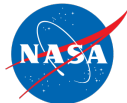


Meanline Analysis of Turbines with Choked Flow in the Object-Oriented Turbomachinery Analysis Code

Eric S. Hendricks

NASA Glenn Research Center

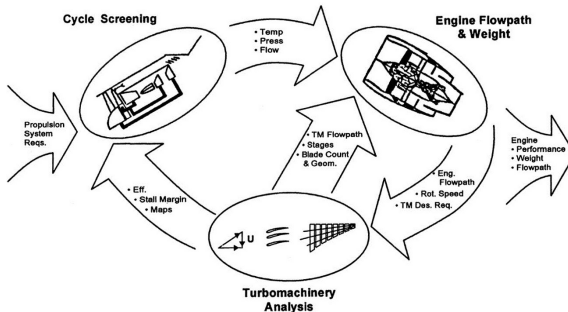


AIAA SciTech 2016
San Diego, CA

Turbomachinery Analysis In Conceptual Design

Conceptual Engine Design Process

Glassman, NASA-CR-198433



- Conceptual design process focuses on a rapid analysis of design alternatives and relies on lower-fidelity analysis tools
- Turbomachinery analysis commonly uses meanline and streamline simulation tools

The Object-Oriented Turbomachinery Analysis Code (OTAC)

- Developed by NASA GRC using the Numerical Propulsion System Simulation (NPSS) code
- Analysis capabilities:
 - Compressor and turbine components
 - Axial and centrifugal designs
 - Meanline and streamline models
 - User defined loss models
- Results for several compressor and turbine models validated against results from similar analysis codes (Jones, ISABE2015-20015)
- Limitation of the code was identified when analyzing turbines with flow near or at the limiting choked mass flow rate

Study Objective

Enhance the analysis capabilities of OTAC by enabling analysis of choked flow in turbine meanline models

Presentation Outline

- 1 Overview of OTAC Models
- 2 Relevant Choked Flow Characteristics
- 3 Improvements to OTAC
- 4 Results
- 5 Conclusions

Presentation Outline

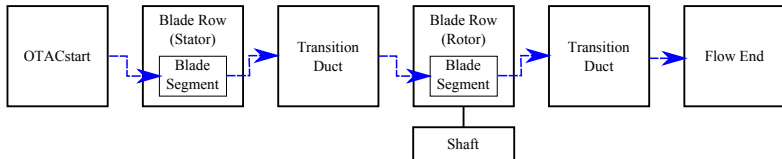
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OTAC Components and Models

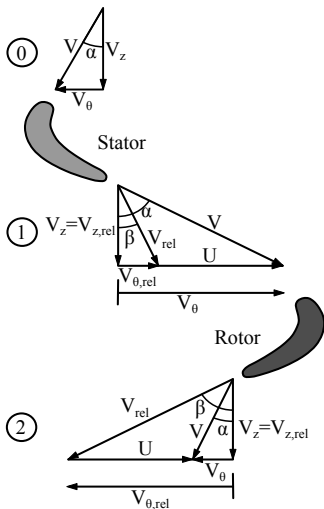
Six new objects created in NPSS for OTAC:

- OTAC Start
- Blade Row
- Blade Segment
- Transition Section
- Expander
- Reducer

Objects are combined to form turbomachinery models



OTAC Blade Segment Equations



$$1 \quad \dot{m}_{in} = \dot{m}_{out}$$

$$2 \quad h_{t,out} - h_{t,in} = \omega (r_{out} V_{\theta,out} - r_{in} V_{\theta,in})$$

$$3 \quad P_{t,out} = P_{t,out,ideal} - f_{loss} (args)$$

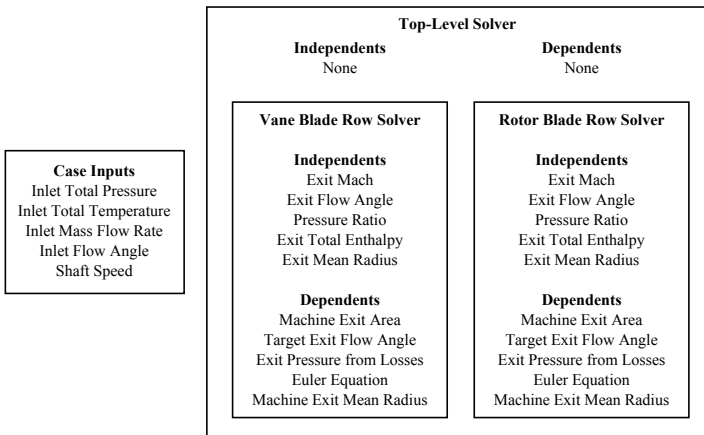
$$4 \quad \beta_{out} = \beta_{m,out} + \delta$$

