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

![Symbol](no_turbines.png)
![Symbol](no_design_prediction.png)
![Symbol](no_centrifuge.png)
![Symbol](no_streamlines.png)

- 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, 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

modified NPSS FlowStation objects
FlowStation Object Extended from NPSS

NPSS 1-D FlowStation (4 inputs):
- \( h_t \), \( P_t \)
- \( MN \)
- \( m \)

OTAC FlowStation (7+1 inputs):
- \( h_t \), \( P_t \)
- \( MN, \alpha, \phi \)
- \( m \)
- radius

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

- Machine area
- Flow area
- Flow mean radius
- Machine mean radius

1

2
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)
- $\dot{m}_{m2} = \dot{m}_{m1}$
- $h_{t2} - h_{t1} = \omega(r_2 V_{θ2} - r_1 V_{θ1})$
- $p_{t2} = p_{t2,\text{ideal}} - \Delta P_t$
- $\beta_2 = \beta_{\text{blade}} + \delta$
- $\text{radius}_2 = r_{\text{machine}}$
- $A_{\text{flow}2} = A_{\text{machine}} - A_{\text{blockages}}$
Empirical Effects

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

- 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></th>
<th>OTAC</th>
<th>Japikse</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>impeller exit</strong></td>
<td></td>
<td></td>
</tr>
<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>
<tr>
<td><strong>diffuser exit</strong></td>
<td></td>
<td></td>
</tr>
<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
Backup Slides
Meanline BladeRow Equation Set

continuity

\[ \dot{m}_{m2} = \dot{m}_{m1} \]

conservation of energy/Euler

\[ h_{t2} - h_{t1} = \omega (r_2 V_{\theta2} - r_1 V_{\theta1}) \]

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

\[ \begin{align*}
    n & \quad \text{continuity} \\
    n & \quad \text{energy/Euler} \\
    n & \quad \text{loss condition} \\
    n & \quad \text{flow follows blade} \\
    n-1 & \quad \text{geometry constraint} \\
    1 & \quad \text{geometry constraint} \\
    n-1 & \quad \text{spanwise eq.} \quad \frac{1}{\rho} \frac{dp}{dr} = \frac{V_{\theta}^2}{r} \\
    1 & \quad \text{geometry constraint}
\end{align*} \]

\[ \begin{align*}
    \dot{m}_{m2i} &= \dot{m}_{m1i} \\
    h_{t2i} - h_{t1i} &= \omega (r_{2i} V_{\theta2i} - r_{1i} V_{\theta1i}) \\
    P_{t2i} &= P_{t2\text{ideal}i} - \Delta P_{ti} \\
    \beta_{2i} &= \beta_{\text{blade}i} + \delta_{i} \\
    r_{2i}\text{inner}_{i+1} &= r_{2i}\text{outer}_{i} \\
    r_{2i}\text{sum} &= r_{\text{machine}} \\
    \frac{1}{\rho_i} \Delta p_i &= \frac{V_{\theta i}^2}{r_i} \\
    A_{flow2sum} &= A_{\text{machine}} - A_{\text{blockages}}
\end{align*} \]

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 $P_t$
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