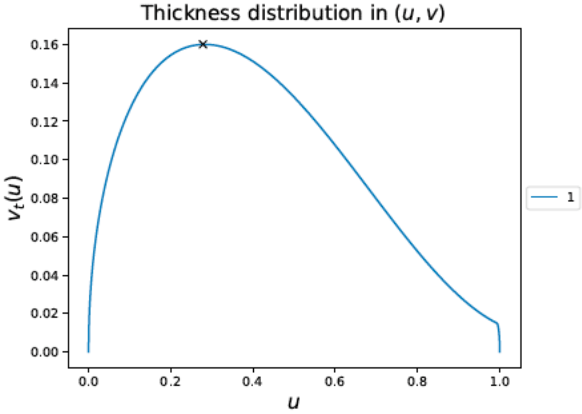


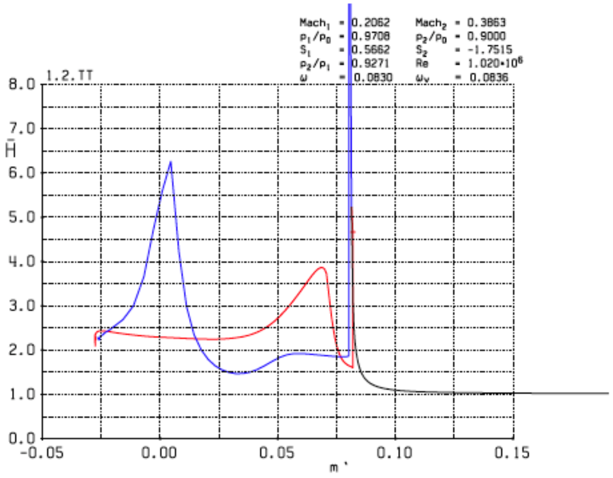
10 variables, not chord so not solidity

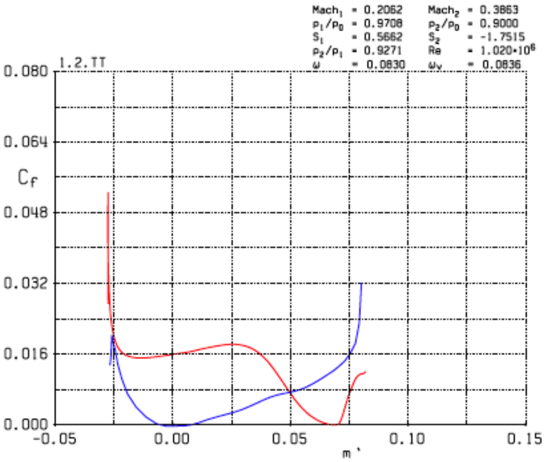
MISES uses an integral boundary layer with transition model

