OTAC:Object-oriented Turbomachinery Analysis Code Overview and Update

NPSS Public Day Presentations

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Yet Another Turbomachinery Code

- **there is a need to perform quick (faster than 3-D CFD) preliminary and conceptual aerodynamic design and analysis of turbomachinery components**

- **many codes exist, but often are focused on only a single aspect of the entire process**
  - design or performance/analysis (off-design)
  - meanline or streamline
  - compressor or turbine
  - axial or centrifugal/radial

- **to make matters worse, these codes frequently**
  - are written in old FORTRAN programming language
  - lack the source, only the executable remains
  - contain scant documentation other than a TM or brief user’s manual
  - have no “keepers”; personnel with intimate knowledge of the code are not accessible

- **for these reasons the codes may be difficult if not impossible to modify, and investigating causes of failed runs/cases can also be problematic**

- **the solution to this is to ~~not do any turbomachinery work~~ create a modern turbomachinery design and analysis code**

OTAC Features

- **OTAC will perform 2-D design and analysis of turbomachinery**
  - throughflow calculation (ductflow), no calculation stations interior to a blade row (but this is possible)
  - meanline and streamline
  - compressor and turbine
  - axial, centrifugal, and mixed types supported
  - effect of streamline slope and curvature can be included

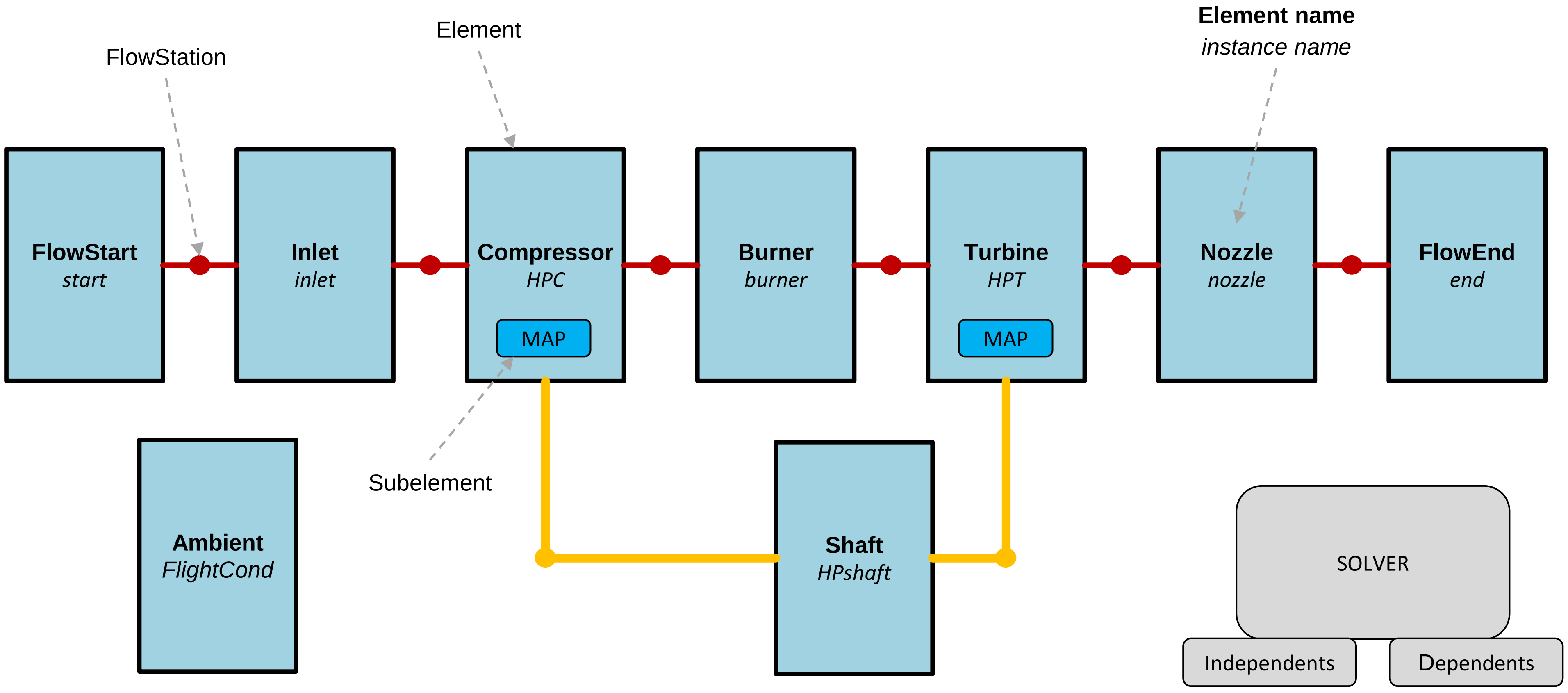
- **OTAC written in Numerical Propulsion System Simulation (NPSS) interpreted language**
  - NPSS is a recognized and state-of-the-art tool for gas turbine engine cycle design, so there is a logical fit to couple them aiding in optimization and calculation of interactions
  - access to the NPSS thermodynamic packages allow easy specification of air and air-fuel mixtures; no thermo discrepancies between cycle and meanline
  - access the NPSS solver object allows “clean physics” where the governing equations are obvious from the object design and implicitly solved, it also allows blade rows to be solved independently of each other
  - access to the Shaft object and the DataViewer object to create custom output

- **OTAC is robust due to its object-oriented architecture**
  - deviation, loss, and blockage correlation models are maintained as separate objects
  - loss correlation models can be switched from blade row to blade row, correlations may be “stacked” within a blade row if individual accounting of loss mechanisms (profile, shock, endwall, etc.) is desired
  - capability for unconventional devices and effects – counter-rotating turbines, tandem stators, non-adiabatic processes, and secondary flow extraction or addition

- **replaces over a dozen codes (CSPAN, TURBAN, AXOD, CMPSTK, ACD, ACOD, CCD, CCOD, RTD, RTOD, others) with a single code which can be maintained and improved for the forseeable future**

NPSS Architecture

- NPSS is an object-oriented environment with the original purpose of the cycle design and performance analysis of aircraft turbine engines



NPSS Input File or Model

- the NPSS input file is not simply a list of variable assigments, it is a set of instructions that are sequentially implemented (i.e., a script)

```
NAME = "Turbojet Model"
SPOOLS = 2
LPCPR = 3.5
HPCPR = 5.0
T4 = 3000.
LP_RPM = 2000.

ALTITUDE = 35000.
FLT_MN = 0.80
END

ALTITUDE = 30000.
END

ALTITUDE = 25000.
END
```

```
NAME = "Turbojet Model"

Compressor LPC {
  PR = 3.5;
}
Compressor HPC {
  PR = 5.0;
}
Burner BRNR { }
Turbine HPT { }
Turbine LPT { }

linkComp( "LPC", "HPC" );
linkComp( "HPC", "BRNR" );
linkComp( "BRNR", "HPT" );
linkShaft( "HPT", "HPC" );

define RunMaxPower() {
   T4 = 3000.;
}

call RunMaxPower()
```

NPSS FlowStation and Solver Objects

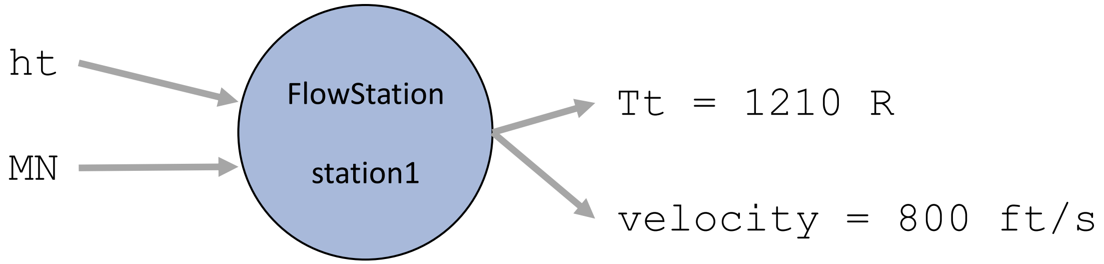
- the NPSS FlowStation object interfaces with the specified thermodynamics fluid property package (e.g., GasTbl, Janaf, CEA) to obtain all fluid properties from a few inputs

- the NPSS Solver uses the Newton-Raphson method to solve a defined set of *Dependent* equations by varying an equal number of *Independent* variables

FlowStation object

inputs	outputs
W	W_c, T_t, T_s, P_s, h_s,
P_t	entropy, velocity,
h_t	ρ, C_p, C_v, γ,
MN	μ, k, area, …

(composition)



NPSS FlowStation Modification

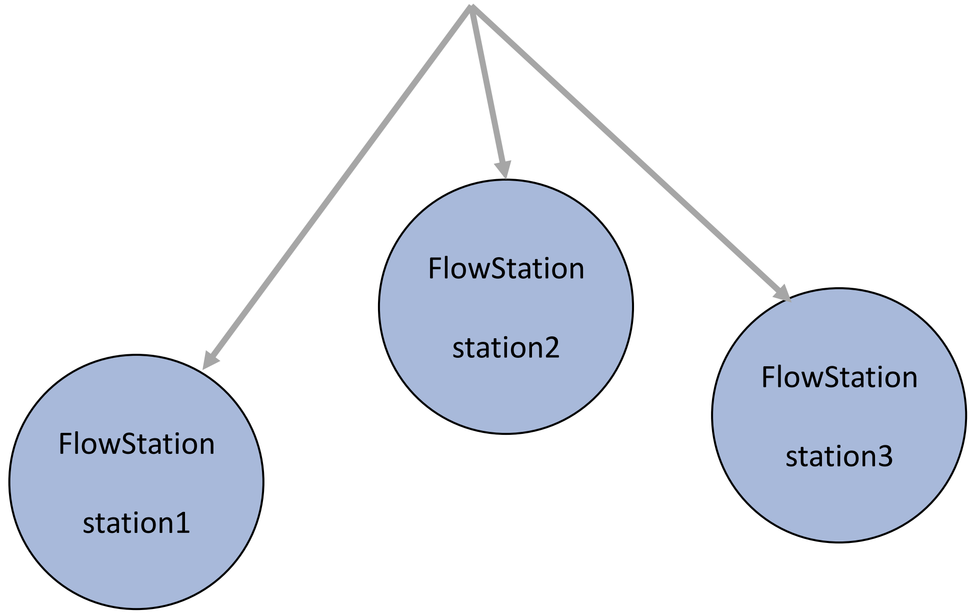
- the original 0-D/1-D NPSS FlowStation object was modified for OTAC by adding the necessary variables and calculations for a 2-D fluid state

OTAC **FlowStation** object

inputs	outputs
W	W_c, T_t, T_s, P_s, h_s,
P_t	entropy, velocity,
h_t	ρ, C_p, C_v, γ,
MN	μ, k, area, ...
α	V_m, V_r, V_z, V_θ,
φ	U, rothalpy, α_{cyl}, β_{cyl},
radius	r_{inner}, r_{outer}, span,
ω	β, MN_{rel}, V_{rel}, $V_{\theta rel}$, ...

(composition)

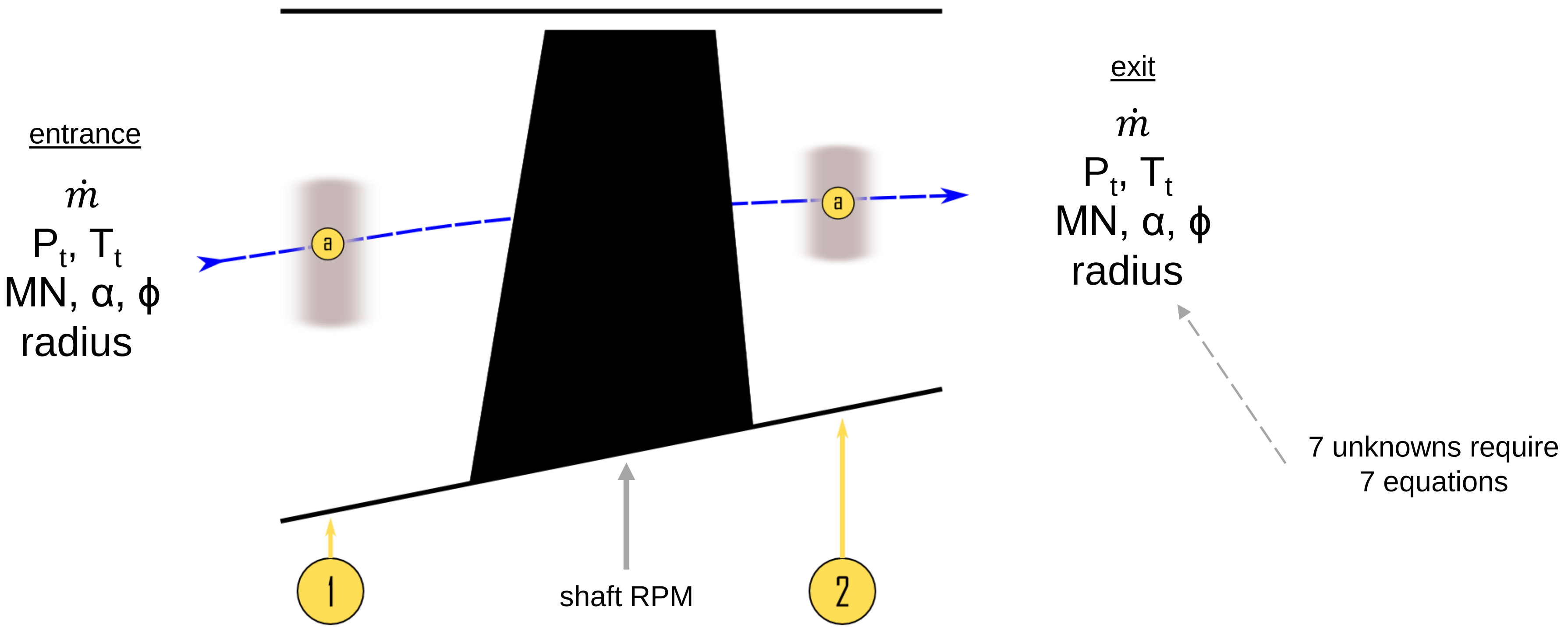
a set of 7 inputs is required for each of these stations to uniquely define their fluid state; a rotational speed is also required to calculate properties in a rotating frame of reference



