Design of an Object-oriented Turbomachinery Analysis Code

Initial Results

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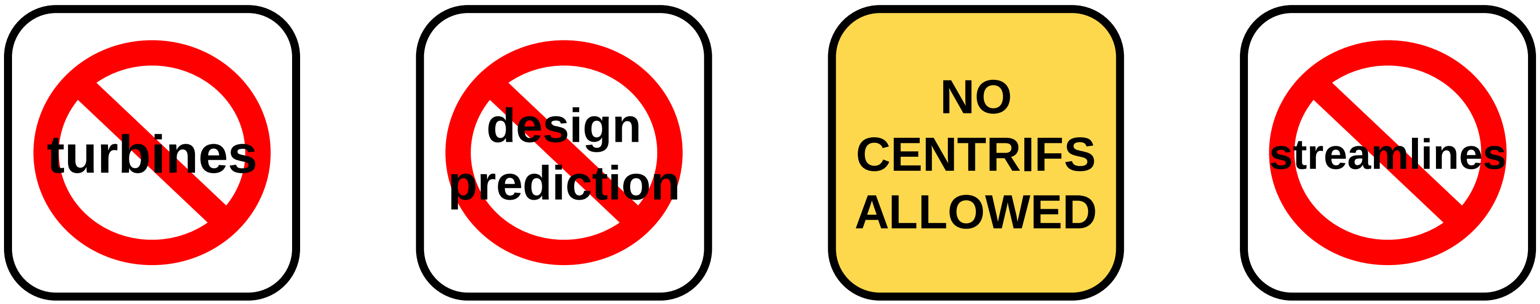
Presentation Outline

- justification - why write yet another turbomachinery code?
- approach - what does an object-oriented turbomachinery code look like?
- results - how do I know the code works?

Justification

- there is still a need for 2-D design/analysis
- codes tend to be focused on one aspect



- specific, individual codes may have undesirable features

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ERROR: SOURCE CODE NOT FOUND
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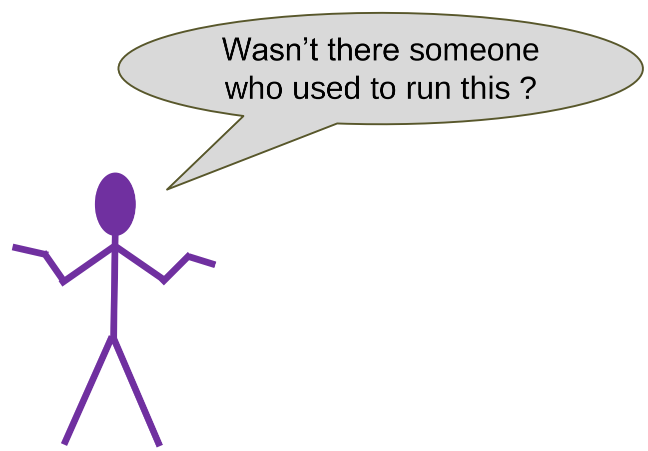
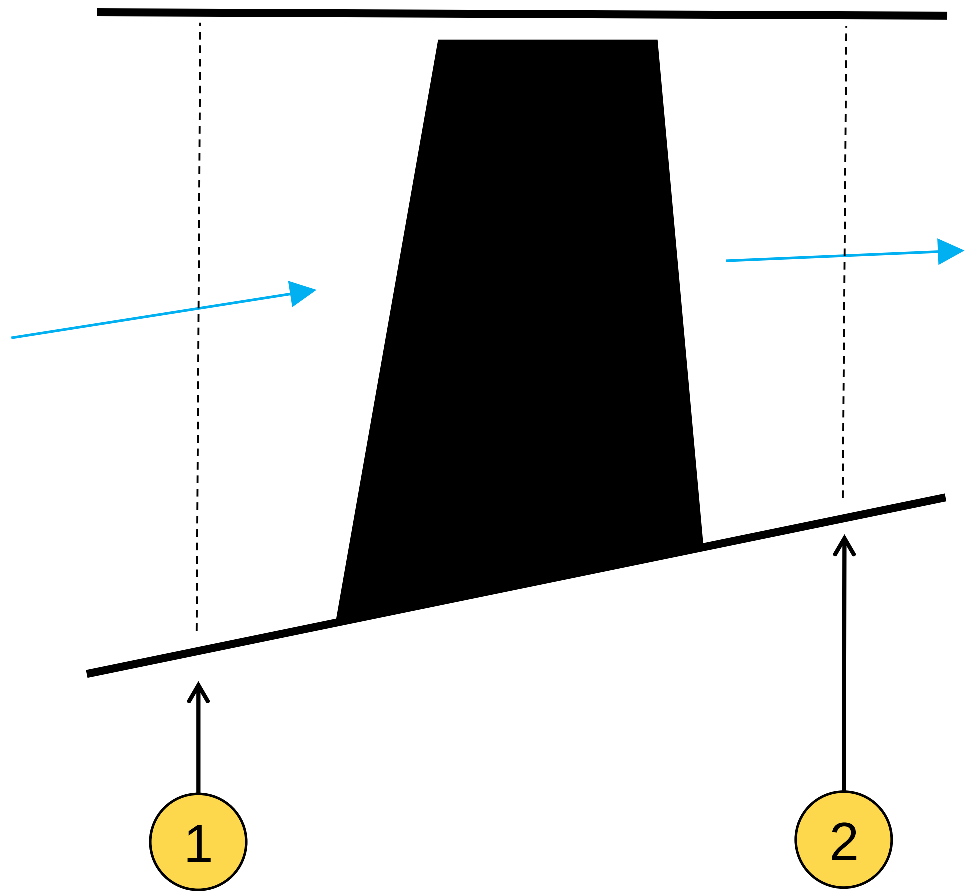
The USER GUIDE to UNHELPFUL USER GUIDES



Problem Description and Assumptions

***CODE REQUIREMENTS*:**
OTAC is applicable for
- compressors and turbines
- design and analysis
- meanline and streamline
- axial, centrifugal/radial, and mixed