Turbine optimum

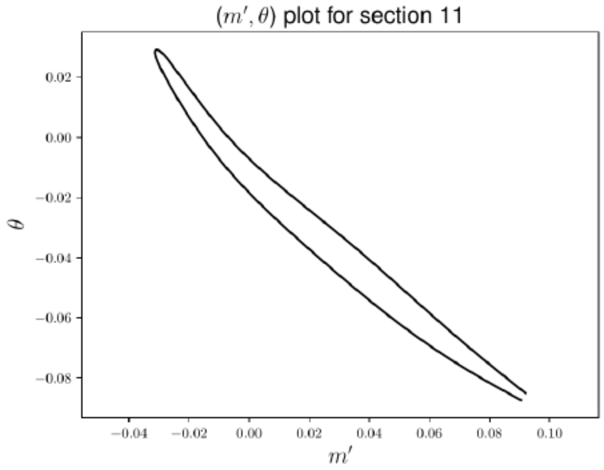








Compressor Rotor Optimum mid span high Mach



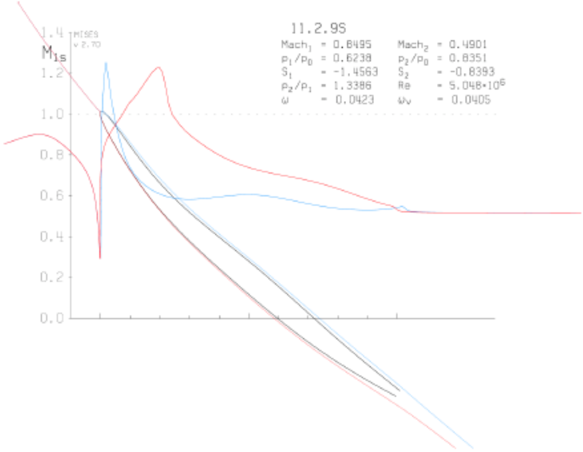


Fig. 26. R1 Surface Mach Number at Design Point, 0.50 Span

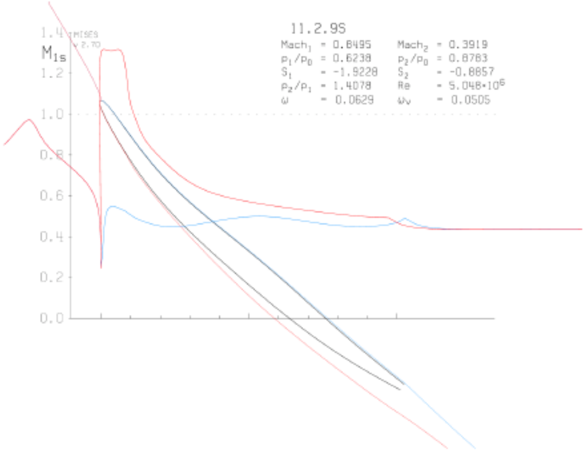


Fig. 27. R1 Surface Mach Number at Off Design Point, 0.50 Span

Objective function is to minimize loss at design incidence and 7 degrees off-incidence

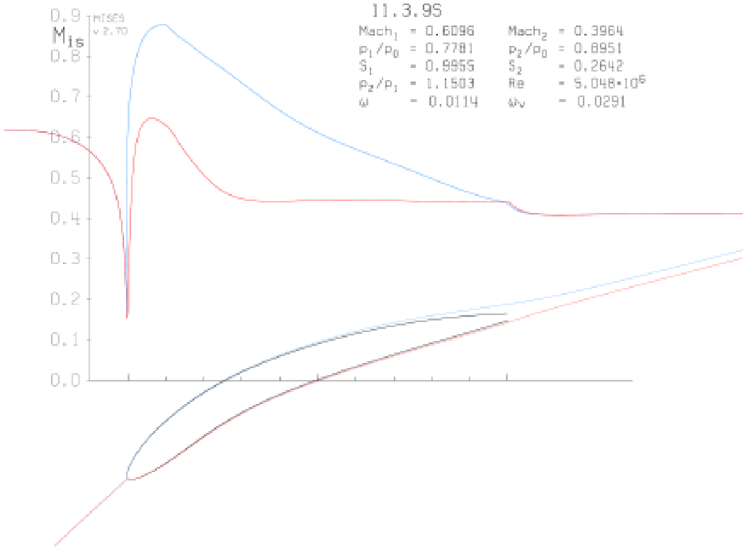


Fig. 44. S1 Surface Mach Number at Design Point, 0.50 Span

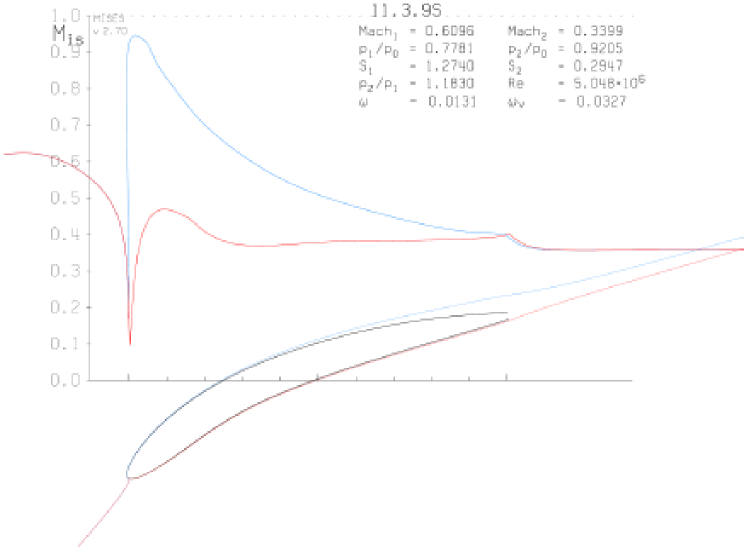
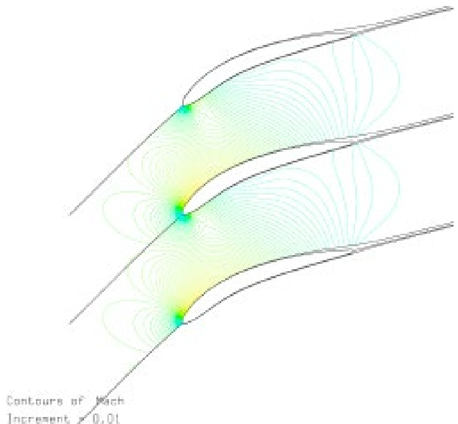