Flow Through an Annulus with a Blade Row

- the goal is to simulate the physics of the process that occurs to some small chunk of fluid, “a”, between station 1 and 2, and solving for the fluid state at station 2

- the state of the fluid at station 1 is assumed to be known (e.g, obtained from the upstream blade row exit solution) as well as the blade rotational speed



Ideal Meanline Equations

- the following 7 equations allow the blade row exit state to be calculated with (design) input of the green variables

conservation of mass	$\dot{m}_2 = \dot{m}_1$
conservation of momentum/energy	$h_{t2} - h_{t1} = \omega(r_2 V_{\theta 2} - r_1 V_{\theta 1})$
ideal process (isentropic)	$s_2 = s_1 \; (P_{t2} = P_{t\,ideal})$
ideal process (perfect turning)	$\beta_2 = \beta_{blade}$
geometry constraint (radius)	$r_2 = r_{machine}$
geometry constraint (area)	$A_2 = A_{machine}$
geometry constraint (slope)	$\phi_2 = \phi_{machine}$

- *direct design* (β_{blade} input) is shown but *indirect design* (e.g., PR input) is easily done by varying β_{blade} such that $P_{t2}/P_{t1} = PR_{desired}$ by adding appropriate solver objects

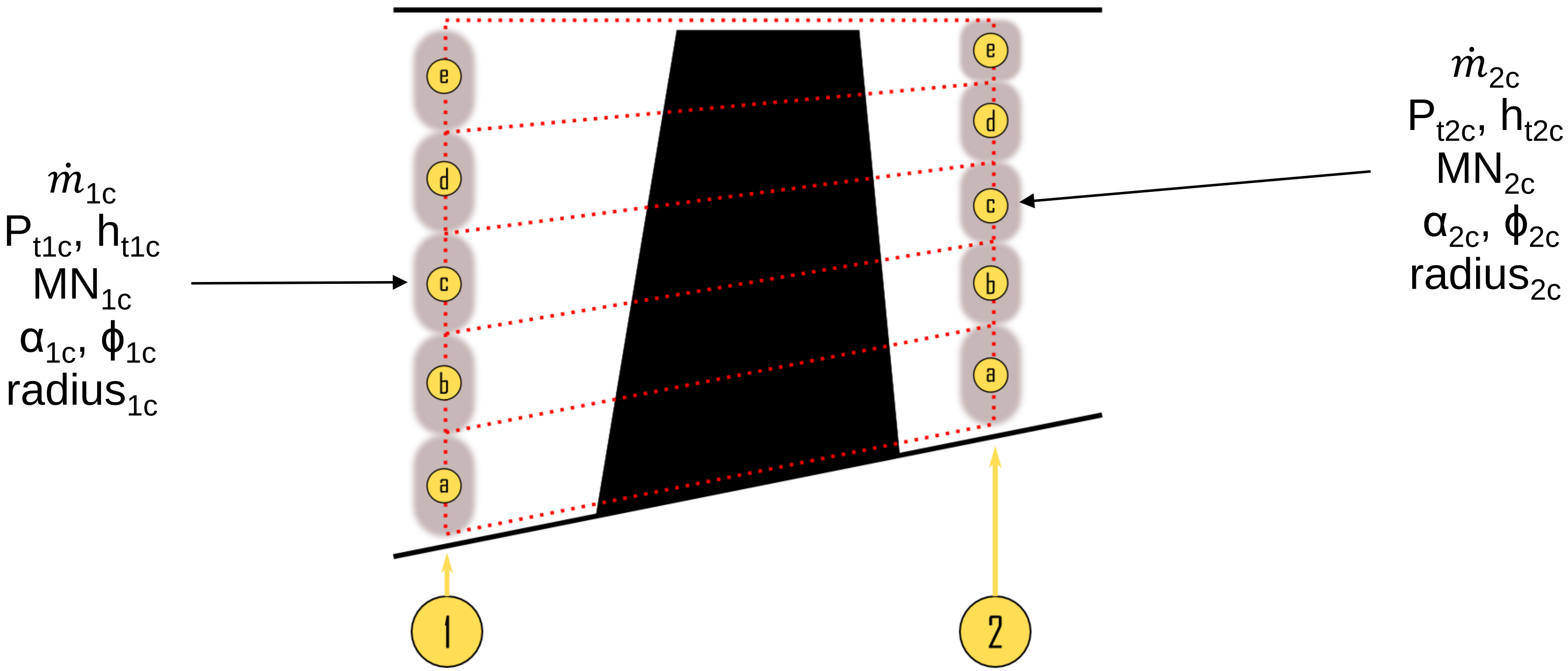
General Meanline Equations

- the trivial nature of the first and last equation permits the problem to be reduced to 5 equations and 5 unknowns (note: the Euler equation also becomes trivial for non-rotating blade rows and can be used in that case to further reduce the problem to 4 equations and 4 unknowns)
- the "real" solution is a function of complicated empirical effects categorized by loss, deviation, and blockage which may be a function of both entrance and exit conditions, and other inputs

conservation of mass	~~$\dot{m}_2 = \dot{m}_1$~~	~~$\dot{m}_2$~~
conservation of momentum/energy	$h_{t2} - h_{t1} = \omega(r_2 V_{\theta 2} - r_1 V_{\theta 1})$	h_{t2}
"real" process (non-isentropic)	$P_{t2} = P_{t\,ideal} - \Delta P_{t\,loss}$	P_{t2}
"real" process (imperfect turning)	$\beta_2 = \beta_{blade} - \delta$	α_2
effective geometry constraint (radius)	$r_2 = r_{machine} - r_{blockage}$	r_2
effective geometry constraint (area)	$A_2 = A_{machine} - A_{blockage}$	MN_2
geometry constraint (slope)	~~$\phi_2 = \phi_{machine}$~~	~~ϕ_2~~

Streamline Equations

- the aggregate flow can be divided into any number of arbitrary chunks (for example, “a” - “e”)
- if each chunk of flow does not alter its own mass flow rate across the blade row, then each segment of flow “a” - “e” can be considered a streamtube

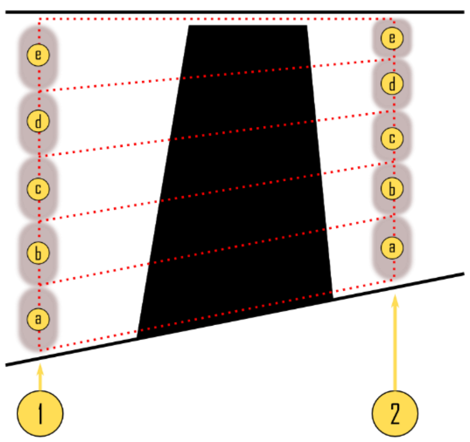


- the process for each separate chunk of flow is similar to the meanline, but with a few changes

Streamline Equations

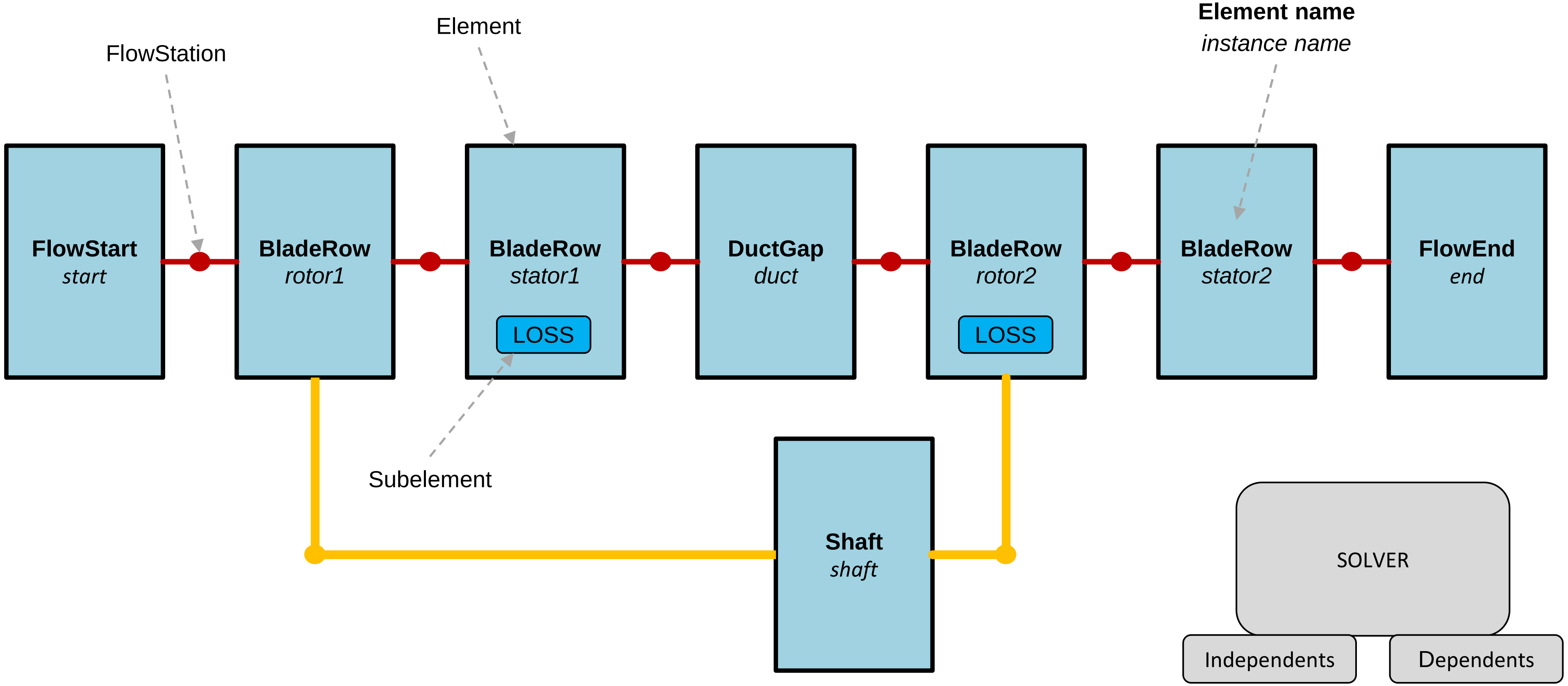
- for *n* number of flow divisions, there are 7*n* unknowns which require 7*n* equations for a solution

n	continuity	$\dot{m}_{2_i} = \dot{m}_{1_i}$
n	Euler TM equation	$h_{t2_i} - h_{t1_i} = \omega(r_{2_i}V_{\theta 2_i} - r_{1_i}V_{\theta 1_i})$
n	loss equation	$P_{t2_i} = P_{t\,ideal_i} - \Delta P_{t\,loss_i}$
n	turning equation	$\beta_{2_i} = \beta_{blade_i} - \delta_i$
n-1	radial continuity	$r_{eff\ inner2_{i+1}} = r_{eff\ outer2_i}$
1	aggregate radius	$r_{2_{aggregate}} = r_{machine} - r_{blockages}$
n-1	radial equilibrium	$\left\{ \frac{1}{\rho}\frac{dp}{dr} = \frac{V_\theta^2}{r} - \frac{V_m^2}{r_s}\cos\phi \right\}_i$
1	aggregate area	$A_{2_{aggregate}} = A_{machine} - A_{blockages}$
n	slope equation	$\phi_{2_i}, r_{s_i} = f_{spline}$
7*n* total		