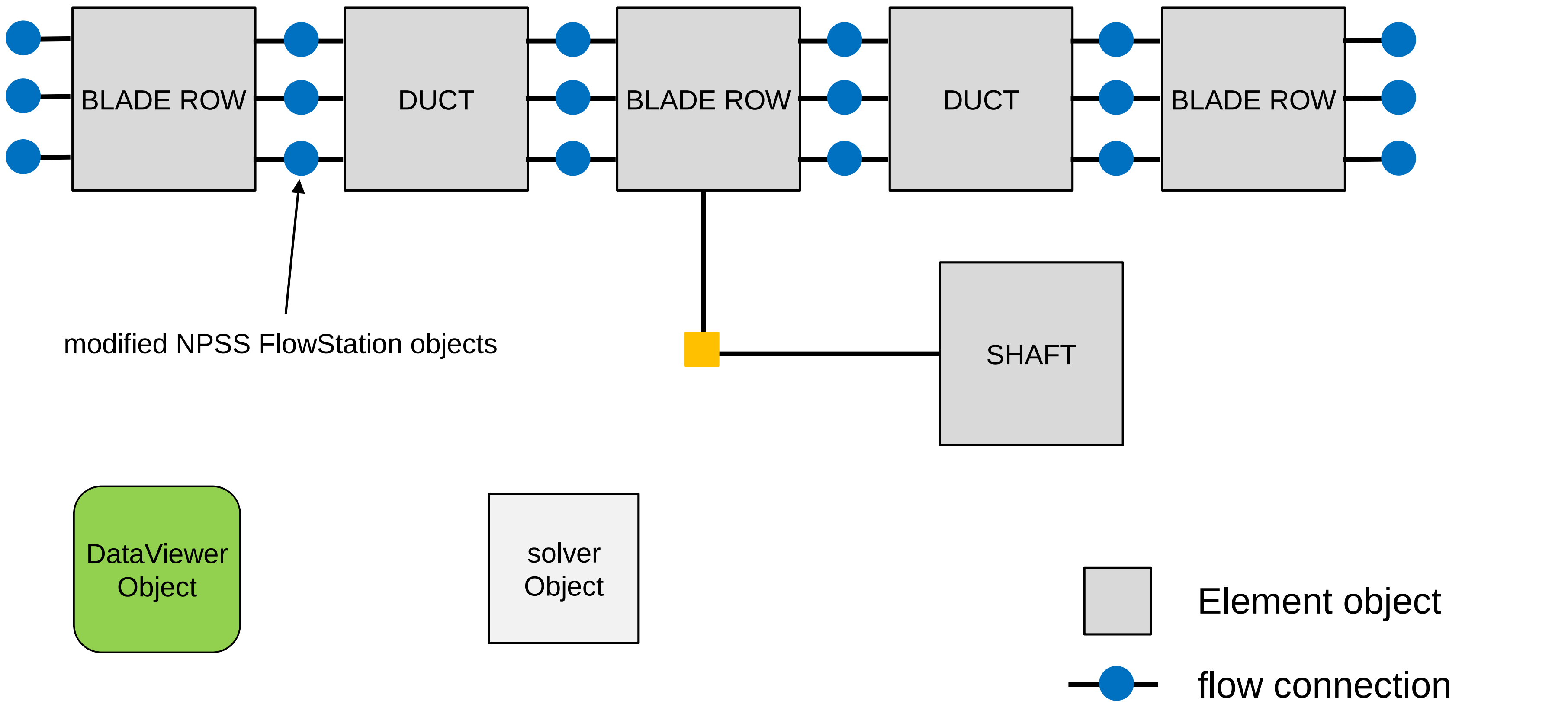


***CODE ASSUMPTIONS*:**
flow going through a blade row in an annulus from station (1) to station (2) :
- steady-state, throughflow
- circumferentially uniform
- adiabatic, simple radial equilibrium
- no change in mass flow rate
- no streamline curvature

***ADDITIONAL GOALS*:**
modular (loss models), good thermo,
simulate unconventional architectures

OTAC Written in NPSS Environment

- allows re-use of Numerical Propulsion System Simulation objects
- model structure similar to NPSS engine cycle model



3-Stream OTAC Example Model

FlowStation Object Extended from NPSS

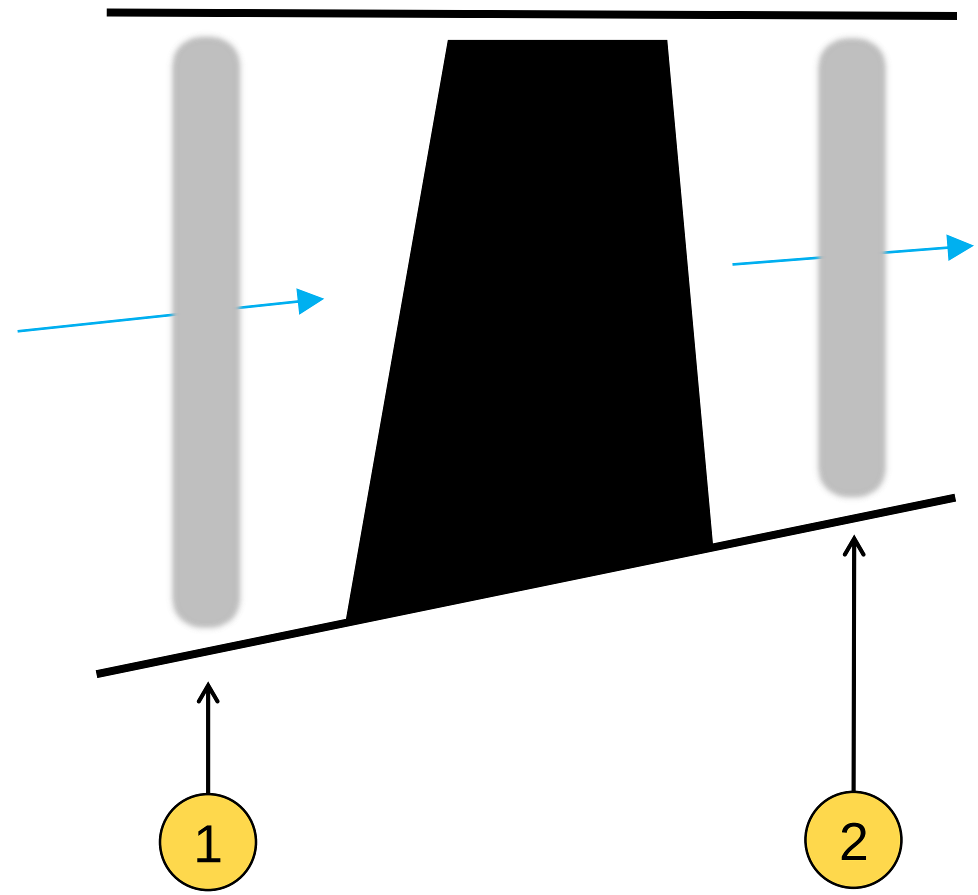
NPSS 1-D FlowStation (4 inputs):

h_t, P_t
MN
$\dot{m}$

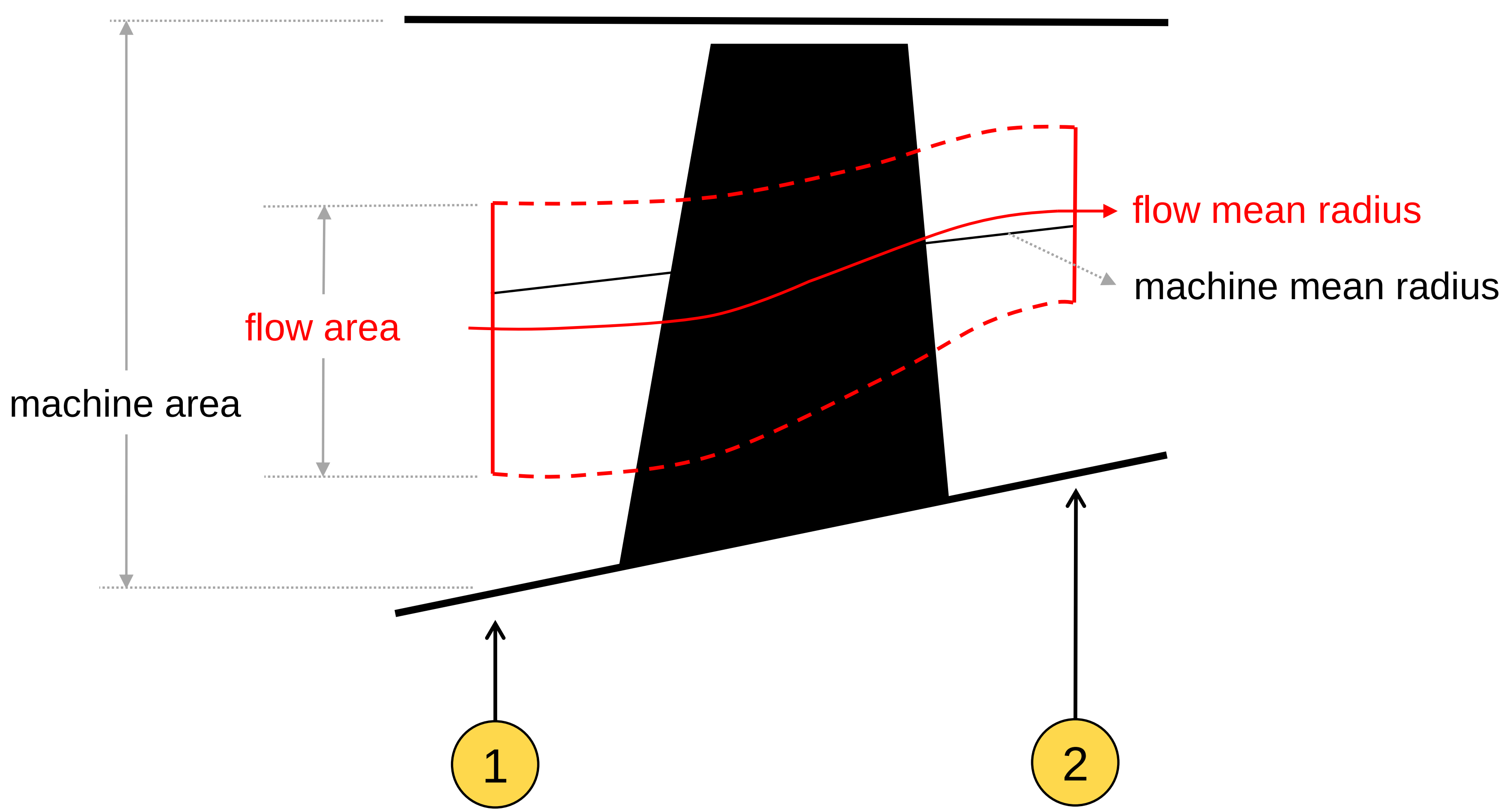
OTAC FlowStation (7+1 inputs):