Fig. 45. S1 Surface Mach Number at Off Design Point, 0.50 Span



Compressor Stator

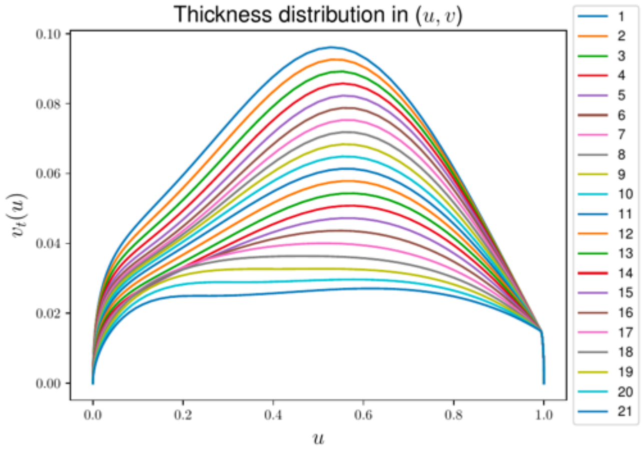
Modified NACA Thickness Distribution

- AIAA Journal Technical Note
- Back to the Future using modified NACA 4-digit thickness
  - Continuous
  - General Finite Thickness Trailing Edge

$$v_t(u) = v_{t,\mathrm{NACA}}$$

$$= \begin{cases} a_0\sqrt{u} + a_1 u + a_2 u^2 + a_3 u^3 & \text{for } 0 \le u < u_{\max} \\ d_0 + d_1(1-u) + d_2(1-u)^2 + d_3(1-u)^3 & \text{for } u_{\max} \le u \le u_{\mathrm{TE}} \end{cases} \quad (3)$$