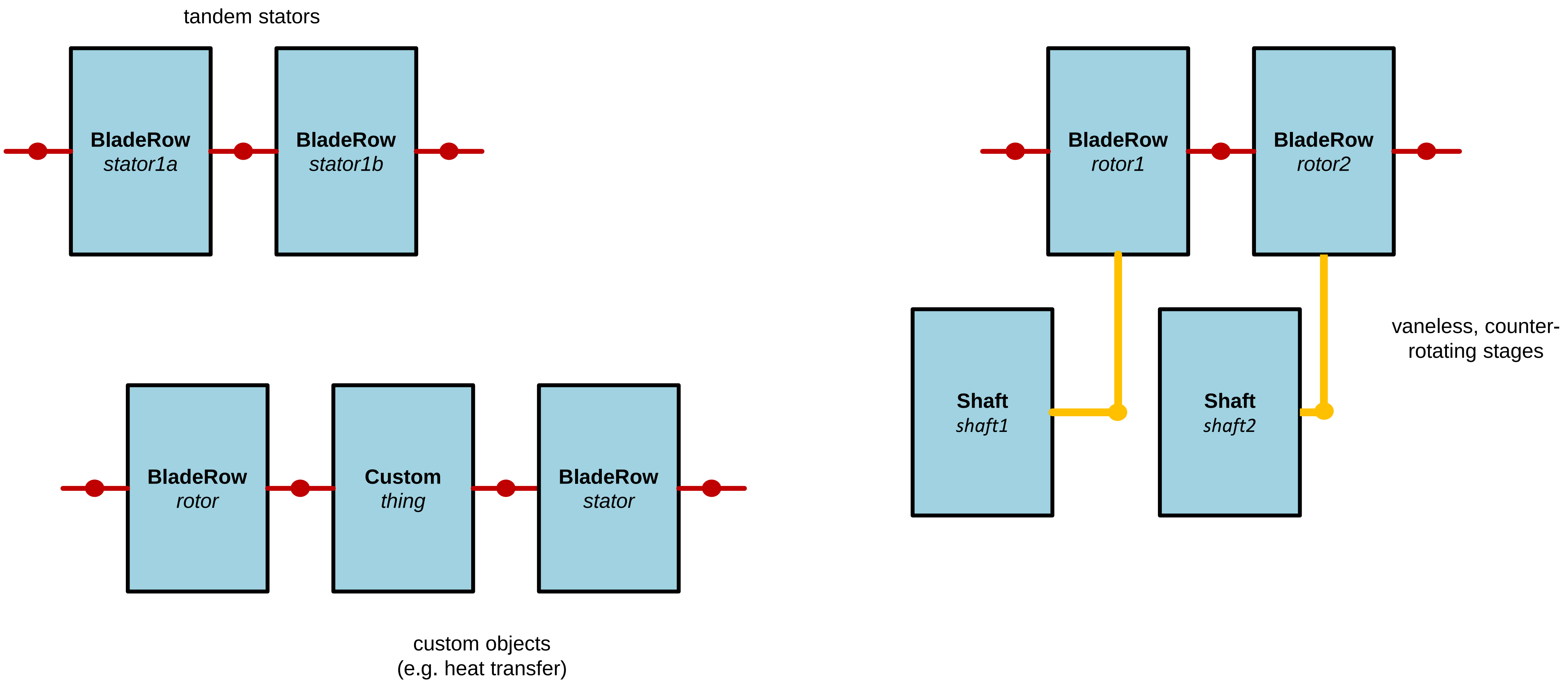


OTAC Architecture is Similar to NPSS

- the set of OTAC objects (Elements, Subelements, etc.) were developed with the idea of closely following the NPSS engine paradigm and using pre-existing objects where possible

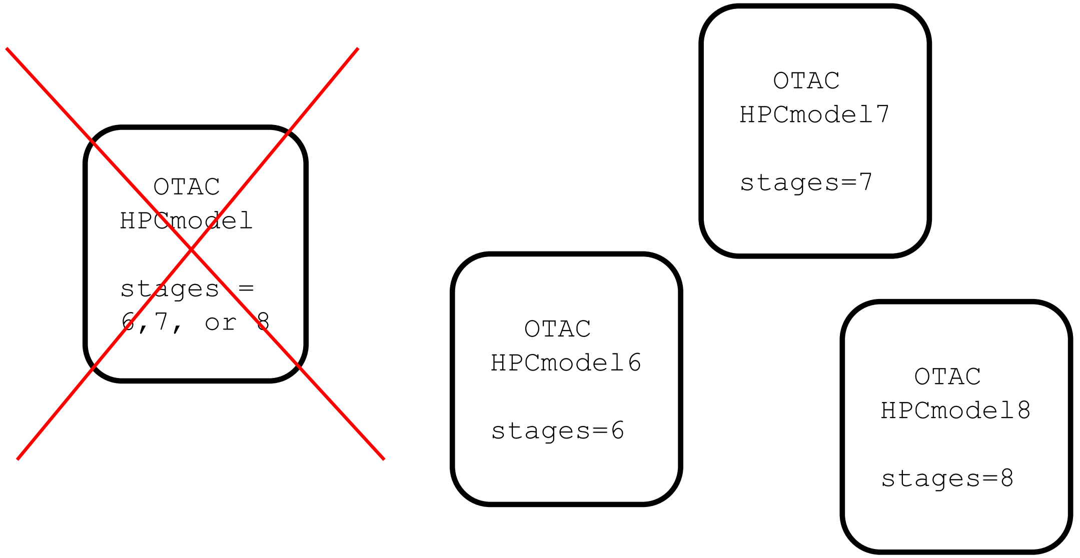


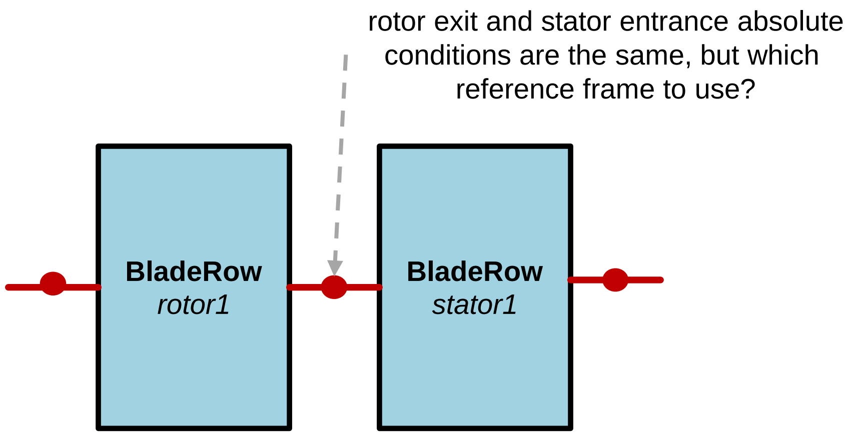
Using the BladeRow as the Primary Object Adds Flexibility



This Does Have Several Drawbacks

- NPSS was not constructed with the idea of adding or deleting Elements during execution (or even during instantiation) even though it can be done
- since OTAC uses the `BladeRow` as the “base” object, adding or removing a blade row (or stage) during execution has not been considered: any OTAC model therefore consists of a fixed number of blade rows
- fluid data properties are passed via ports (which notionally sit between blade rows), which is where the rotating and non-rotating reference frame overlap



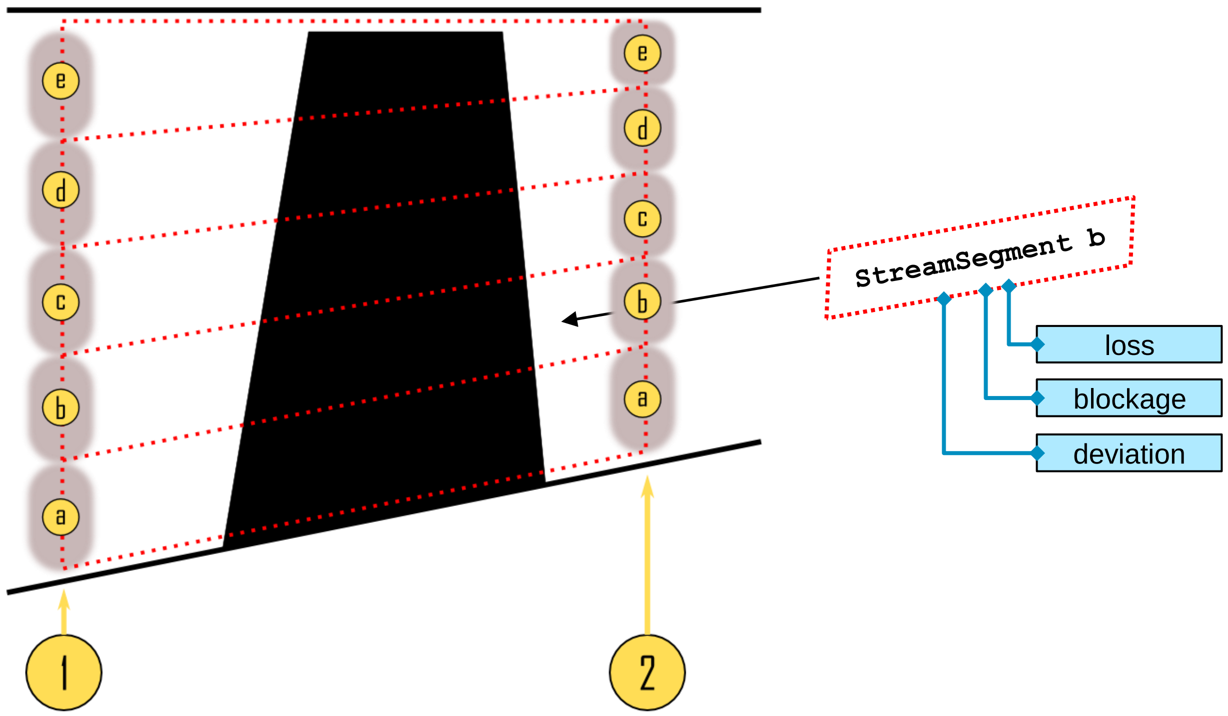


OTAC Object Responsibilties

- `FlowStation` – interface with NPSS thermo property packages
- `OTACstart` – starts a flow of given Pt, Tt, MN, and composition
- `Expander` – computational division of a flow into multiple streams
- `Reducer` – computational summation of multiple streams into a single stream
- `BladeRow` – holds overall blade row features
  - `BladeGeometry` – holds gross blade row geometry features
  - `Blockage` – hub and tip blockage calculations
  - `StreamSegment` – holds stream tube features across a single blade row
    - `Loss` – pressure loss calculation for this stream tube
    - `Deviation` – deviation calculation for this stream tube
    - `Blockage` – wake blockage calculation for this stream tube
- `DuctGap` – represents a small gap of changing area between blade rows
  - `DuctGapSegment` – holds stream tube features across the duct gap
- `Shaft` – NPSS rotating shaft Element
- `Incidence` – incidence calculation at design for this stream tube
- `SlopeAndCurvature` – calculates slope and curvature across the device

BladeRow and StreamSegment Objects

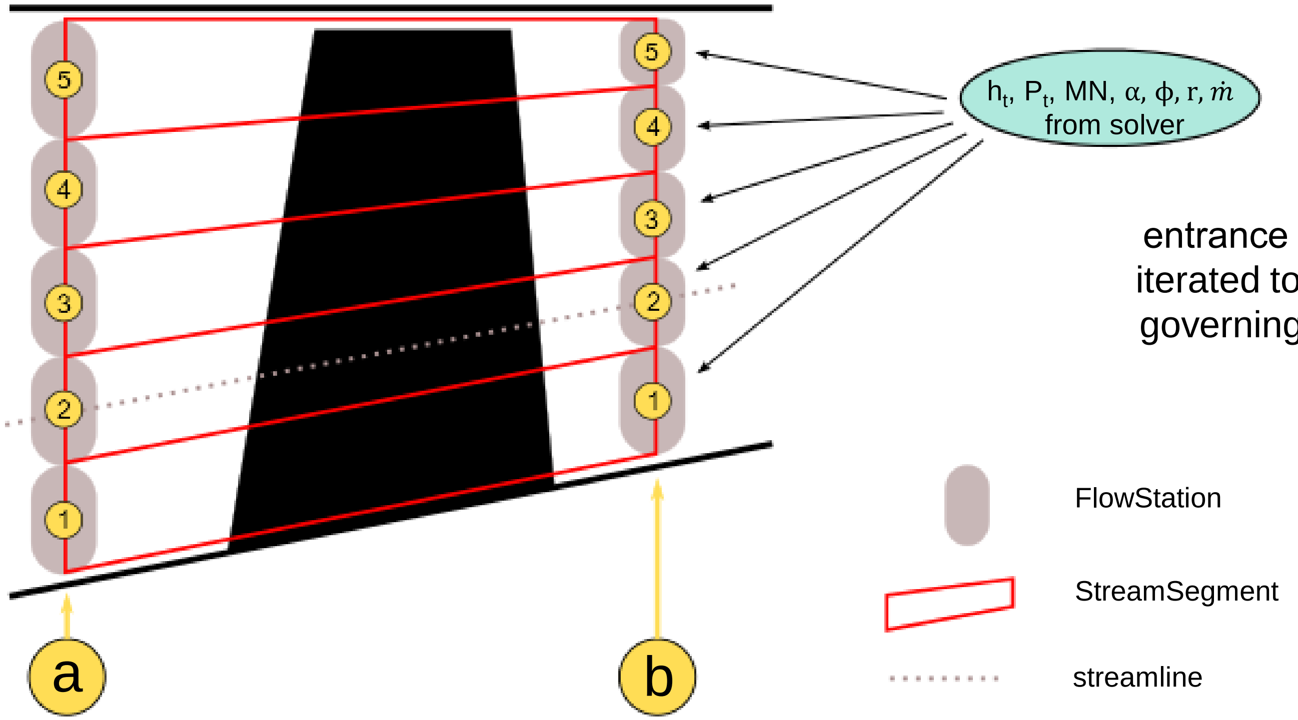
- each BladeRow contains a set of StreamSegments (one StreamSegment per streamtube) and works with the solver to obtain the final BladeRow solution