h_t, P_t
MN, α, ϕ
$\dot{m}$
radius

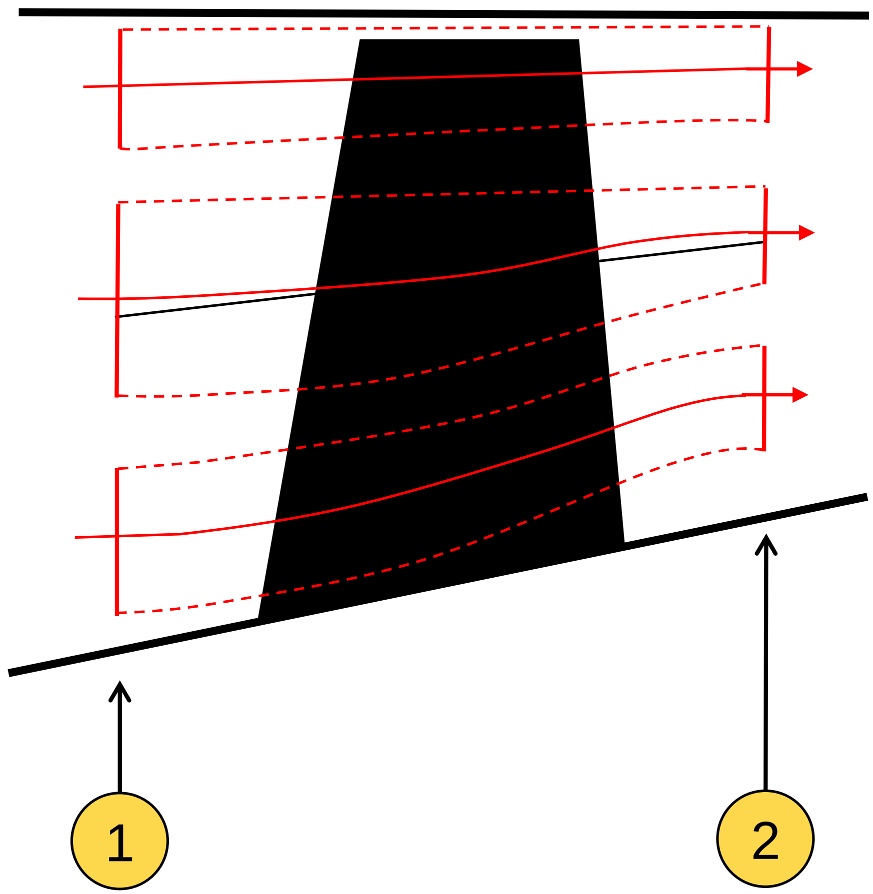
+ relative frame angular speed: ω



Streamtube in an Annulus



Multiple Streamtubes

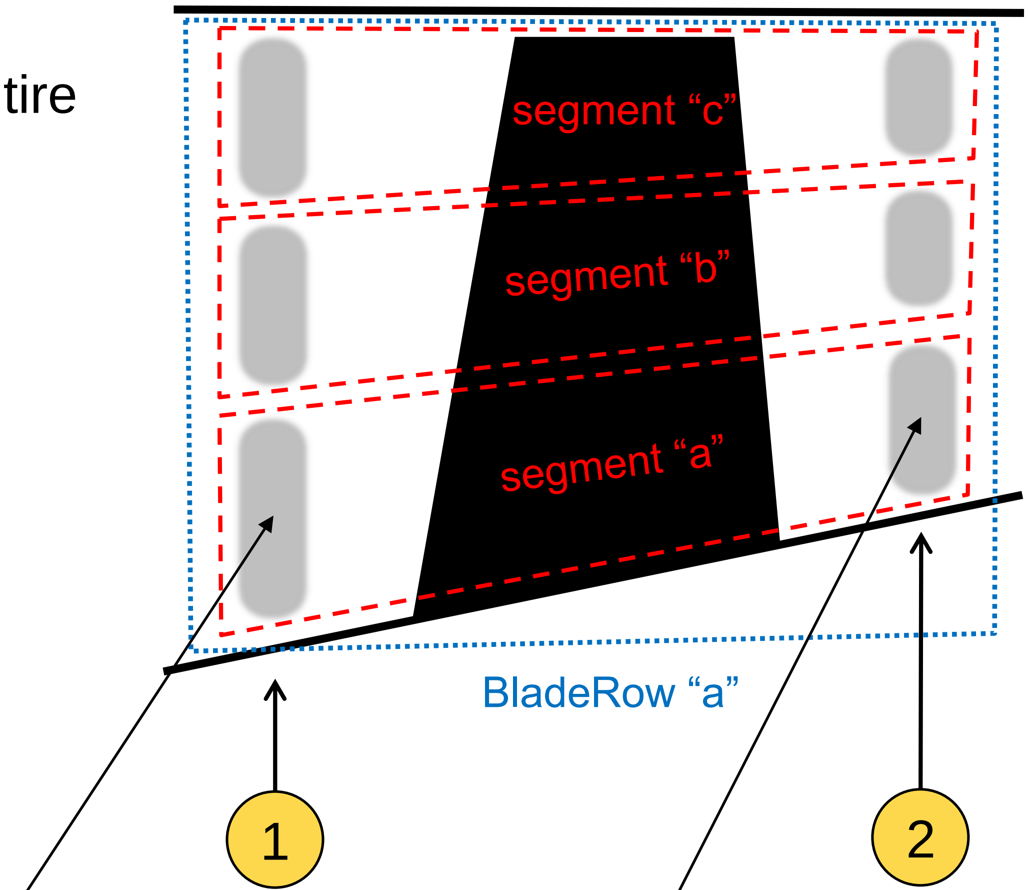


NPSS BladeRow Objects

the ***BladeRow*** represents the entire blade row and contains its own “sub-objects”