$$5 \quad r_{out} = r_{m,out}$$

$$6 \quad A_{out} = A_{m,out}$$

$$7 \quad \phi_{out} = \phi_{m,out}$$

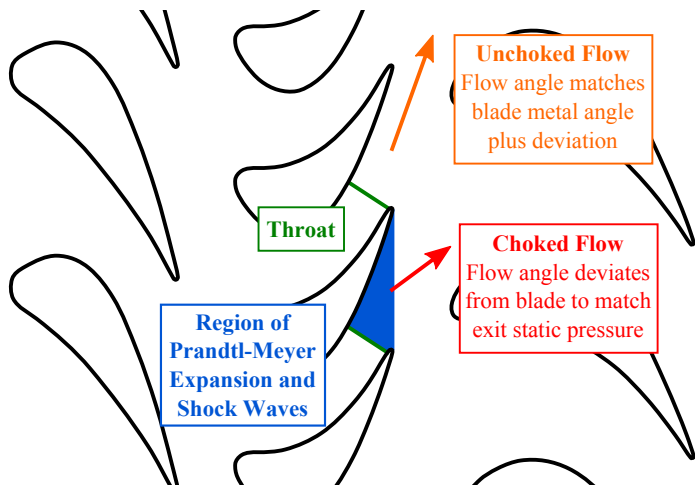
Typical OTAC Model Inputs and Solver Setup



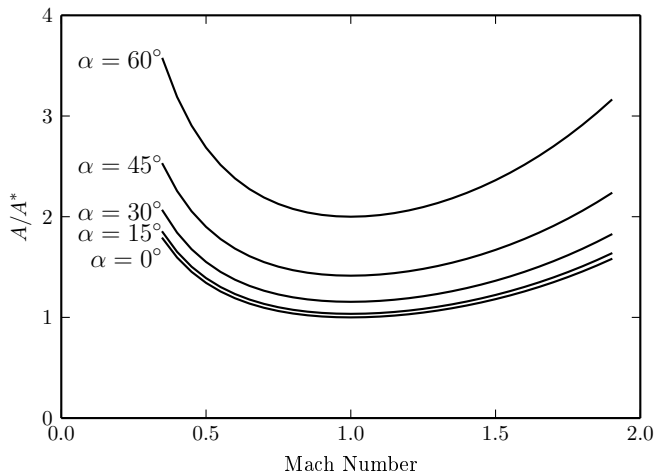
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Supersonic Flow Characteristics



Mach-Area Relationship as a Function of Flow Angle



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Three Improvements Required for Turbine Meanline Models

- 1 Add calculations for throat area and choked flow constraint to each blade row
- 2 Revise case inputs to define a unique solution
- 3 Revise the model solver setup to enable application of the flow constraint, determine the proper exit flow angle and change the case inputs

Calculations for Throat Area and Choked Flow Constraint in Each Blade Row

- 1 Calculate the critical pressure ratio and actual pressure ratio

$$PR_{cr} = \frac{P_{t,rel,in}}{P_{s,th,M=1.0}} \qquad PR = \frac{P_{t,rel,in}}{P_{s,out}}$$

- 2 Determine throat properties

- Choked flow ($PR \geq PR_{cr}$): throat properties and area determined from a sonic Mach number
- Unchoked flow ($PR < PR_{cr}$): throat properties and area determined based on the exit static pressure

- 3 If model is in design mode, throat area is saved for off-design analysis
- 4 Blade row throat flow constraint equation compares actual flow per throat area to the flow per area required for choked conditions

