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

![icons showing turbines, design prediction, no centrifs allowed, streamlines prohibited]

- 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):
- $h_t$, $P_t$
- $\dot{m}$
- $MN$

OTAC FlowStation (7+1 inputs):
- $h_t$, $P_t$
- $\dot{m}$
- $MN$, $\alpha$, $\phi$
- radius
- + relative frame angular speed: $\omega$
Streamtube in an Annulus

machine area

flow area

flow mean radius

machine mean radius
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)

\[ \dot{m}_{m2} = \dot{m}_{m1} \]
\[ h_{t2} - h_{t1} = \omega (r_2 V_\theta 2 - r_1 V_\theta 1) \]
\[ P_{t2} = P_{t2\text{ideal}} - \Delta P_t \]
\[ \beta_2 = \beta_\text{blade} + \delta \]
\[ \text{radius}_2 = \text{radius}_\text{machine} \]
\[ A_{\text{flow}_2} = A_{\text{machine}} - A_{\text{blockages}} \]
Empirical Effects

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

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

  - profile loss method “b”
  - shock loss method “a”
  - tip loss 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

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<th>Japikse</th>
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*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

conservation of energy/Euler

non-ideal process loss

non-ideal process turning

geometry constraint (radius)

geometry constraint (area)

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

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

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

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

\[ r_2 = r_{machine} \]

\[ A_{flow2} = A_{machine} - A_{blockages} \]

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

- $n$ continuity
- $n$ energy/Euler
- $n$ loss condition
- $n$ flow follows blade
- $n-1$ geometry constraint
- $1$ geometry constraint
- $n-1$ spanwise eq. $\frac{1}{\rho} \frac{dp}{dr} = \frac{V_{\theta}^2}{r}$
- $1$ geometry constraint

$n = \text{number of streams}$
$i = \text{stream number, 1 to } n$
$\text{sum} = \text{aggregate value}$

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