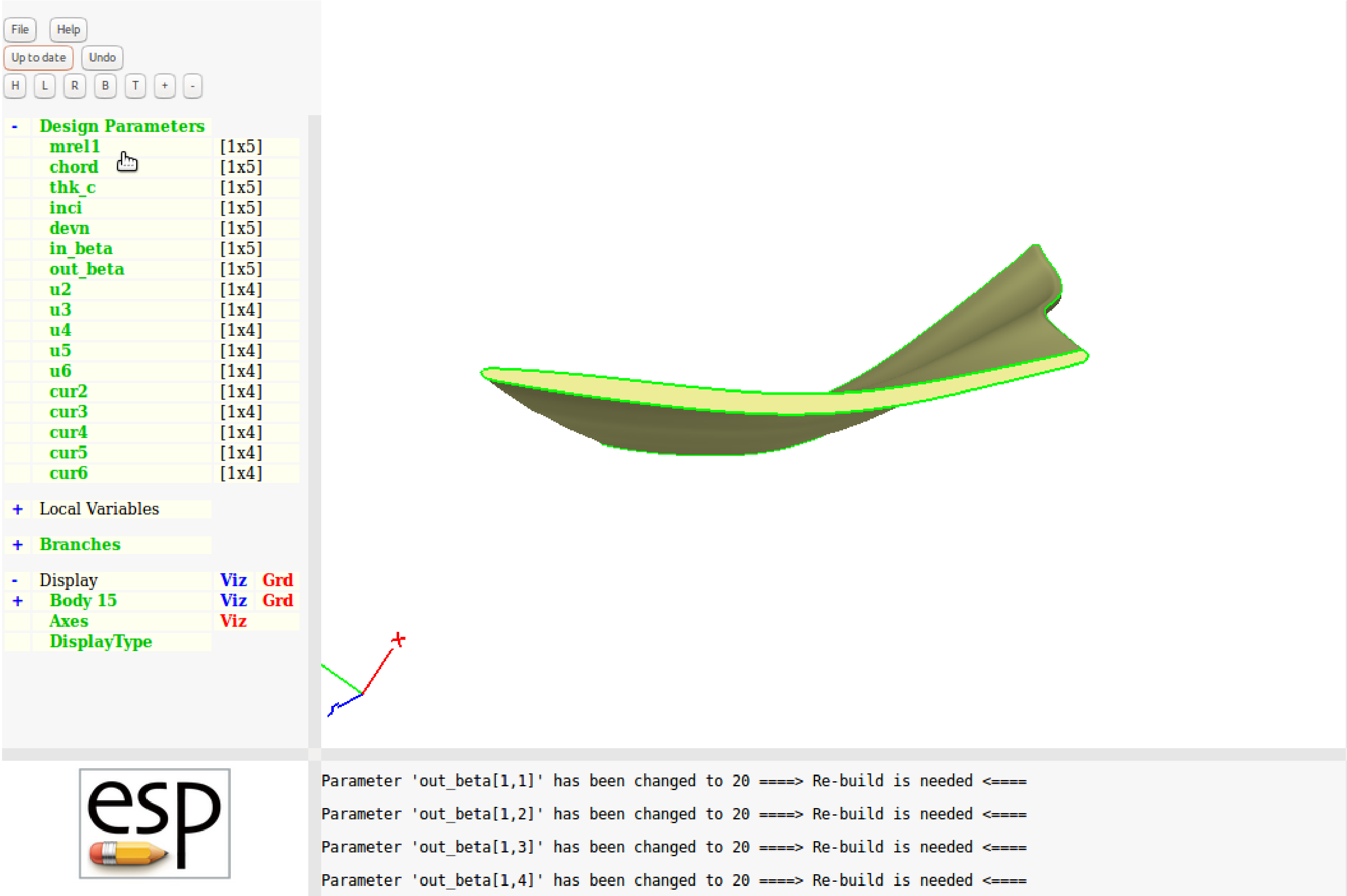
Square root term allows for infinite slope at LE



Engineering Sketch Pad (ESP)

- Developed by Bob Haimes of MIT and John Dannenhoffer of Syracuse
- Development largely funded by AFRL, mostly for airframe design and optimization, but now also includes Turbomachinery at AFRL
- Integrated with T-Blade3 (recent TurboExpo paper)
- Integration is part of T-Blade3 source
- Framework instead of CAD
- Integrates with Pointwise & FUN3D
- Enabled Automatic Hot to Cold
- Analytic derivatives now available in T-Blade3 and enabled by ESP for gradient-based optimization

