Design of an Object-oriented Turbomachinery Analysis Code

Initial Results

Scott Jones, NASA Glenn Research Center
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

ERROR: SOURCE CODE NOT FOUND

The USER GUIDE to UNHELPFUL USER GUIDES

Wasn’t there someone who used to run this?
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, throughput flow
- 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

DataViewer Object

Element object
- flow connection
- mechanical connection
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, \( \alpha, \phi \)
- \( \dot{m} \)
- radius

+ relative frame angular speed: \( \omega \)
Streamtube in an Annulus

- **Machine Area**
- **Flow Area**
- **Flow Mean Radius**
- **Machine Mean Radius**

Numbers 1 and 2 indicate the positions along the streamtube.
Multiple Streamtubes
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
**Independents** represent variables the NPSS solver is allowed to vary

**Dependents** represent equations or conditions the NPSS solver must satisfy

- **FlowStation Independents**
  - $\dot{m}_2$
  - $h_{t2}$
  - $P_{t2}$
  - $\alpha_2$
  - $\text{radius}_2$
  - $MN_2$

- **BladeRow Dependents**
  - Continuity
  - Conservation of energy/Euler
  - Non-ideal process loss
  - Non-ideal process turning
  - Geometry constraint (radius)
  - Geometry constraint (area)
  - $\dot{m}_{m2} = \dot{m}_{m1}$
  - $h_{t2} - h_{t1} = \omega (r_2 V_\theta 2 - r_1 V_\theta 1)$
  - $P_{t2} = P_{t2\text{ideal}} - \Delta P_t$
  - $\beta_2 = \beta_{\text{blade}} + \delta$
  - $\text{radius}_2 = r_{\text{machine}}$
  - $A_{\text{flow2}} = A_{\text{machine}} - A_{\text{blockages}}$
Empirical Effects

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

  - profile loss method “a”
  - deviation “c”
  - blockage method “a”

- 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

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

Test Cases and Results

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

<table>
<thead>
<tr>
<th>impeller exit</th>
<th>OTAC</th>
<th>Japikse</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pt, psi</td>
<td>31.17</td>
<td>31.17</td>
</tr>
<tr>
<td>Tt, R</td>
<td>653.5</td>
<td>653.7</td>
</tr>
<tr>
<td>Vm, ft/s</td>
<td>342.4</td>
<td>342.4</td>
</tr>
<tr>
<td>Vθ, ft/s</td>
<td>843.8</td>
<td>843.8</td>
</tr>
<tr>
<td>β flow, degrees</td>
<td>19.04</td>
<td>-19.04</td>
</tr>
<tr>
<td>α flow, degrees</td>
<td>67.91</td>
<td>67.91</td>
</tr>
<tr>
<td>slip factor</td>
<td>0.8772</td>
<td>0.8772</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>diffuser exit</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Pt, psi</td>
<td>30.04</td>
<td>30.04</td>
</tr>
<tr>
<td>Ps, psi</td>
<td>26.71</td>
<td>26.64</td>
</tr>
<tr>
<td>α flow, deg</td>
<td>55.99</td>
<td>50.94</td>
</tr>
</tbody>
</table>

*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
Meanline BladeRow Equation Set

**continuity**

\[ \dot{m}_2 = \dot{m}_1 \]

**conservation of energy/Euler**

\[ h_{t2} - h_{t1} = \omega (r_2 V_{\theta 2} - r_1 V_{\theta 1}) \]

**non-ideal process loss**

\[ P_{t2} = P_{t2_{\text{ideal}}} - \Delta P_t \]

**non-ideal process turning**

\[ \beta_2 = \beta_{\text{blade}} + \delta \]

**geometry constraint (radius)**

\[ r_2 = r_{\text{machine}} \]

**geometry constraint (area)**

\[ A_{\text{flow}2} = A_{\text{machine}} - A_{\text{blockages}} \]

Note: at design, \( \beta_{\text{blade}} \) and \( A_{\text{machine}} \) may be input (direct-design) or varied to produce specific performance (indirect-design).
Streamline BladeRow Equation Set

- **Continuity**: \( n \) for \( n \) streams
- **Energy/Euler**: \( n \) for \( n \) streams
- **Loss Condition**: \( n \) for \( n \) streams
- **Flow Follows Blade**: \( n \) for \( n \) streams
- **Geometry Constraint**: \( n-1 \) for \( n-1 \) streams
- **Geometry Constraint**: \( 1 \) for \( 1 \) stream
- **Spanwise Eq.**: \( n-1 \) for \( n-1 \) streams
- **Geometry Constraint**: \( 1 \) for \( 1 \) stream

\[
\begin{align*}
    \dot{m}_{m2_i} &= \dot{m}_{m1_i} \\
    h_{t2_i} - h_{t1_i} &= \omega (r_{2i} V_{\theta 2i} - r_{1i} V_{\theta 1i}) \\
    p_{t2_i} &= p_{t2\text{\_ideal}i} - \Delta p_{t_i} \\
    \beta_{2i} &= \beta_{\text{blade}i} + \delta_i \\
    r_{2\text{\_inner}i+1} &= r_{2\text{\_outer}i} \\
    r_{2\text{\_sum}} &= r_{\text{machine}} \\
    \frac{1}{\rho_i} \frac{\Delta p_i}{\Delta r_i} &= \frac{V_{\theta i}^2}{r_i} \\
    A_{\text{flow2\_sum}} &= A_{\text{machine}} - A_{\text{blockages}}
\end{align*}
\]

- \( n \) = number of streams
- \( i \) = stream number, 1 to \( n \)
- \( \text{sum} \) = aggregate value
BladeSegment Object

responsible for differences between certain flow states
entrance
exit - actual
exit - ideal $h_t$
exit - ideal $P_t$
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