- each StreamSegment has an entrance and exit FlowStation and represents the change in flow conditions that occur across a section of a blade
- StreamSegments contain “sockets” which allow for subelements to be plugged in, providing values for complex effects which require empirical correlations to estimate

Schematic of how the `FlowStation`, `BladeRow`, `StreamSegment`, and `solver` interact

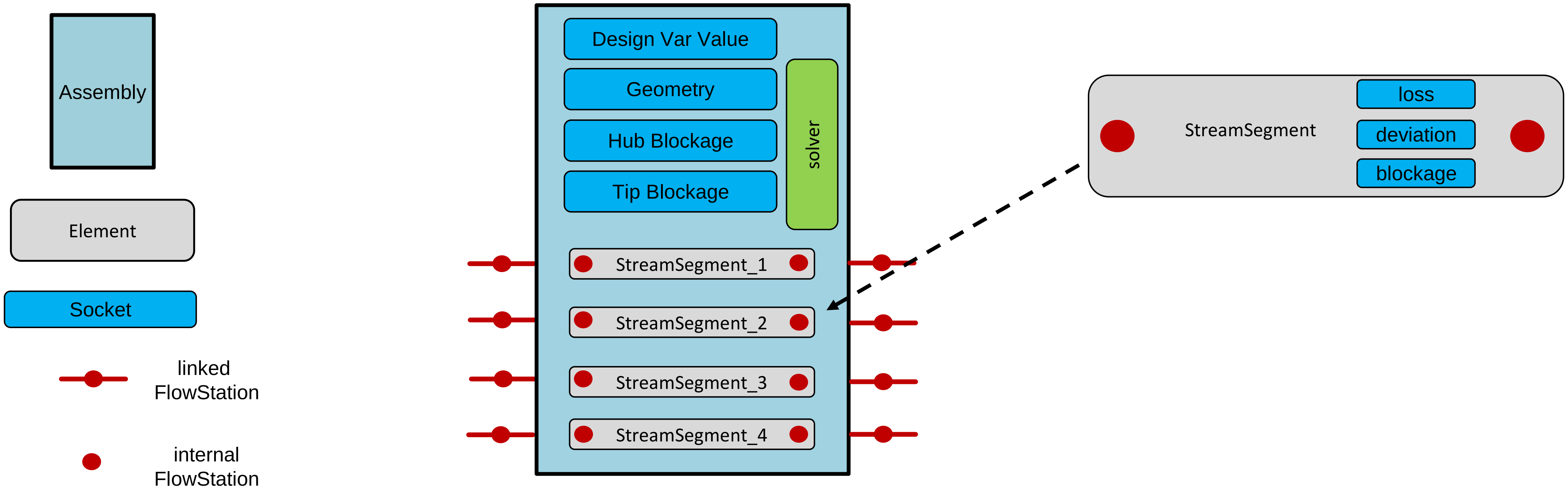
entrance state "a" is known



entrance state "b" is iterated to satisfy the governing equations

The Assembled `BladeRow` Object

- the `BladeRow` is an Assembly of `StreamSegment` Elements, with `Sockets` for hub/tip blockage, geometry, and a spanwise design value for the desired input variable
- the `BladeRow` also has its own dedicated `solver`
- each `StreamSegment` Element contains its own sockets
- each `StreamSegment` also has its own `FlowStation` copy of the entrance and exit flow



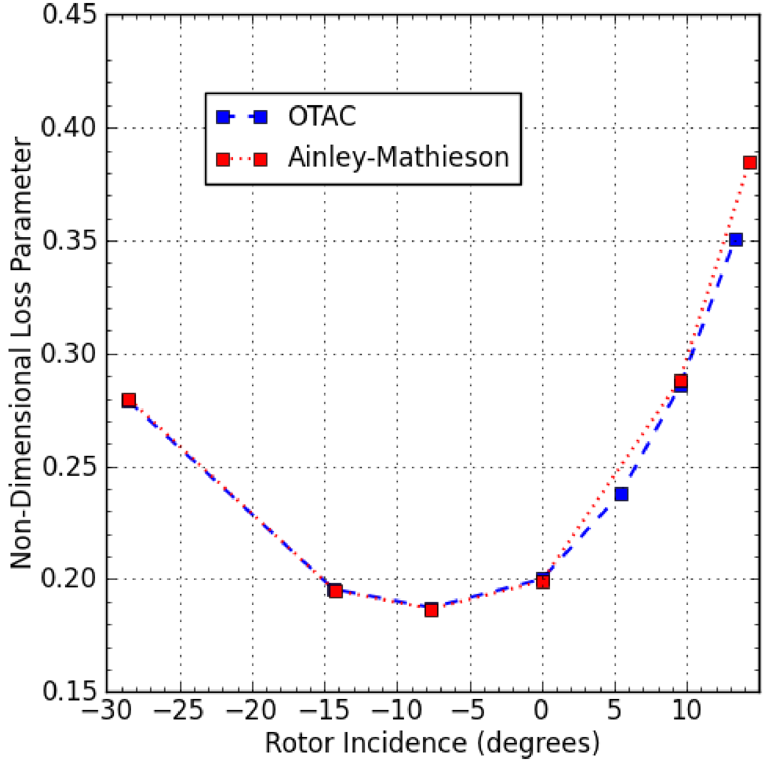
Sockets and Subelements

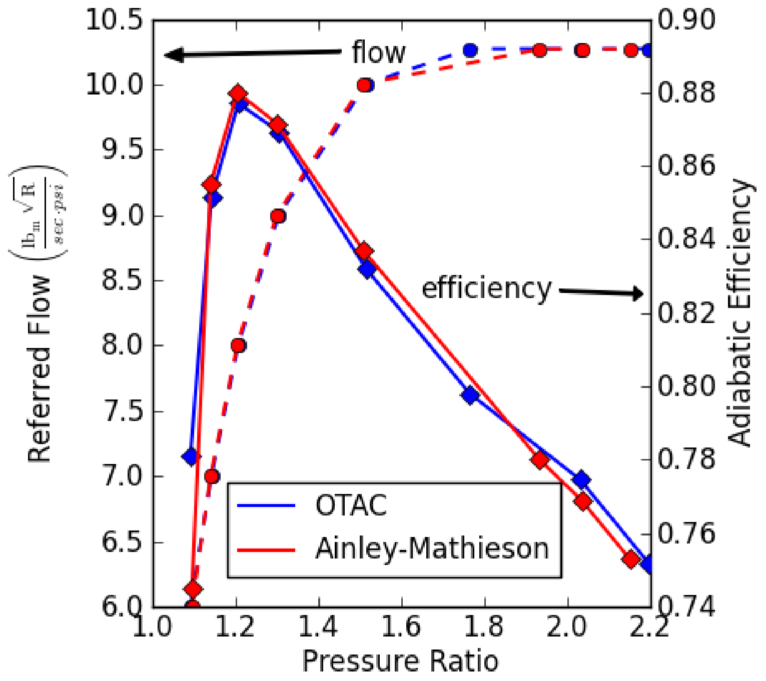
- the `BladeRow` and `StreamSegment` objects contain `Sockets`
- `Sockets` allow the insertion of Subelements which perform (normally very complex, normally very empirical) calculations related to a specific variable (such as loss or deviation); these Subelements can be tables or functions
- OTAC (and NPSS) allow the user to create custom Subelements to use as part of the simulation
- advantages are:
  - separation of what is common (e.g., Euler turbomachinery equation, the definition of deviation) with what is different (the prediction of deviation)
  - incorporation of new/experimental correlations without need to recompile or alter the base source (includes the ability to add and use internal/proprietary correlations in OTAC)
  - the ability to mix and match correlations as desired within an analysis (e.g., the form of the shock loss is different for each blade row)

OTAC Test Cases and Results

Axial Turbine Flow and Efficiency Characteristics

- comparison of OTAC and Ainley-Mathieson single stage turbine calculation, meanline, losses calculated

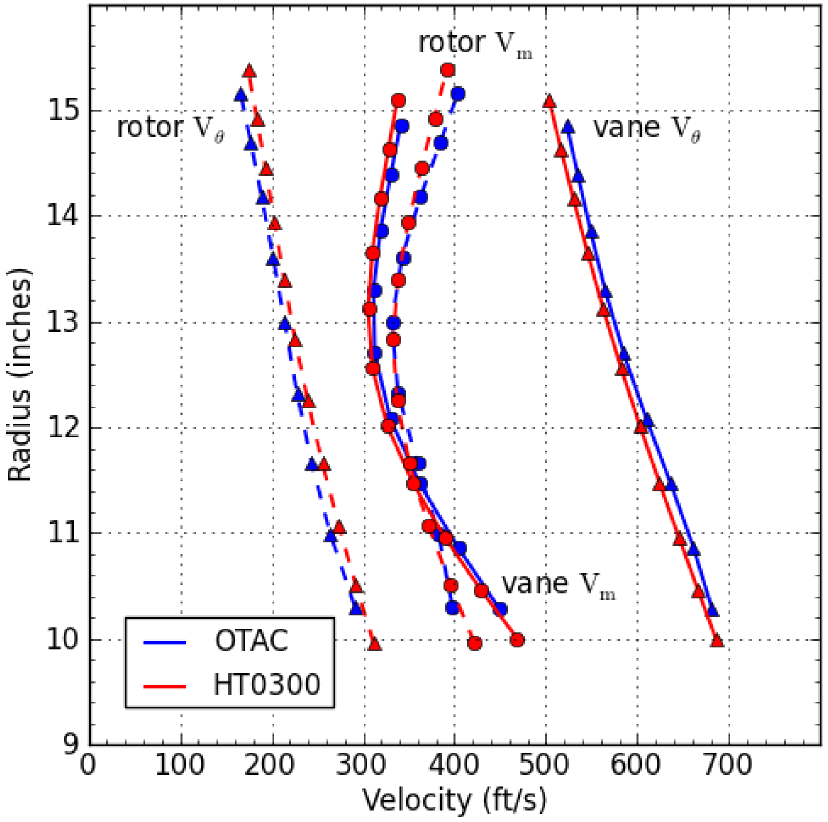




Spanwise Flow Velocities

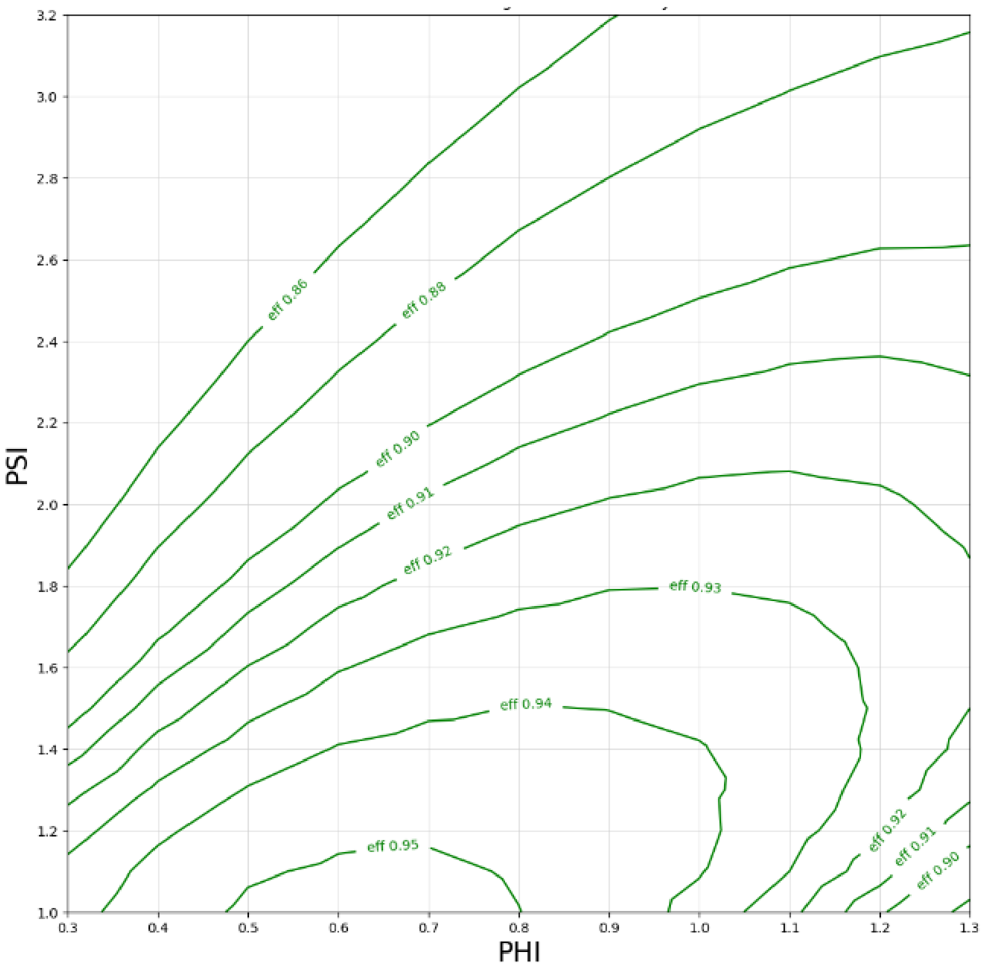
- comparison of OTAC and HT0300 5-stage turbine calculation, streamline (no slope or curvature), losses calculated using Ainley-Mathieson with Kacker/Okapuu revisions

stage 4 results



Smith Chart Diagram Generation

- axial turbine "Smith" chart for a meanline single-stage turbine using the AMDC loss model with Kacker/Okapuu revisions