each ***BladeSegment*** tracks a streamtube through a section of blade

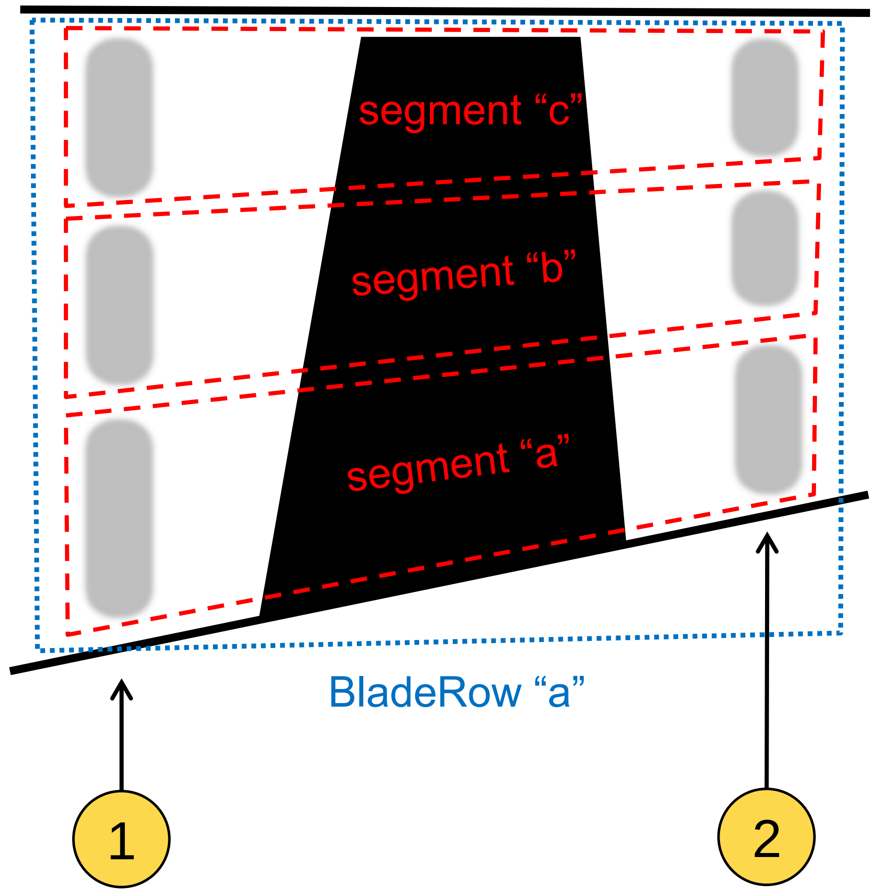
each ***FlowStation*** contains the entire state of the fluid at its particular location



NPSS Solver

Independents represent variables the NPSS solver is allowed to vary

Dependents represent equations or conditions the NPSS solver must satisfy



FlowStation Independents

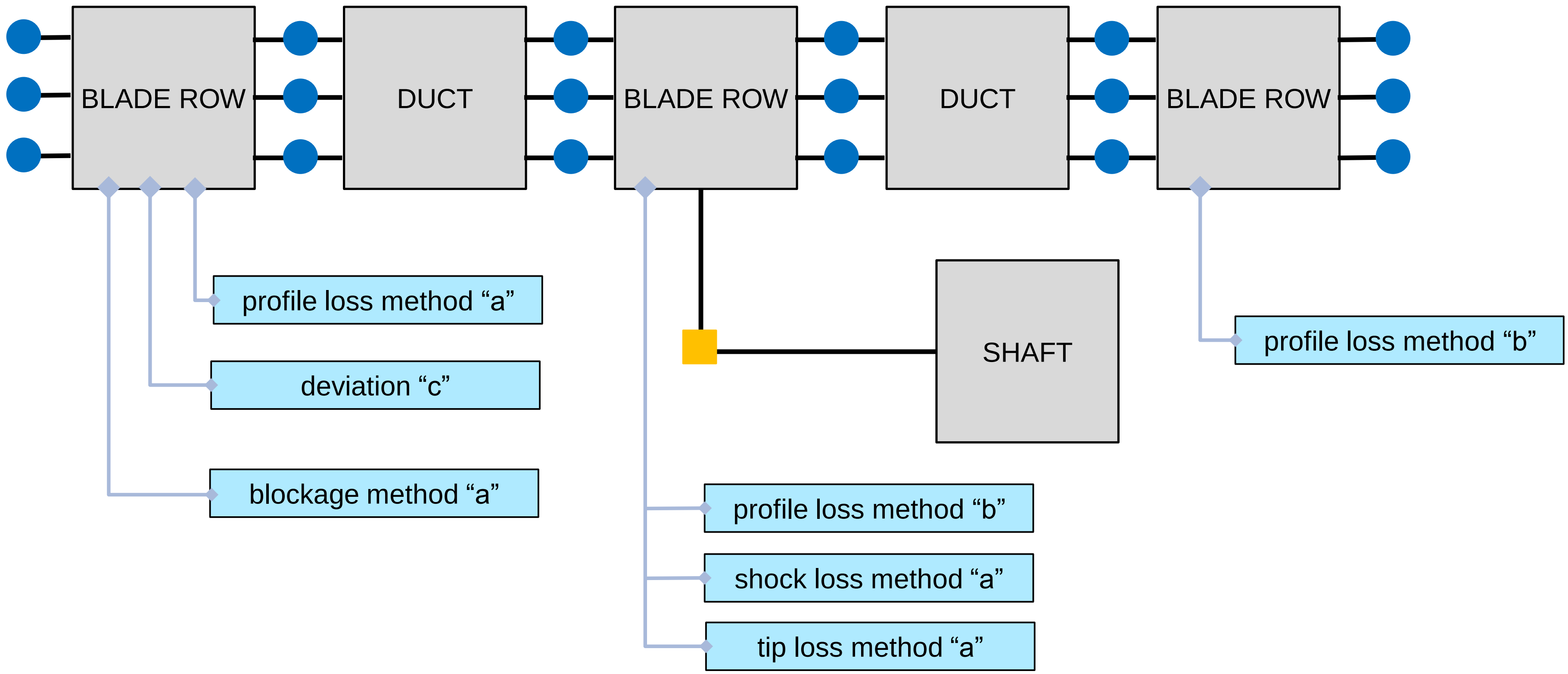
- $\dot{m}_2$
- h_{t2}
- P_{t2}
- α_2
- $radius_2$
- MN_2

BladeRow Dependents

continuity	$\dot{m}_{m2} = \dot{m}_{m1}$
conservation of energy/Euler	$h_{t2} - h_{t1} = \omega(r_2 V_{\theta 2} - r_1 V_{\theta 1})$
non-ideal process loss	$P_{t2} = P_{t2_{ideal}} - \Delta P_t$
non-ideal process turning	$\beta_2 = \beta_{blade} + \delta$
geometry constraint (radius)	$radius_2 = r_{machine}$
geometry constraint (area)	$A_{flow2} = A_{machine} - A_{blockages}$

Empirical Effects

- **BladeRows** contain **Sockets**, placeholders to insert code that calculates a certain variable such as non-dimensional pressure loss