ESP is a key enabler for Multi-Disciplinary Design and Optimization

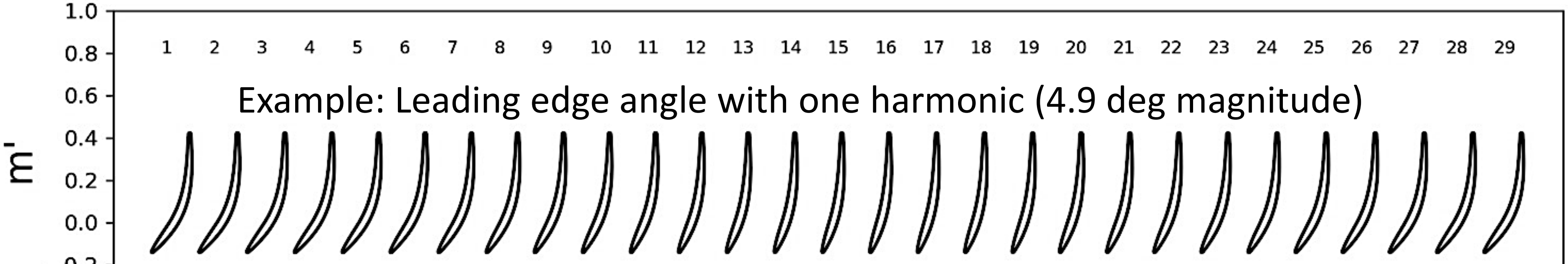

File
Help
Up to date
Undo
H L R B T + -
- Design Parameters
mrel1 [1x5]
chord [1x5]
thk_c [1x5]
inci [1x5]
devn [1x5]
in_beta [1x5]
out_beta [1x5]
u2 [1x4]
u3 [1x4]
u4 [1x4]
u5 [1x4]
u6 [1x4]
cur2 [1x4]
cur3 [1x4]
cur4 [1x4]
cur5 [1x4]
cur6 [1x4]
+ Local Variables
+ Branches
- Display Viz Grd
+ Body 15 Viz Grd
Axes Viz
DisplayType
esp
Parameter 'out_beta[1,1]' has been changed to 20 ====> Re-build is needed <====
Parameter 'out_beta[1,2]' has been changed to 20 ====> Re-build is needed <====
Parameter 'out_beta[1,3]' has been changed to 20 ====> Re-build is needed <====
Parameter 'out_beta[1,4]' has been changed to 20 ====> Re-build is needed <====

T-Blade3 Applications

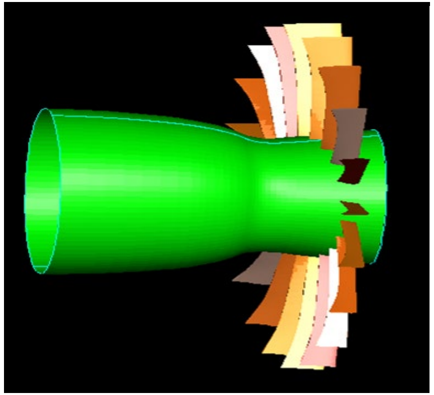
- Student projects:
  - APOP – propulsor, low pressure turbine, prop, radial-axial diffuser, DAGSI turbine
  - Wind Turbine design
  - Centrifugal compressor – traditional and advanced
- DAGSI small Additive Ti Compressor
- BLI
  - Institute of Aviation in Warsaw, Poland (low speed)
  - NASA (high speed)
  - Susan Aircraft at NASA
- Turbine
  - Film cooling cascade test
- NAVY underwater propulsors
- 3 stage Axial Compressor with S-CO2
  - Testing planned at Notre Dame late this fall