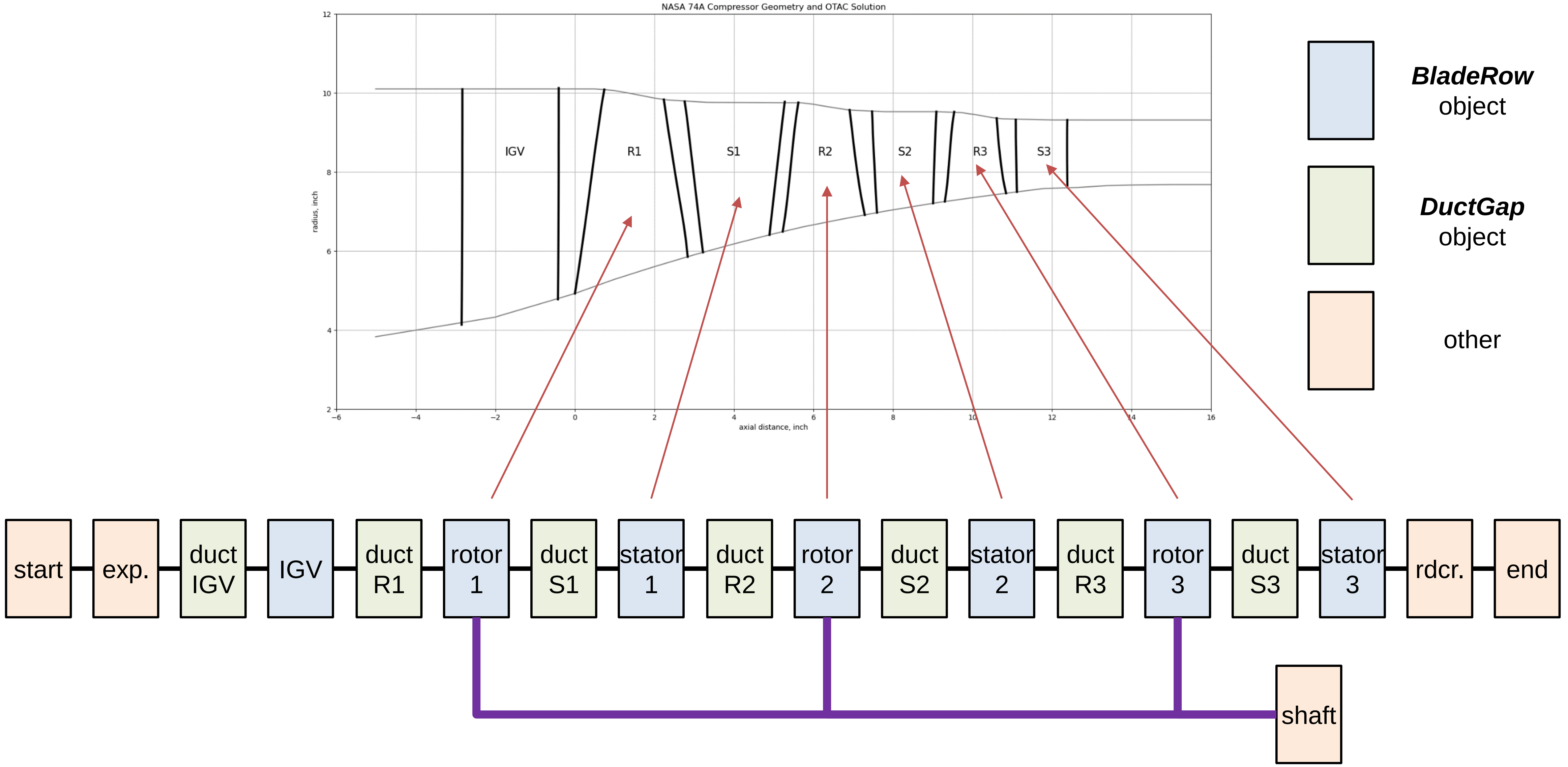


OTAC Comparison with NASA 74A Compressor

- goal is to test the final desired OTAC functionality with regard to handling of loss models, blockage, incidence and deviation, and slope and curvature effects

- using compressor design and performance detailed in NASA-TP-2597, “Design of 9.271-Pressure-Ratio Five-Stage Core Compressor and Overall Performance for First Three Stages”, by R.J. Steinke
  - report provides a simple profile loss model that is a function of diffusion factor and spanwise distance, and a simple shock loss model that is only a function of relative Mach number
  - wake blockage is also provided for each blade row
  - incidence and deviation values are given, but no off-design correlations

OTAC 74A Compressor Model

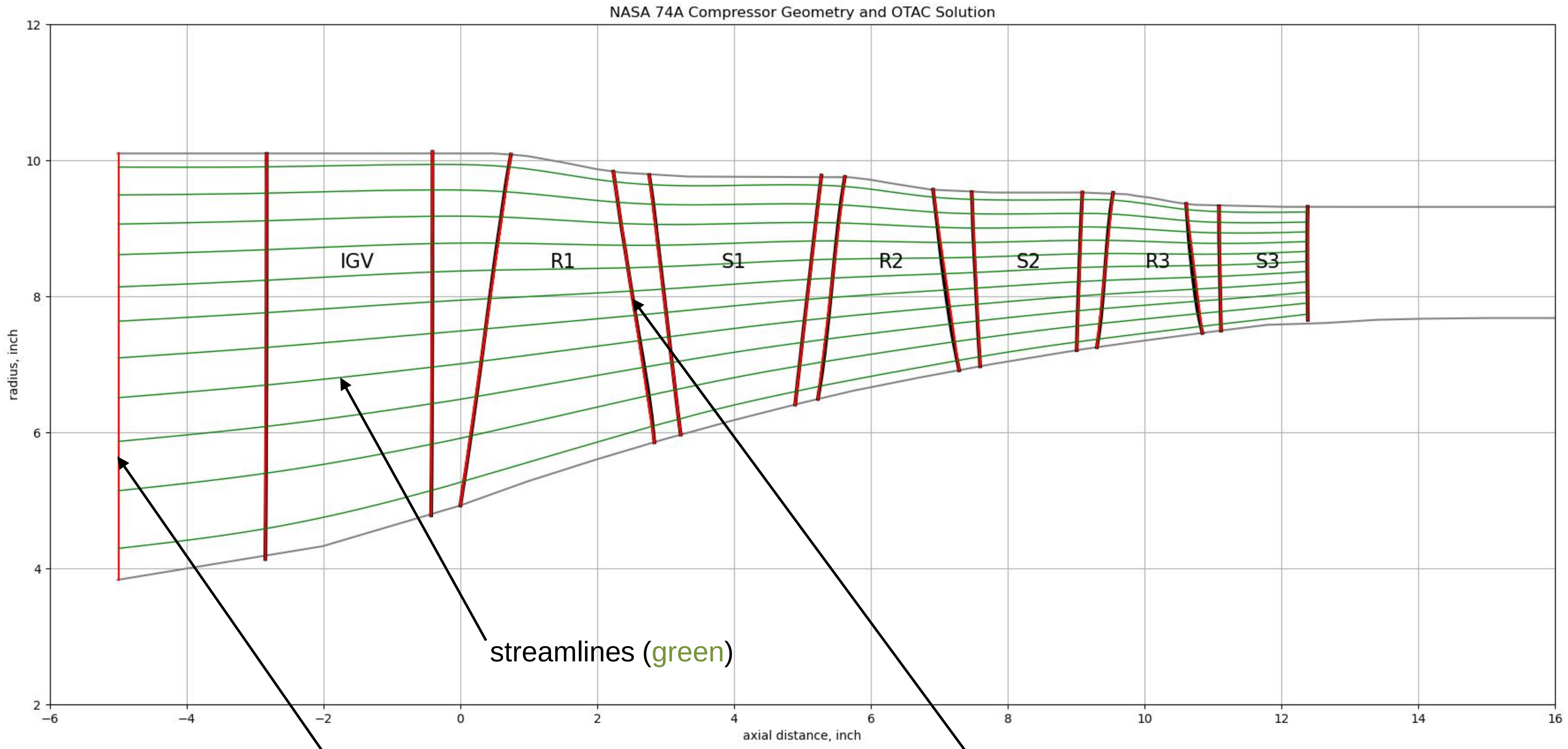


OTAC 74A Model Assumptions and Inputs

Test of OTAC's design mode:

- uses hub and tip geometry and entrance conditions (massflow rate, pressure, temperature) from the report
- uses blade counts and chord lengths from the report
- uses the profile loss and shock loss correlations and blockage values from the report
- exit calculation stations defined to match blade row entrance and exits
- rotor pressure ratios taken from the report, stator exit flow angles set to zero (as done in the report)
- no incidence or deviation (no impact at design)
- has ***DuctGap*** objects to account for minor spacing and area changes between blade rows
- 11 streamlines, with slope and curvature effects

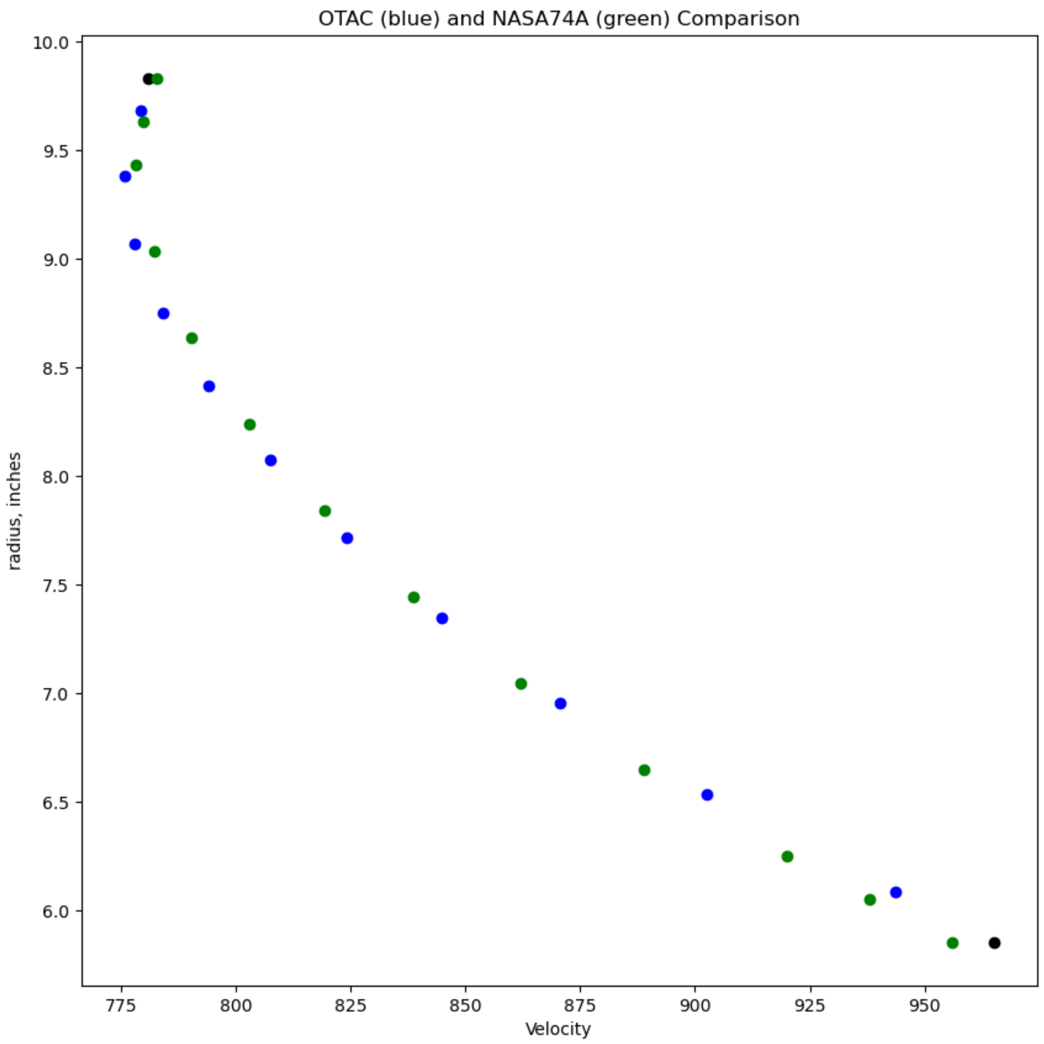
OTAC 74A Compressor Results - Streamlines