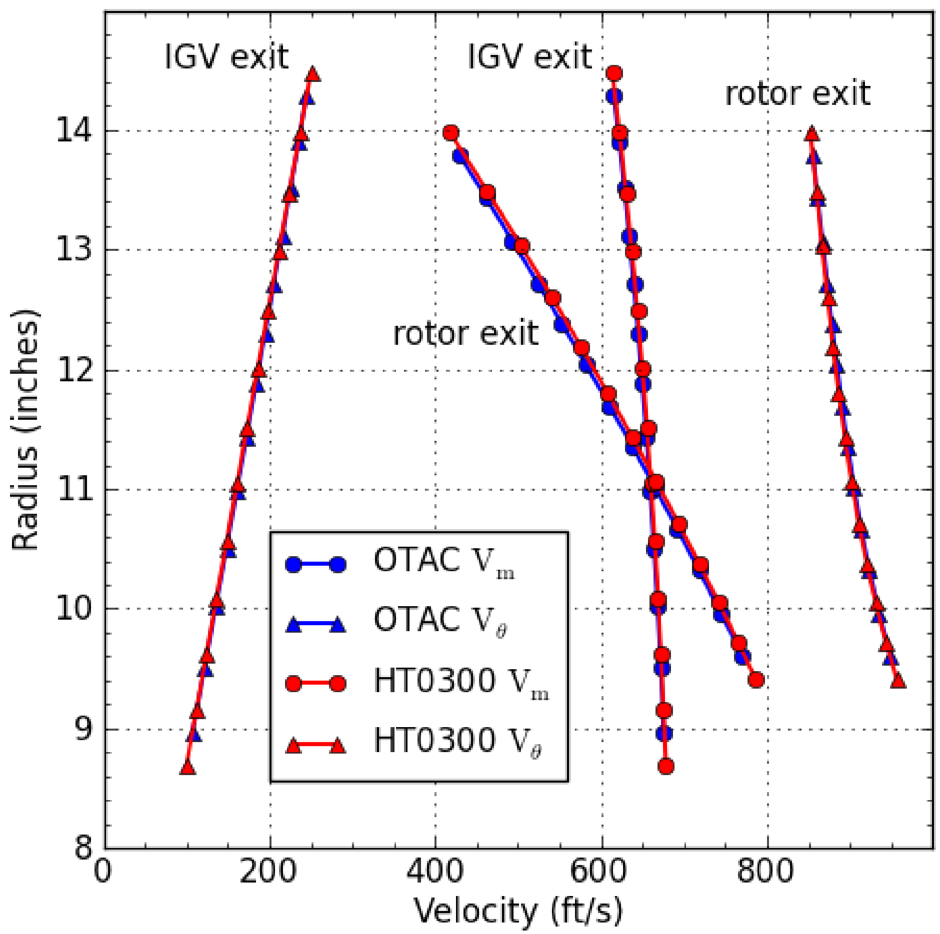
- this allows for considerable versatility in applying losses to the simulation; other benefits include testing and proprietary considerations

Results

- comparison against other codes and calculations
- investigation to determine even if the NPSS solver could reliably converge with matrix sizes over 50x50
- more test cases have been run than shown here

Test Cases and Results

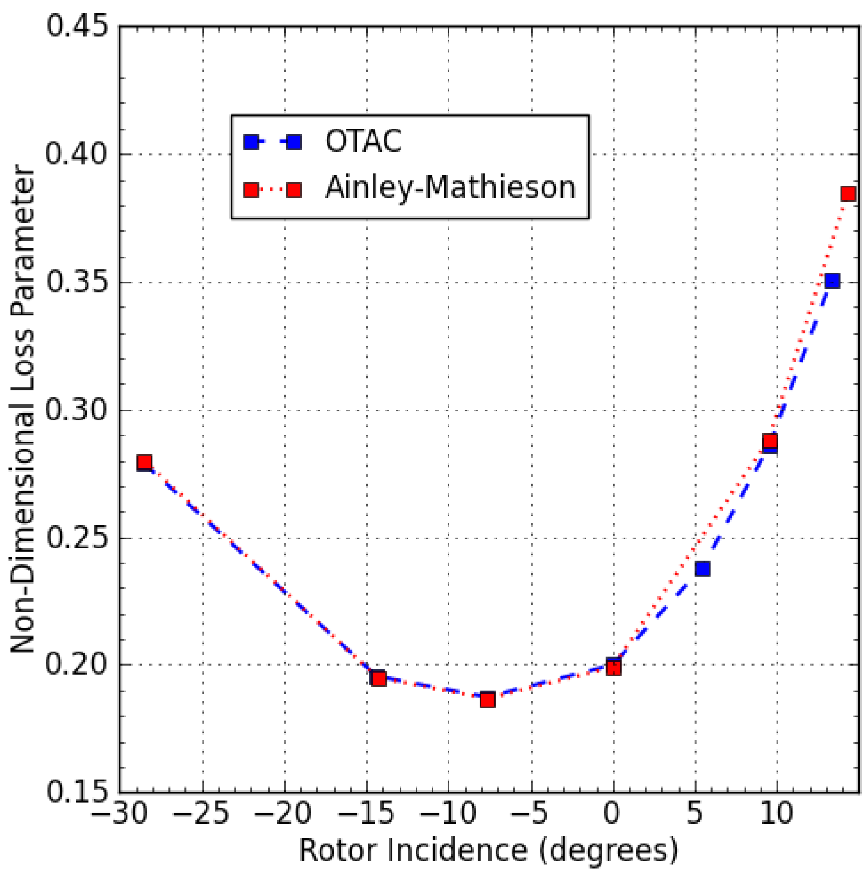
- comparison of OTAC and HT0300 for a compressor IGV plus rotor, streamline, losses input