$$\frac{\dot{m}}{A_{cr}} \leq \frac{\dot{m}}{A_{th}}$$

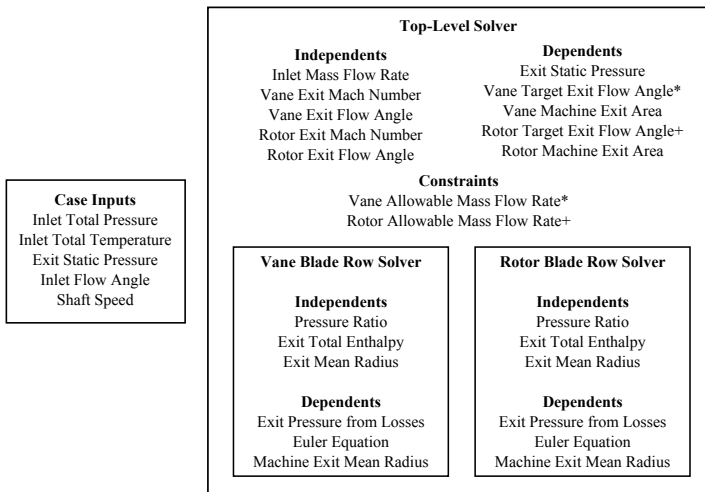
Revisions to Case Inputs

- Default OTAC model setup had mass flow as a case input producing three possible results:
 - Mass flow rate is below choked value producing a unique solution
 - Mass flow rate matches choked value producing an infinite number of solutions
 - Mass flow rate is above choked value producing no feasible solutions
- Specifying the turbine exit static pressure as a case input provides a unique solution for all flow regimes
 - Unchoked case: exit static pressure sets mass flow rate
 - Choked case: exit static pressure sets exit flow angle from choked blade row

Revisions to Model Solver Setup

- Attach flow constraints computed for each blade row to the flow angle dependent (Eq. 4) using feature of NPSS Newton solver
- Move independents and dependents from each blade row solver to the top-level solver
 - Mach number independent
 - Exit flow angle independent
 - Exit area dependent
 - Target flow angle dependent (including flow constraint)
- Add mass flow rate as an independent and exit static pressure as a dependent to the top-level solver

Revised OTAC Model Inputs and Solver Setup



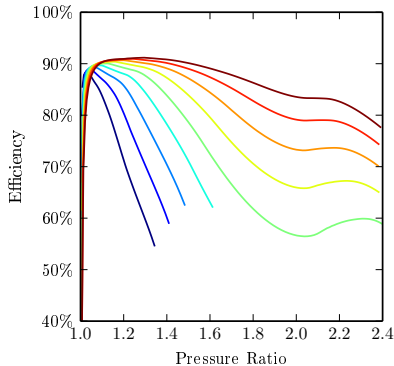
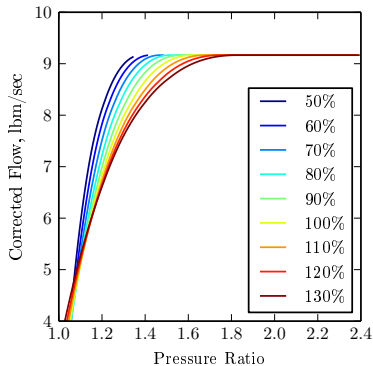
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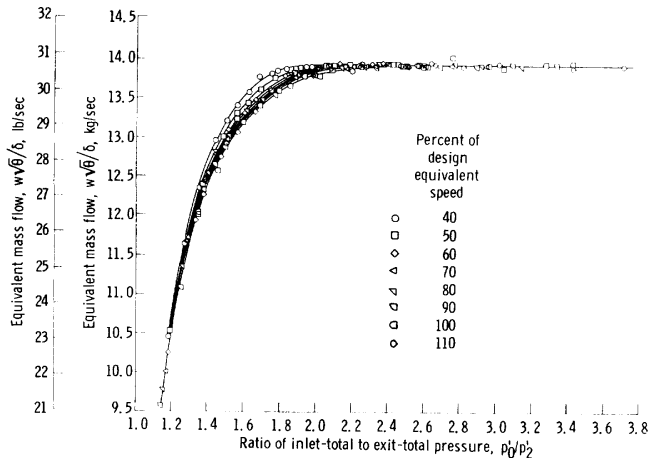
Results Overview

- Several single-stage and multi-stage turbines were modeled using the new method for all cases (subsonic and supersonic)
- Results shown in the form of turbine performance maps with corrected flow and efficiency as functions of pressure ratio and percent corrected speed
- All models use the Kacker-Okapuu loss correlations with incidence losses from Moustapha, Kacker and Tremblay