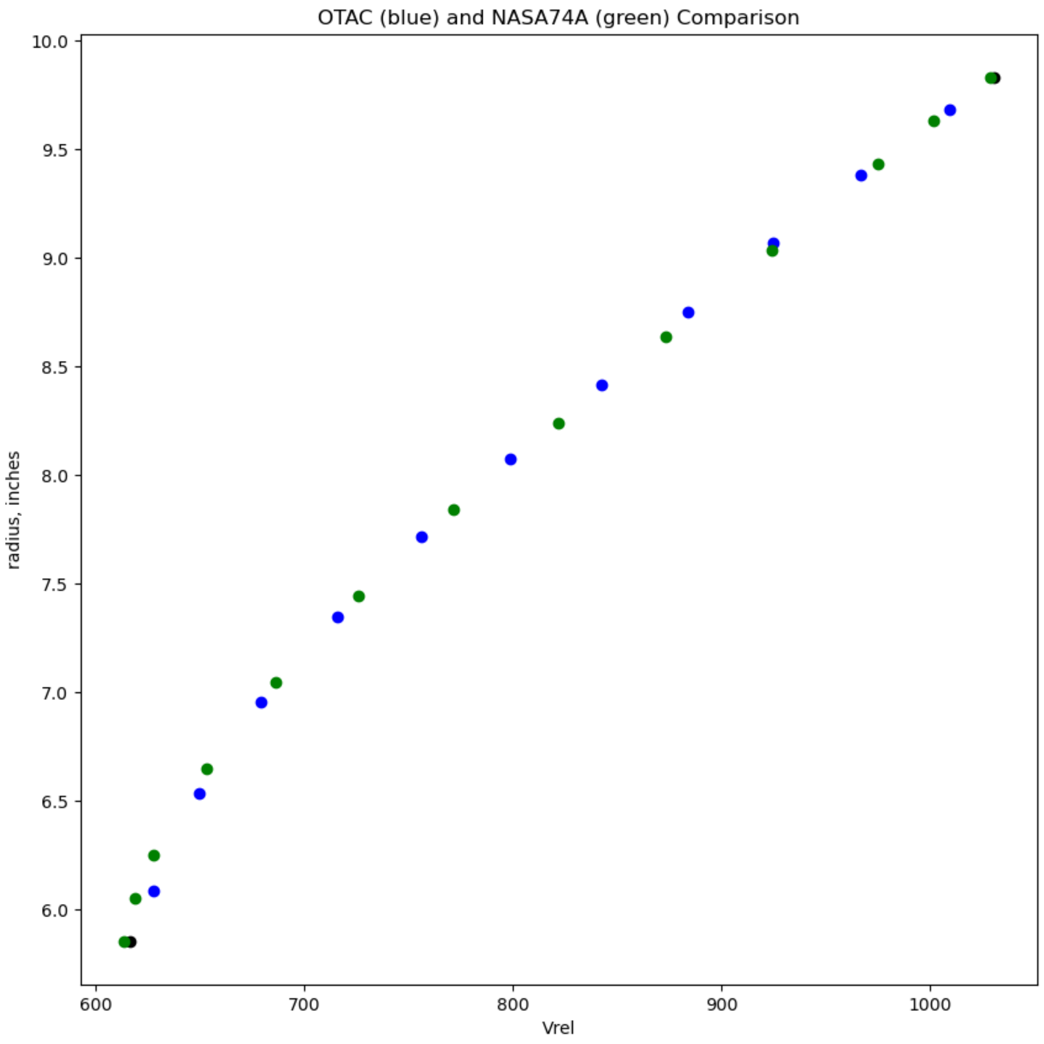
OTAC calculation stations (red) placed to coincide with blade row leading and trailing edges

the following charts show the exit solution at this location (rotor1 exit, arbitrarily selected)

OTAC 74A Results – Rotor 1 Exit Solution

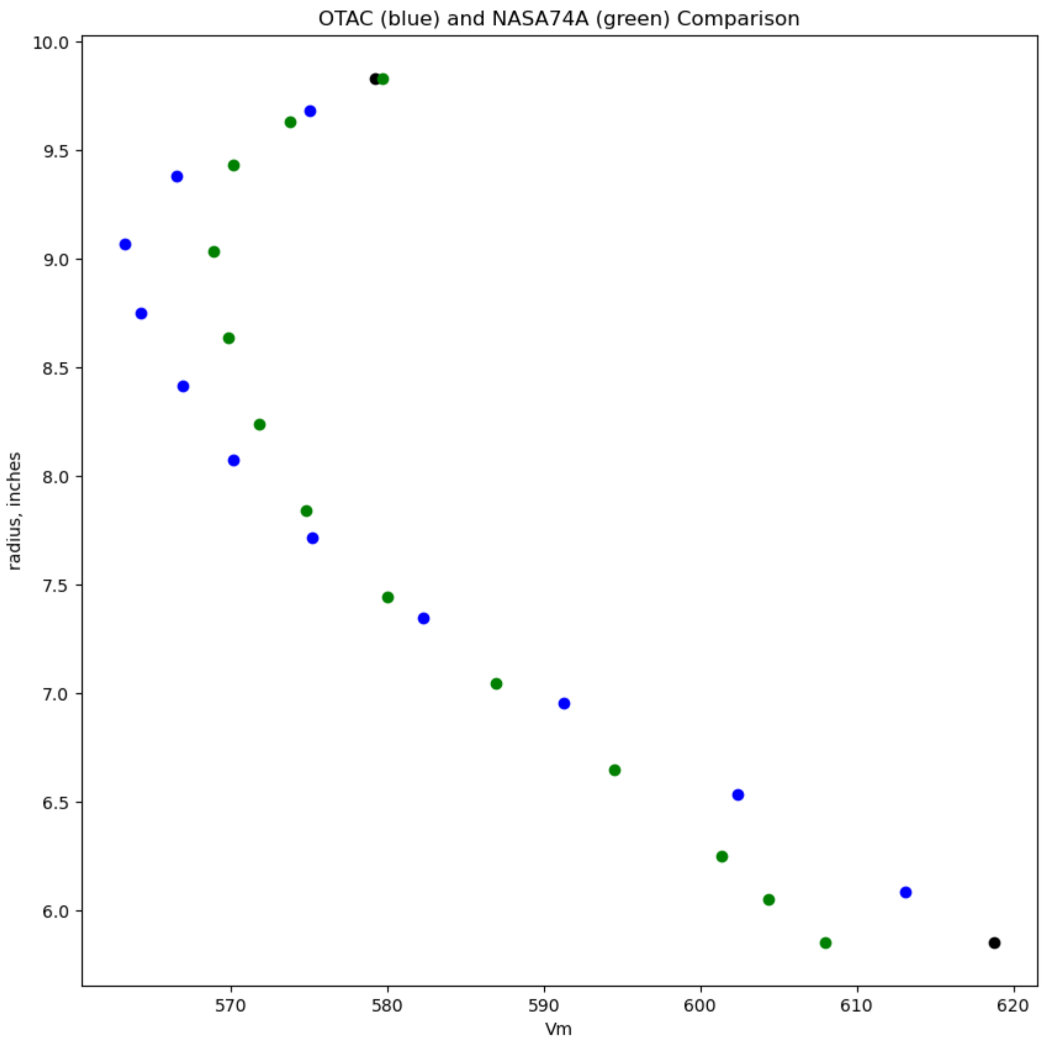


Velocity (full, actual)

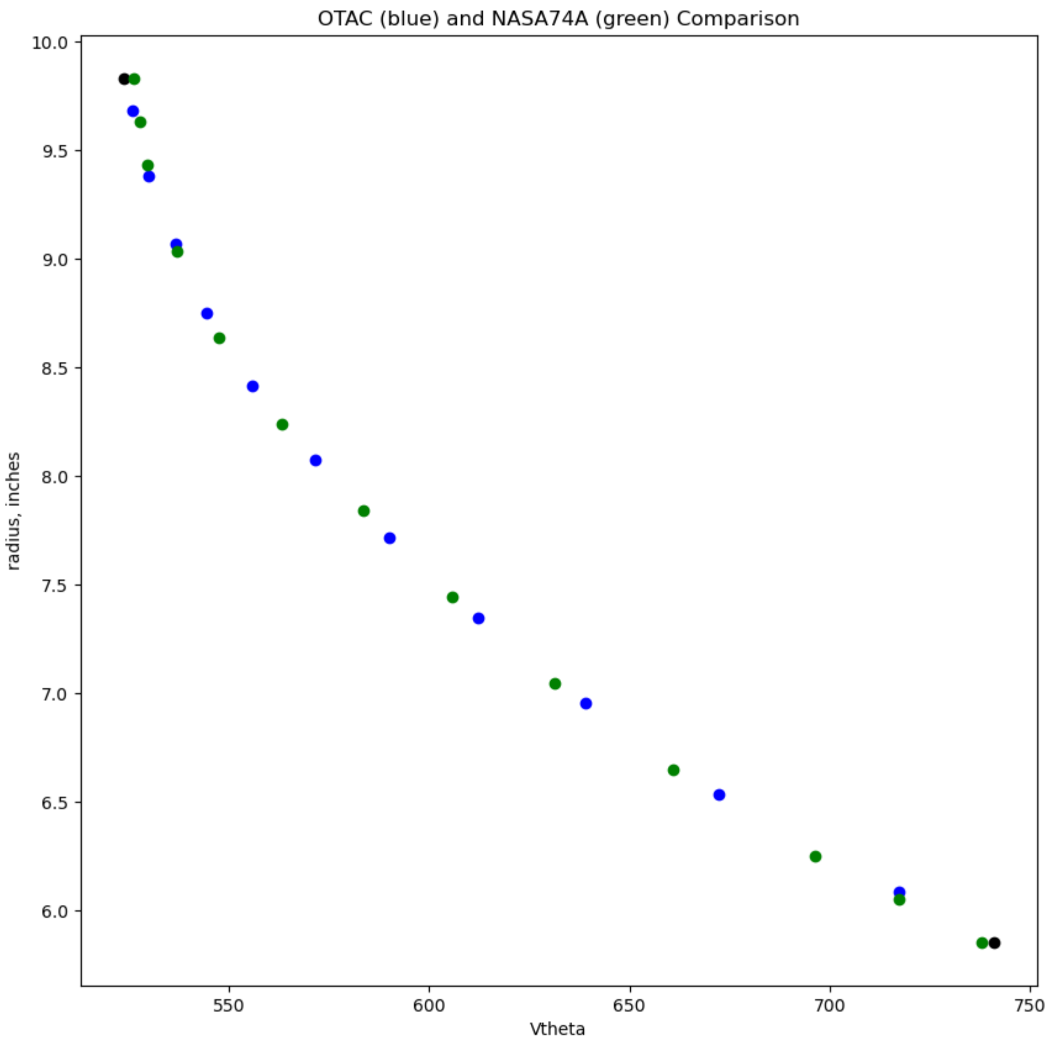


Velocity (relative component)