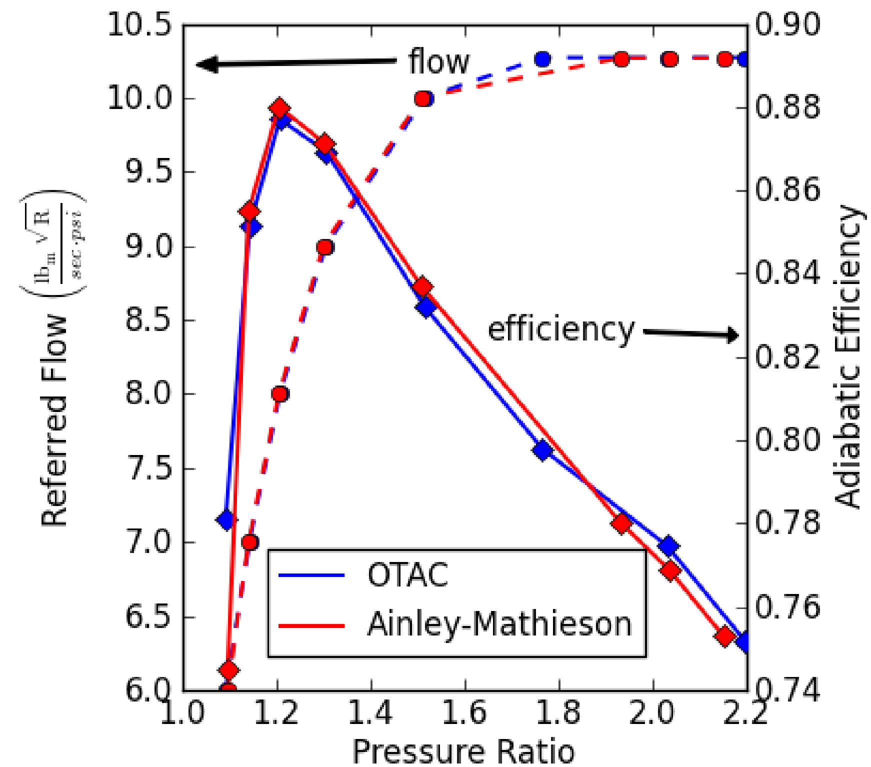


Program HT0300, Richard M. Hearsey, 2011

Test Cases and Results

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

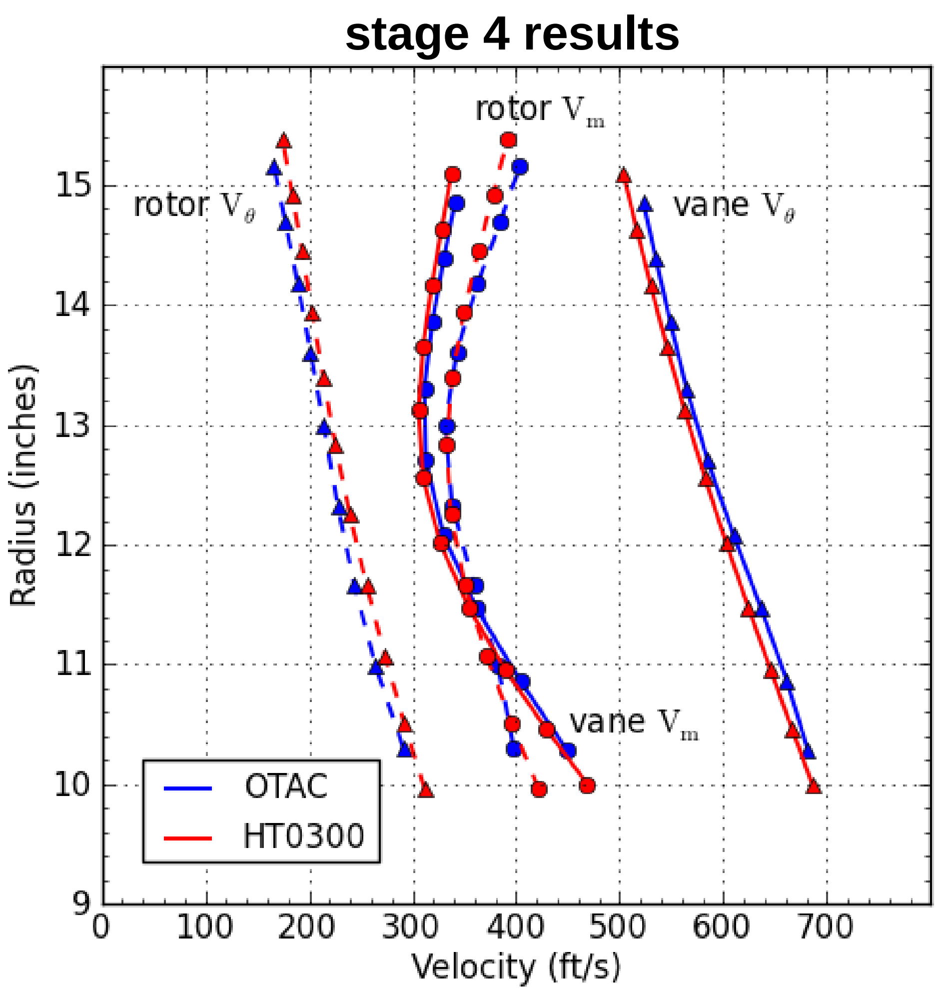




A Method of Performance Estimation for Axial-Flow Turbines, D.G. Ainley and G.C.R. Mathieson, 1957

Test Cases and Results

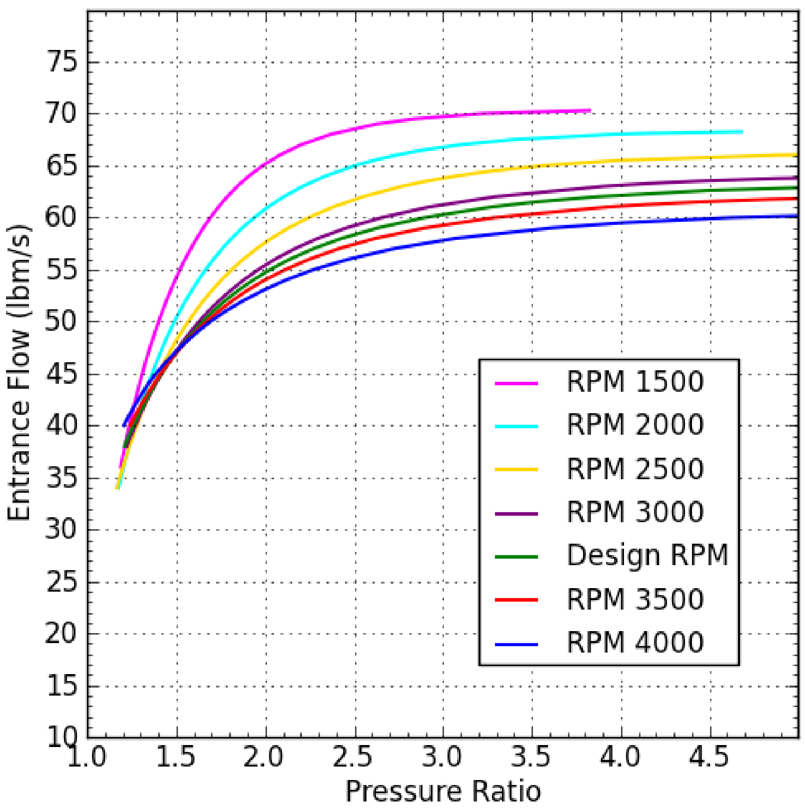
- comparison of OTAC and HT0300 5-stage turbine calculation, streamline, losses calculated using Ainley-Mathieson with Kacker/Okapuu modifications

