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

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AIAA SciTech 2016
San Diego, CA
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
1. Overview of OTAC Models
2. Relevant Choked Flow Characteristics
3. Improvements to OTAC
4. Results
5. Conclusions
Overview of OTAC Models

Relevant Choked Flow Characteristics

Improvements to OTAC

Results

Conclusions
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. \( \dot{m}_{in} = \dot{m}_{out} \)
2. \( h_{t,out} - h_{t,in} = \omega (r_{out} V_{\theta,out} - r_{in} V_{\theta,in}) \)
3. \( P_{t,out} = P_{t,out,ideal} - f_{loss}(args) \)
4. \( \beta_{out} = \beta_{m,out} + \delta \)
5. \( r_{out} = r_{m,out} \)
6. \( A_{out} = A_{m,out} \)
7. \( \phi_{out} = \phi_{m,out} \)
## Typical OTAC Model Inputs and Solver Setup

### Case Inputs
- Inlet Total Pressure
- Inlet Total Temperature
- Inlet Mass Flow Rate
- Inlet Flow Angle
- Shaft Speed

### Top-Level Solver

<table>
<thead>
<tr>
<th>Independents</th>
<th>Dependents</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
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</table>

### Vane Blade Row Solver

<table>
<thead>
<tr>
<th>Independents</th>
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<tbody>
<tr>
<td>Exit Mach</td>
<td>Machine Exit Area</td>
</tr>
<tr>
<td>Exit Flow Angle</td>
<td>Target Exit Flow Angle</td>
</tr>
<tr>
<td>Pressure Ratio</td>
<td>Exit Pressure from Losses</td>
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### Rotor Blade Row Solver

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Supersonic Flow Characteristics

Unchoked Flow
Flow angle matches blade metal angle plus deviation

Choked Flow
Flow angle deviates from blade to match exit static pressure

Region of Prandtl-Meyer Expansion and Shock Waves

Throat
Mach-Area Relationship as a Function of Flow Angle

\[ \frac{A}{A^*} = \begin{cases} \alpha = 0^\circ \\ \alpha = 15^\circ \\ \alpha = 30^\circ \\ \alpha = 45^\circ \\ \alpha = 60^\circ \end{cases} \]

\[ \text{Mach Number} \]

\[ 0.0 \ 0.5 \ 1.0 \ 1.5 \ 2.0 \]

\[ \frac{A}{A^*} \] vs Mach Number
Presentation Outline

1. Overview of OTAC Models
2. Relevant Choked Flow Characteristics
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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

\[ PR_{cr} = \frac{P_{t,rel,in}}{P_{s,th,M=1.0}} \quad PR = \frac{P_{t,rel,in}}{P_{s,out}} \]

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

\[ \frac{\dot{m}}{A_{cr}} \leq \frac{\dot{m}}{A_{th}} \]
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

#### Top-Level Solver

<table>
<thead>
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<tr>
<td>Inlet Mass Flow Rate</td>
<td>Exit Static Pressure</td>
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<tr>
<td>Vane Exit Mach Number</td>
<td>Vane Target Exit Flow Angle*</td>
</tr>
<tr>
<td>Vane Exit Flow Angle</td>
<td>Vane Machine Exit Area</td>
</tr>
<tr>
<td>Rotor Exit Mach Number</td>
<td>Rotor Target Exit Flow Angle+</td>
</tr>
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<td>Rotor Machine Exit Area</td>
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#### Constraints

- Vane Allowable Mass Flow Rate*
- Rotor Allowable Mass Flow Rate+

#### Case Inputs

- Inlet Total Pressure
- Inlet Total Temperature
- Exit Static Pressure
- Inlet Flow Angle
- Shaft Speed

#### Vane Blade Row Solver

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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

![Graph showing Corrected Flow and Efficiency vs. Pressure Ratio for different corrected flows and efficiency levels.

- For Corrected Flow, the graph displays a relationship between pressure ratio and corrected flow rate. The corrected flow rate is plotted on the y-axis, ranging from 4 to 14 lbm/sec, and the pressure ratio on the x-axis, ranging from 1.0 to 2.2.
- For Efficiency, there is a graph showing the efficiency levels for different pressure ratios. The efficiency is plotted on the y-axis, ranging from 40% to 100%, and the pressure ratio on the x-axis, ranging from 1.0 to 2.2.

Legend:
- 50%
- 60%
- 70%
- 80%
- 90%
- 100%
- 110%
- 120%
- 130%
Experimental Results for a Single-Stage Turbine with Choking in Rotor

Szanca and Schum, NASA-SP-290
Four-Stage Turbine

- Corrected Flow, lbm/sec vs. Pressure Ratio
- Efficiency vs. Pressure Ratio

Legend:
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- 60%
- 70%
- 80%
- 90%
- 100%
- 110%
- 120%
- 130%
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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