OTAC 74A Results – Rotor 1 Exit Solution

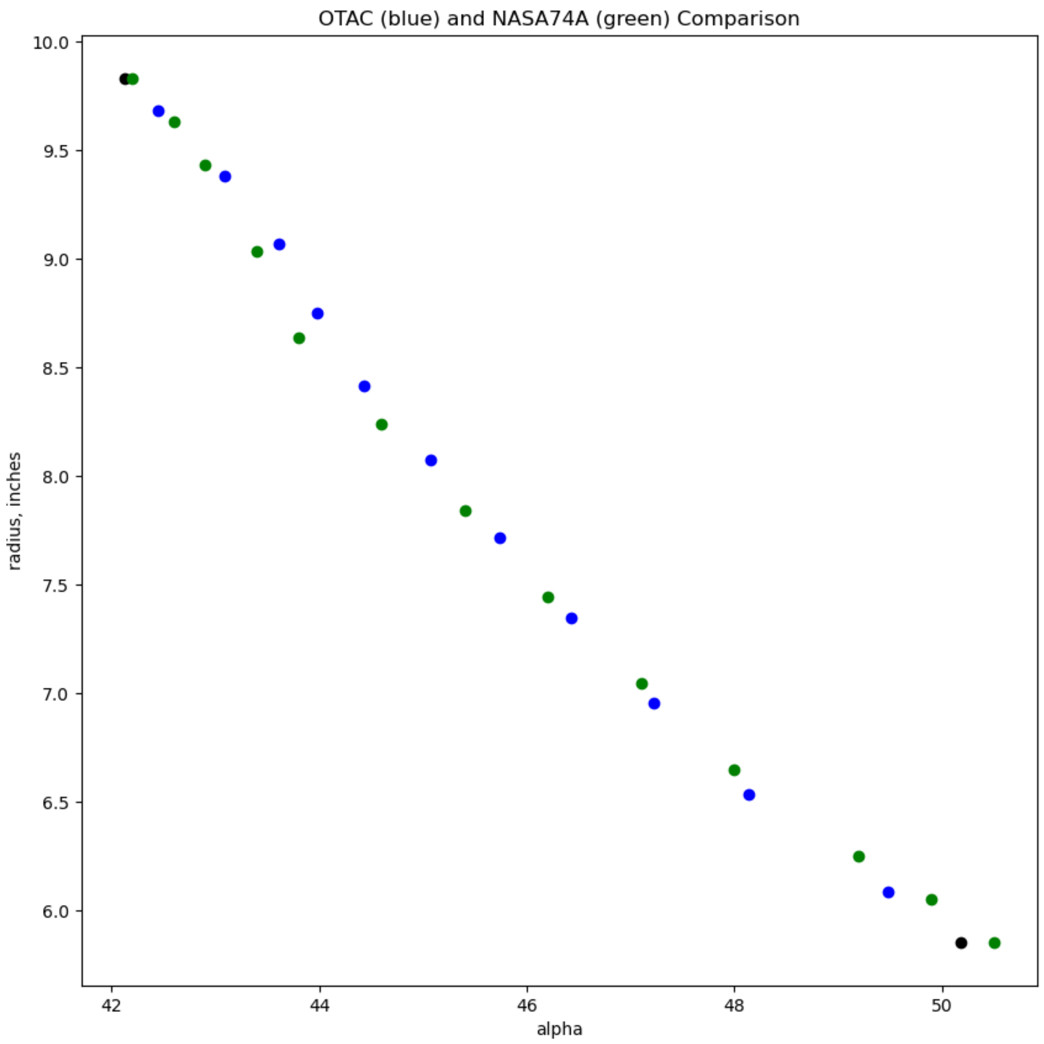


Velocity (meridional component)

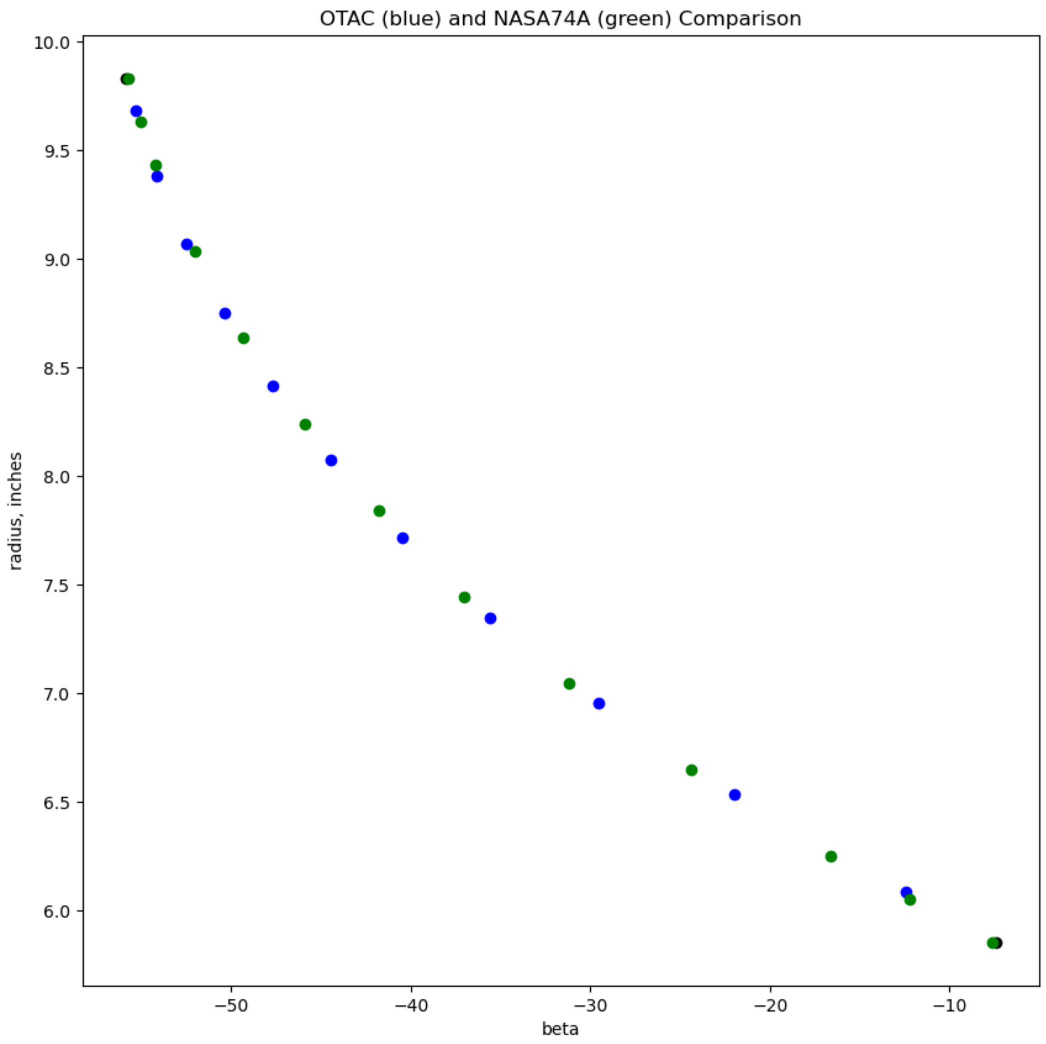


Velocity (tangential component)

OTAC 74A Results – Rotor 1 Exit Solution

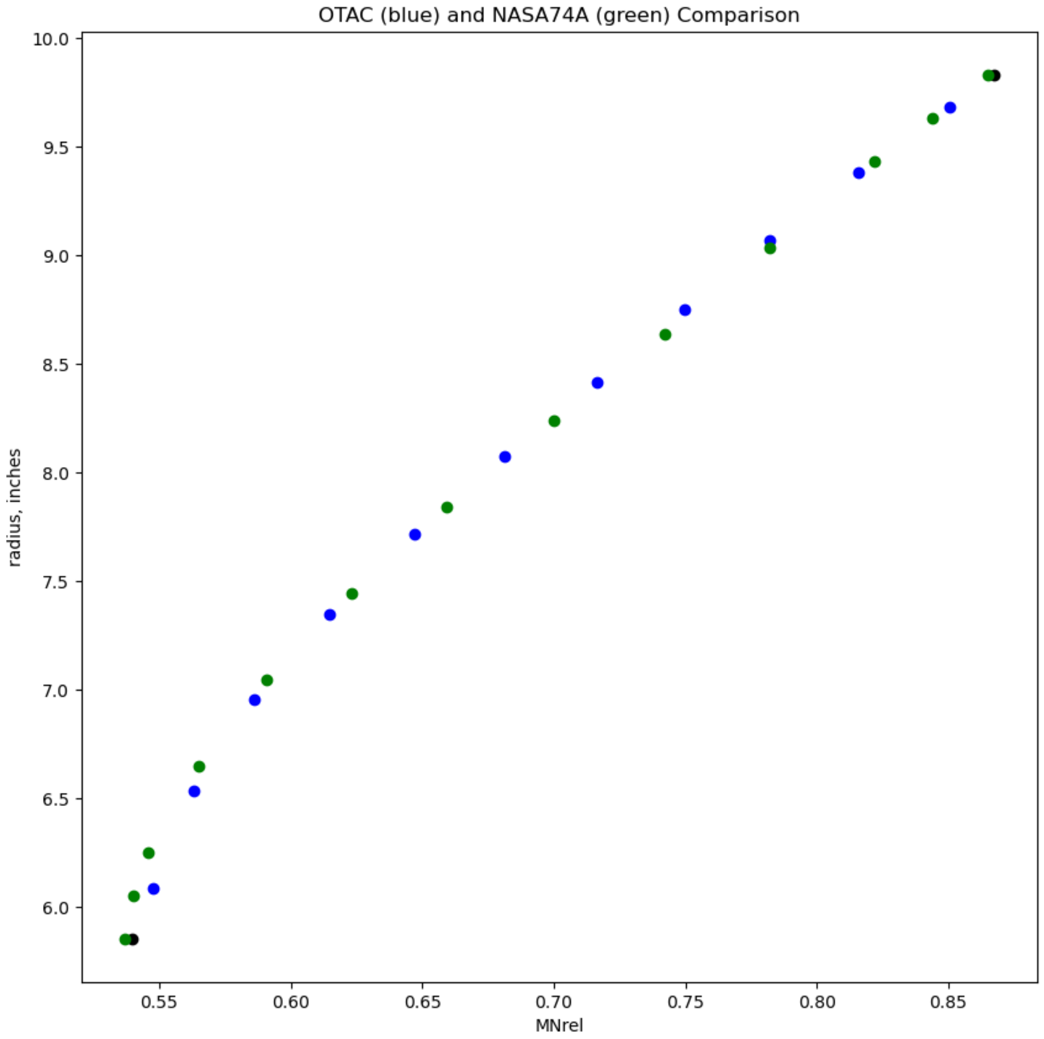


Tangential Flow Angle (actual)

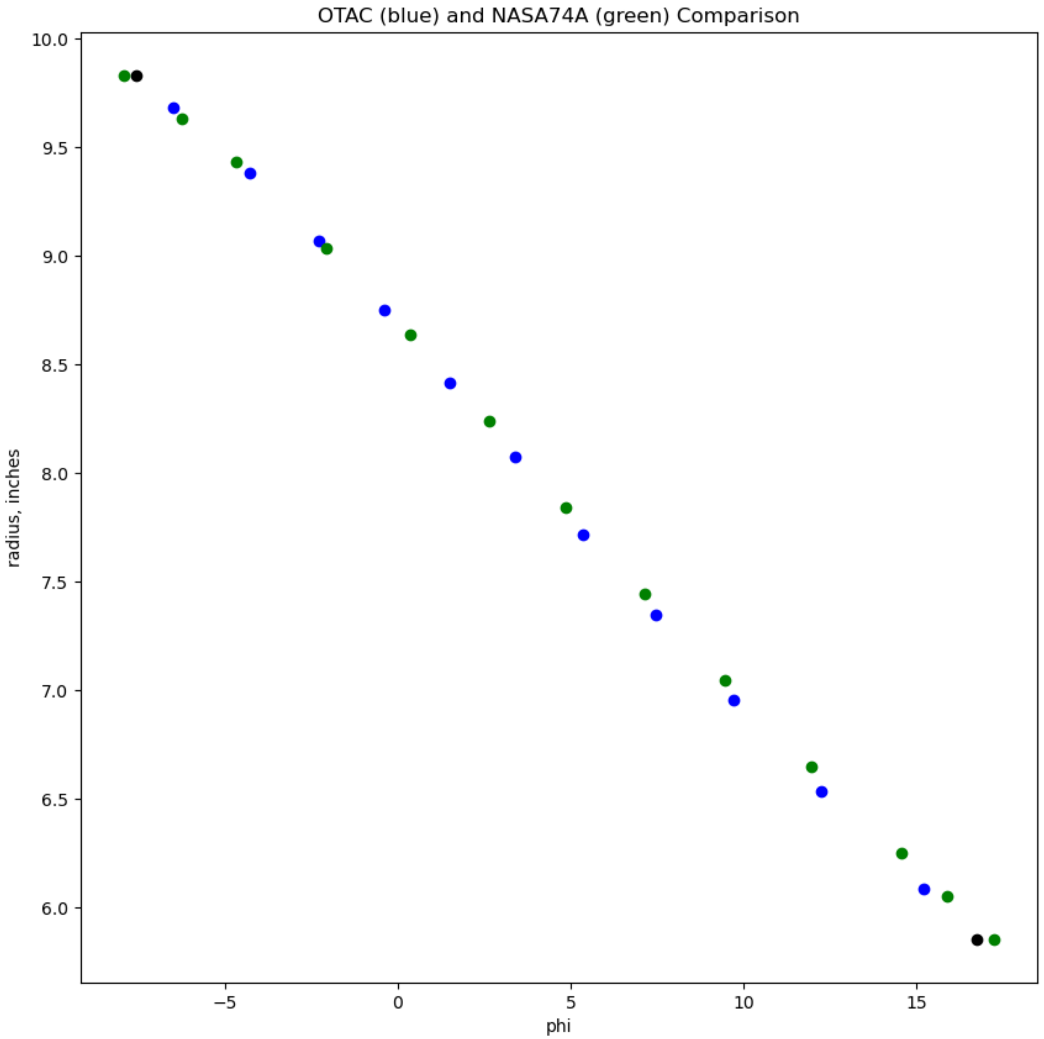


Tangential Flow Angle (relative)