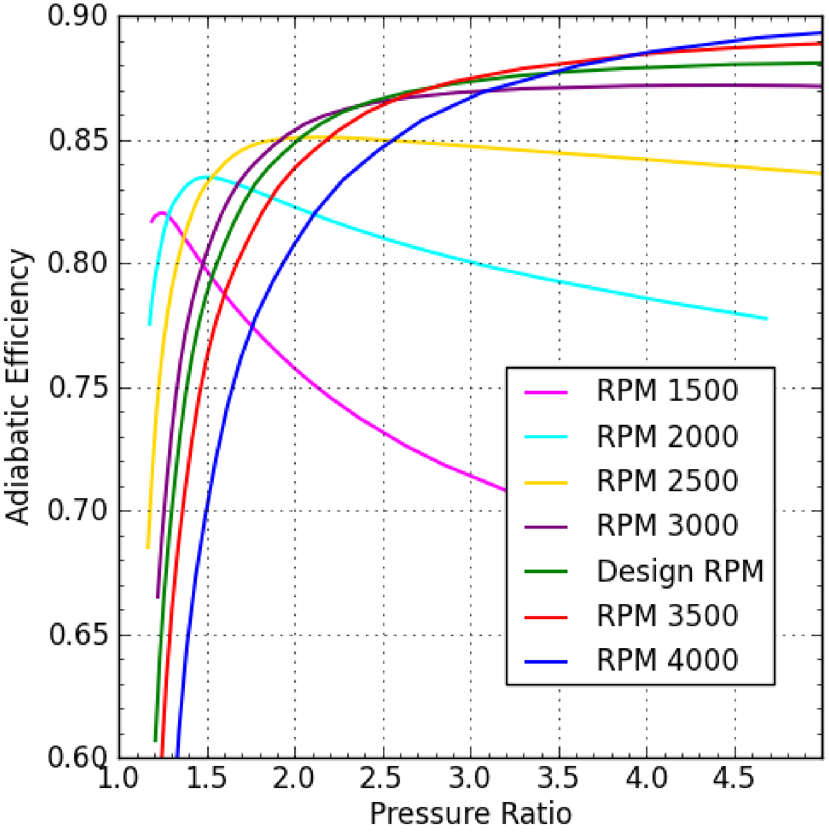


Program HT0300,
Richard M. Hearsey, 2011

Test Cases and Results

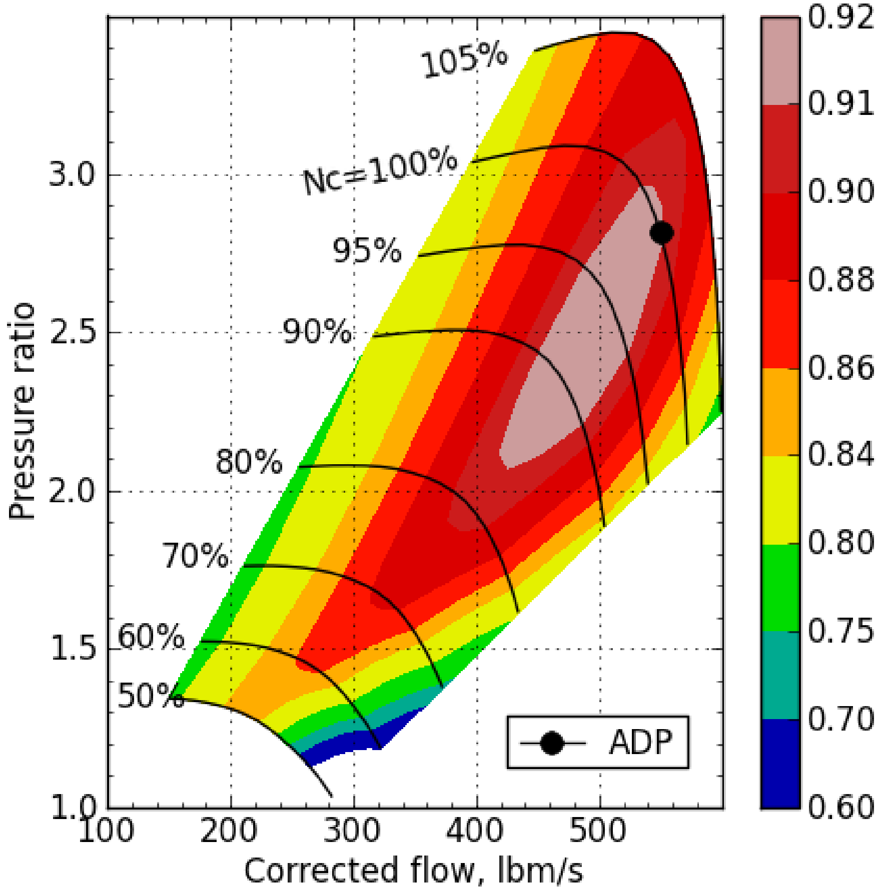
- OTAC analysis of 5-stage turbine (from previous slide), streamline





Test Cases and Results

- OTAC analysis of 2-stage compressor, streamline, losses calculated using Aungier correlations



Axial-Flow Compressors: A Strategy for Aerodynamic Design and Analysis, Ronald H. Aungier, 2003

Test Cases and Results

- comparison of OTAC and Japikse & Baines centrifugal compressor calculation, meanline, losses input

impeller exit	OTAC	Japikse
Pt, psi	31.17	31.17
Tt, R	653.5	653.7
Vm, ft/s	342.4	342.4
Vθ, ft/s	843.8	843.8
β flow, degrees	19.04	-19.04
α flow, degrees	67.91	67.91
slip factor	0.8772	0.8772
diffuser exit		
Pt, psi	30.04	30.04
Ps, psi	26.71	26.64
α flow, deg	55.99	50.94

Introduction to Turbomachinery, David Japikse and Nicholas C. Baines, 1994

Summary

- OTAC proof of concept verified – correct results for compressors, turbines, axial, centrifugal, meanline, streamline, design and analysis
- extensive work on turbine loss models: Ainley-Mathieson, Kacker-Okappu, Dunham-Came, Moustapha-Kacker-Tremblay
- compressor loss model based on Aungier’s method implemented
- further work includes additional loss models, improved logic for choked flow operation

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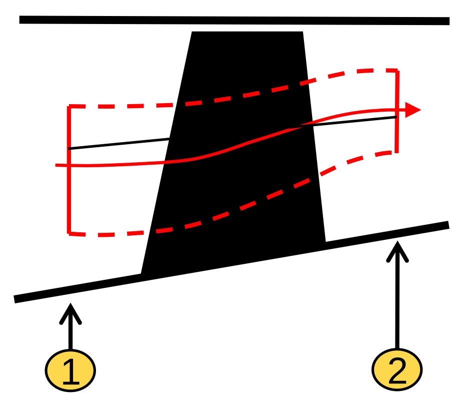
Backup Slides

Meanline BladeRow Equation Set

continuity	$\dot{m}_{m2} = \dot{m}_{m1}$
conservation of energy/Euler	$h_{t2} - h_{t1} = \omega(r_2 V_{\theta 2} - r_1 V_{\theta 1})$
non-ideal process loss	$P_{t2} = P_{t2_{ideal}} - \Delta P_t$
non-ideal process turning	$\beta_2 = \beta_{blade} + \delta$
geometry constraint (radius)	$r_2 = r_{machine}$
geometry constraint (area)	$A_{flow2} = A_{machine} - A_{blockages}$

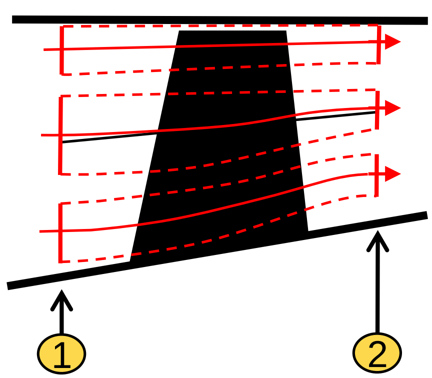
note: at design, β_{blade} and $A_{machine}$ may be input (direct-design) or varied to produce specific performance (indirect-design)



Streamline BladeRow Equation Set

n	continuity	$\dot{m}_{m2_i} = \dot{m}_{m1_i}$
n	energy/Euler	$h_{t2_i} - h_{t1_i} = \omega(r_{2_i} V_{\theta 2_i} - r_{1_i} V_{\theta 1_i})$
n	loss condition	$P_{t2_i} = P_{t2_{ideal\,i}} - \Delta P_{t_i}$
n	flow follows blade	$\beta_{2_i} = \beta_{blade_i} + \delta_i$
n-1	geometry constraint	$r_{2inner_{i+1}} = r_{2outer_i}$
1	geometry constraint	$r_{2_{sum}} = r_{machine}$
n-1	spanwise eq. $\frac{1}{\rho}\frac{dp}{dr} = \frac{V_\theta^2}{r}$	$\frac{1}{\rho_i}\frac{\Delta p_i}{\Delta r_i} = \frac{V_{\theta_i}^2}{r_i}$
1	geometry constraint	$A_{flow2_{sum}} = A_{machine} - A_{blockages}$