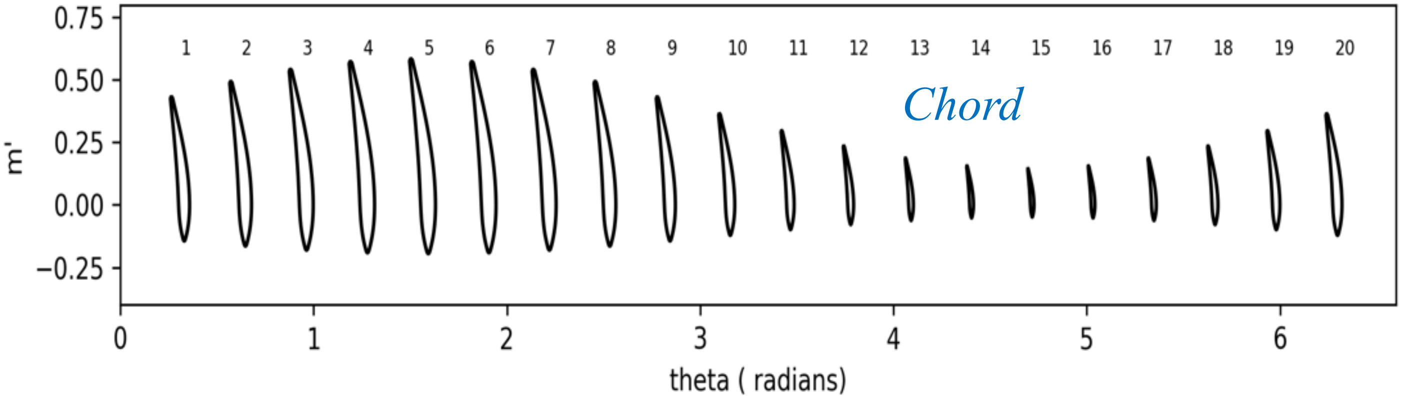
Non-Axisymmetric (NAX) Blading

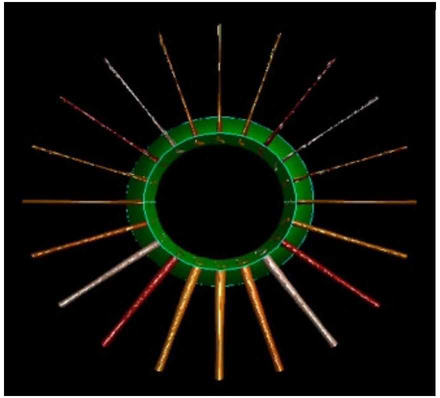
- TurboExpo paper GT2018-77042 & GPPS-2020-0151
- Parameters vary as a truncated Fourier series around the annulus
- Applications
  - Use for OGV designs under BLI (IGVs too)
  - Centrifugal diffusers with volute
  - ?

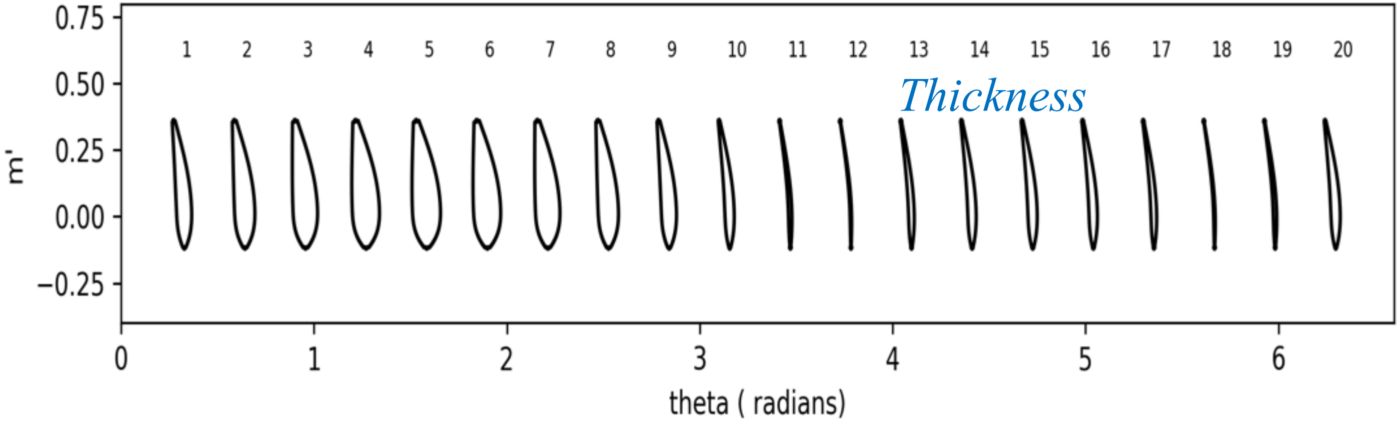


Examples of Non-Axisymmetric Parameters









Future Efforts at NASA

- Uncooled HPT for small engine
- BLI fan for Tail Cone Thruster
- Contra-Rotating BLI Propulsor for Susan Aircraft
- Integrate NewtTS into NASA workflow
- Get 3D optimization with APNASA working
- Improve FUN3D turbomachinery capability
- Demonstrate FUN3D Adjoint Optimization of a turbomachinery blade row

Conclusions

- Collaboration with AFRL is happening
- Multi-disciplinary is key
  - Design system needs to work with both aerodynamics and structures (acoustics, heat transfer …)
  - People need to be multi-disciplinary. – Remove Silos
- ESP
  - integrated with T-Blade3 allows for automated CAD with Sensitivities
  - Being integrated with Turbomachinery at AFRL
- Turbomachinery Blade Optimization Requires Parametric Geometry Generator based on Flow Physics
  - T-Blade3 - Open Source
  - Curvature, LE and TE angles, chord, thickness
  - BLI design and other designs require blades to vary circumferentially
- Optimization system
  - Parameters and Process must be driven by Design Understanding
  - Multi-fidelity
  - Multidisciplinary
  - Multi-Objective Function – Pareto

For more Information

- gtsl.ase.uc.edu/T-Axi
  - Can get to Blade Disk codes from here too
- gtsl.ase.uc.edu/t-blade3
- github.com/GTSL-UC/T-Blade3
  - In future will also have py-BEM & centrif PD too
- acdl.mit.edu/ESP

Questions?