Single-Stage Turbine with Choking in Vane

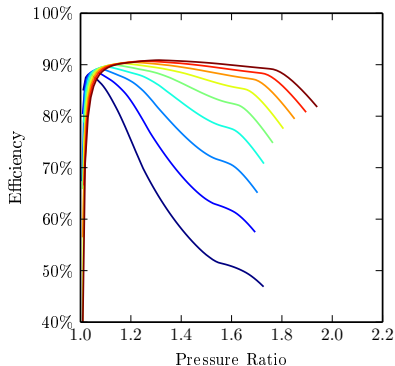
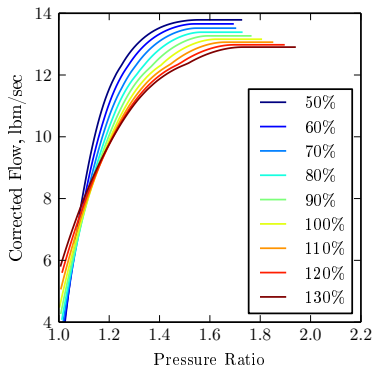


Experimental Results for a Single-Stage Turbine with Choking in Vane

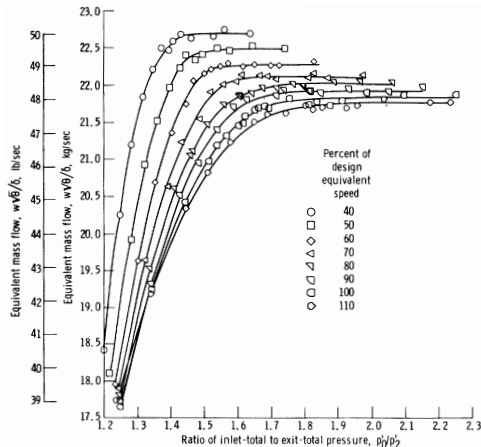


Szanca and Schum, NASA-SP-290

Single-Stage Turbine with Choking in Rotor

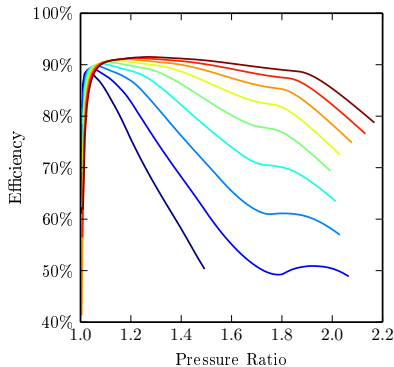
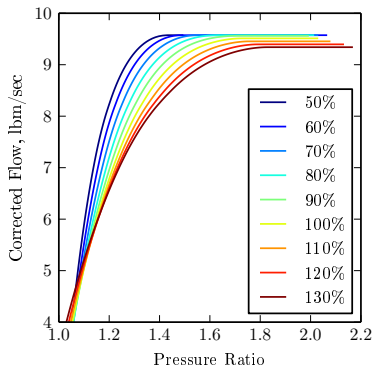


Experimental Results for a Single-Stage Turbine with Choking in Rotor

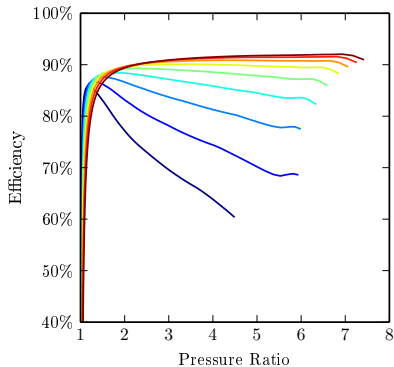
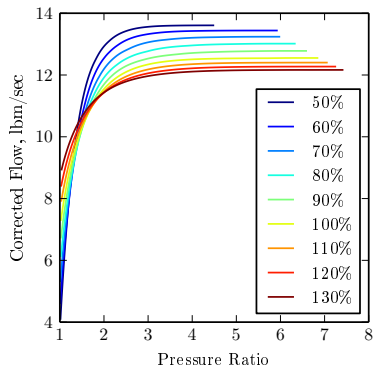


Szanca and Schum, NASA-SP-290

Single-Stage Turbine with Choking Transition



Four-Stage Turbine



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Summary and Future Work

- Improvements were made to the Object-Oriented Turbomachinery Analysis Code (OTAC) to enable analysis of meanline turbine models with choked flow
 - Adds calculations for throat area and choked flow constraint
 - Modifies analysis case inputs to include exit static pressure
 - Revises the internal solver setup
- Maps produced with new method exhibit characteristics matching those found in experimental results
- Areas for future work:
 - Extending this method for application to streamline turbine models
 - Developing a similar method for capturing choked flow in compressors