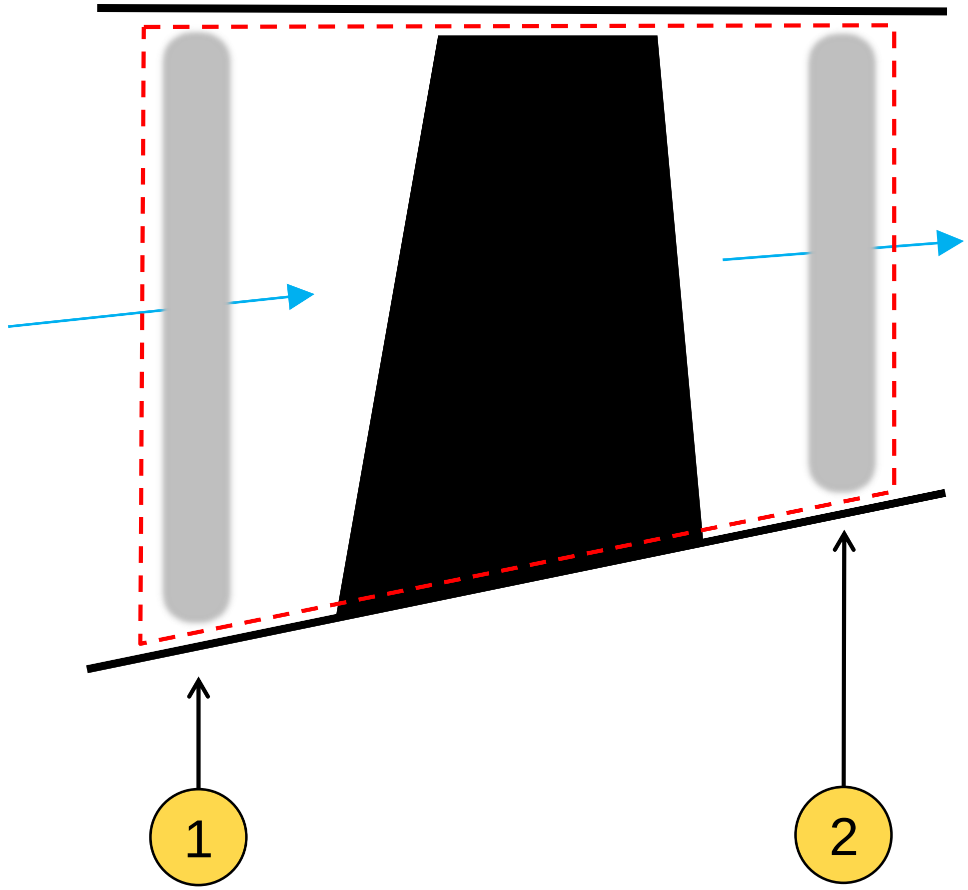
n = number of streams
i = stream number, 1 to *n*
sum = aggregate value



BladeSegment Object

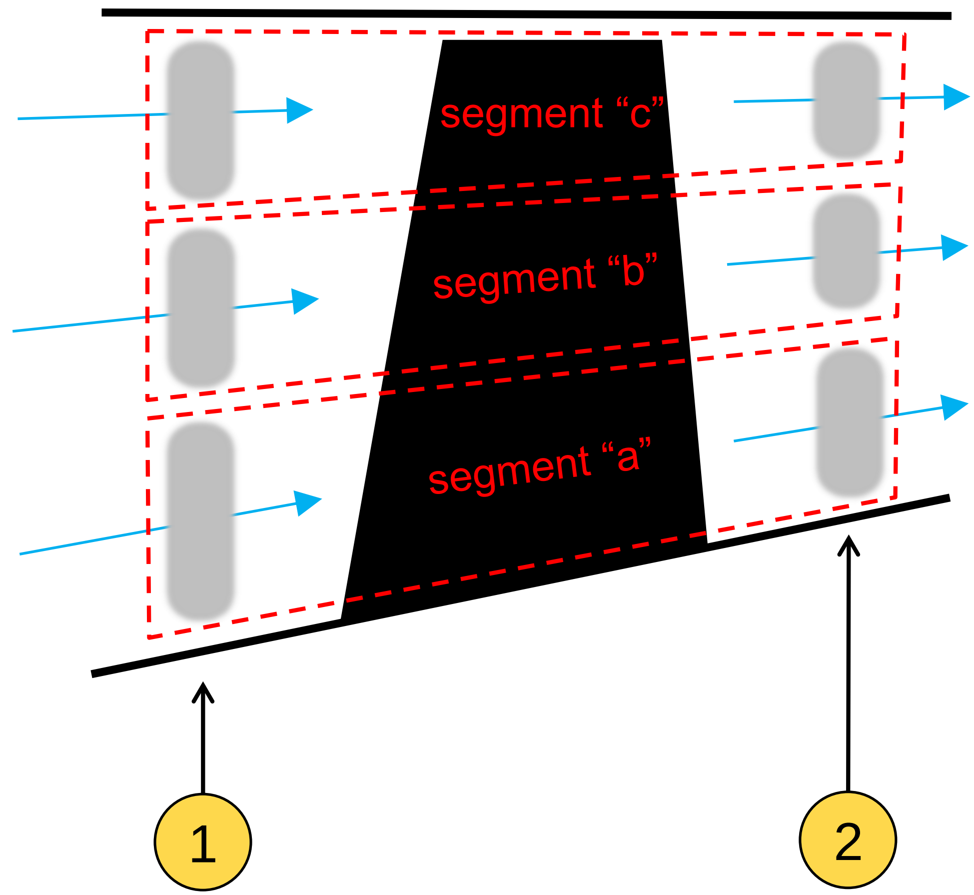
responsible for differences between certain flow states

- entrance
- exit - actual
- exit - ideal h_t
- exit - ideal P_t



BladeSegment Object

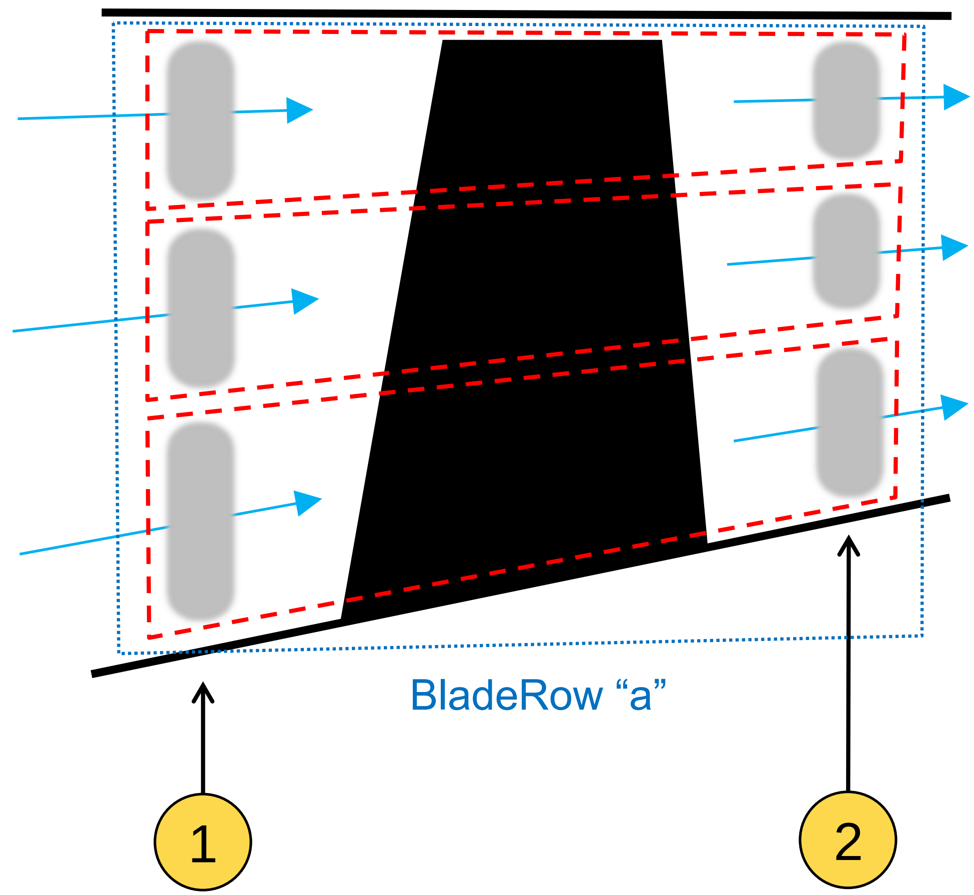
multiple BladeSegments allow for radial variation of flow properties



BladeRow Object

responsible for differences between BladeSegments

holds blade row specific variables: annulus areas, number of blades, blade angles, power, etc.



Slide Master