OTAC 74A Results – Rotor 1 Exit Solution

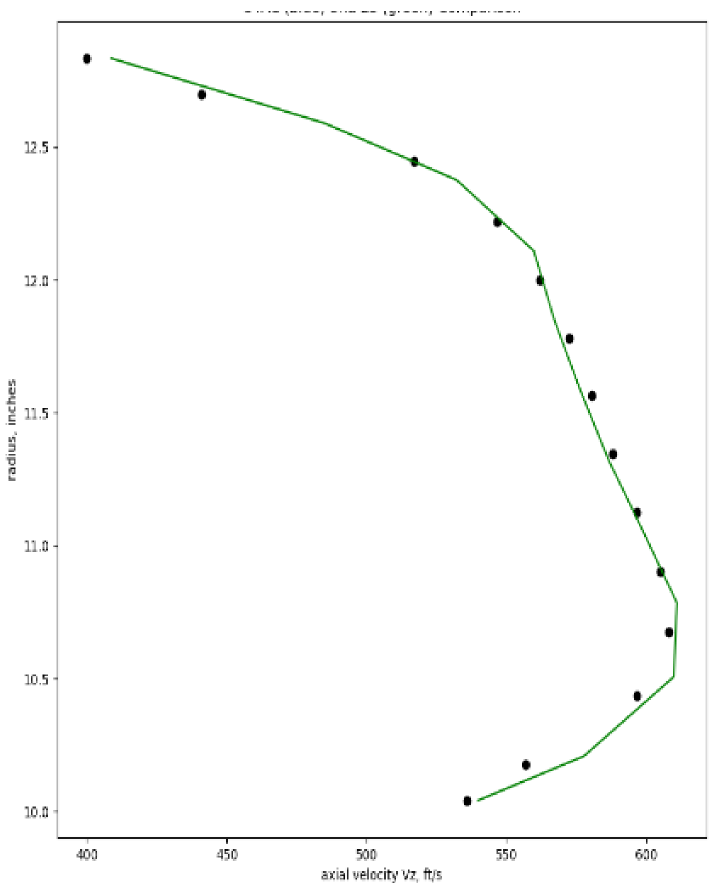


Mach Number (relative)

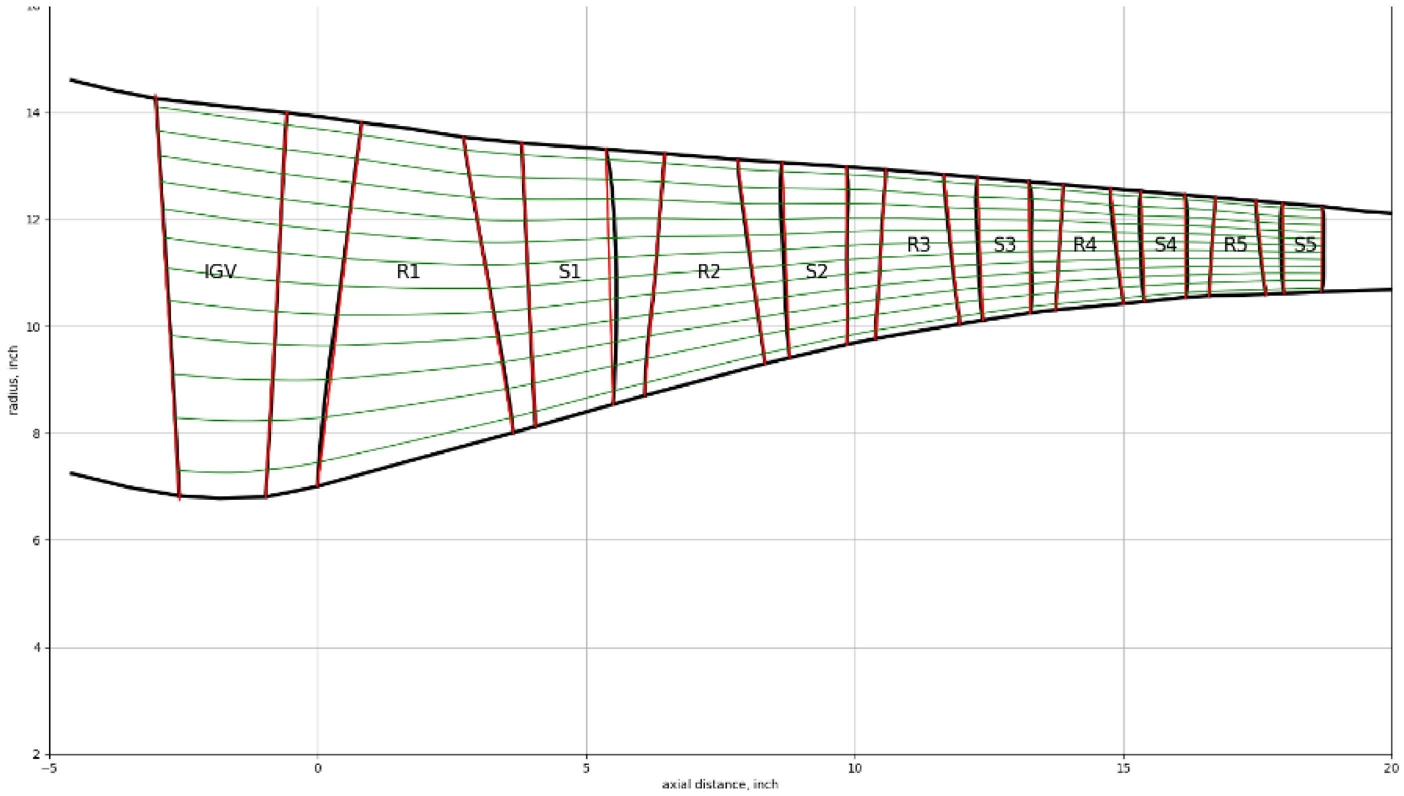


Slope Flow Angle

OTAC E³ High Pressure Compressor Results



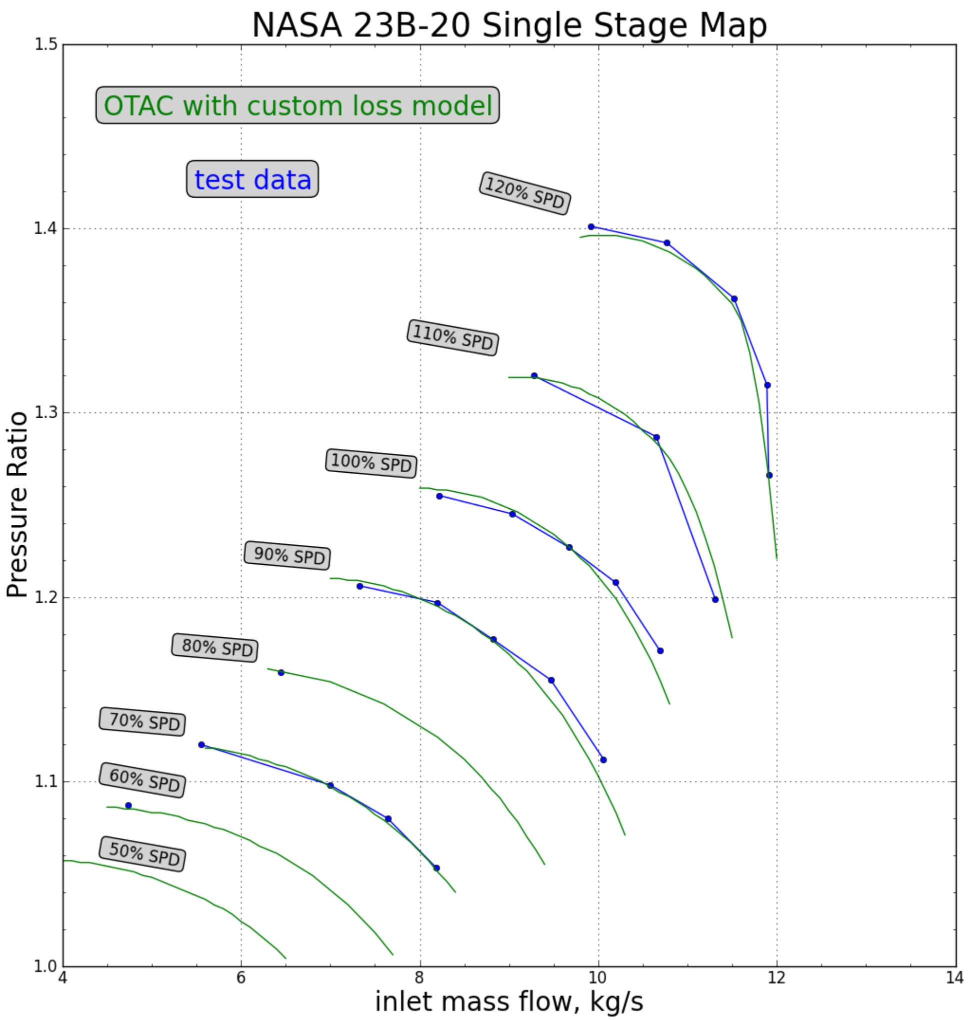
E³ Rotor3 Spanwise Axial Velocity Distribution

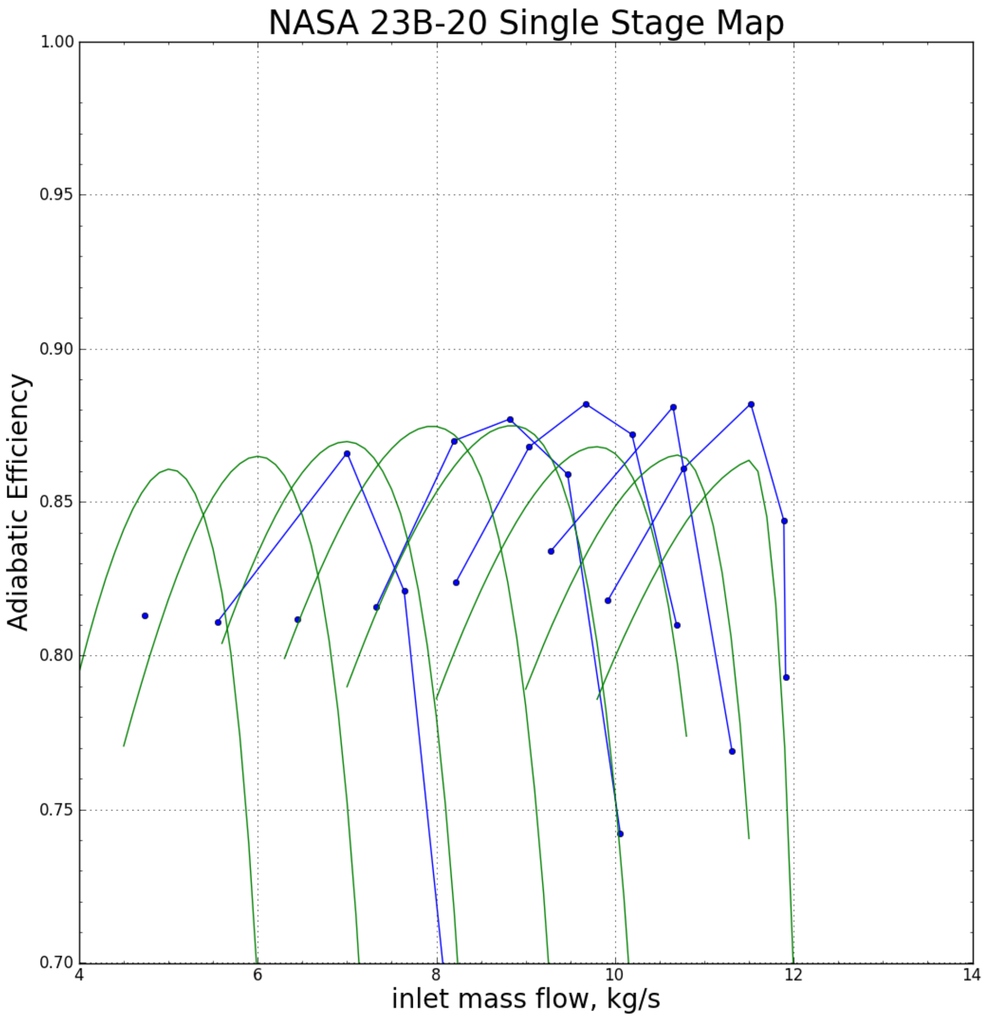


E³ Axial Compressor Streamline Solution (first 5 stages)

note: geometry, design data, and losses taken from E³ report

OTAC 23B-20 Single Stage Axial Compressor Results





OTAC meanline design and off-design analysis of the NASA 23B-20 rotor and stator

OTAC Current Status and Other Issues

- version 1 with documentation, object tests, and example models was completed September 2023
- working on official release policy
- lack of robust (accurate) compressor loss and deviation correlations
- entropy-based compressor loss models being tested/developed at GRC
- some centrifugal compressor loss, blockage, and deviation models developed, but were tested with older version of OTAC and used for comparison with experimental data
- no secondary flow modeling (e.g., cooling flow) capability at the moment
- convergence issues with supersonic and near-supersonic flows
- convergence issues with free-vortex flows and centrifugal streamline models

Documentation: OTAC User Guide and Reference

Contents

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Documentation has been completed, explaining the theory, sign conventions, and use of OTAC with many figures and most equations presented