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

- specific, individual codes may have undesirable features

ERROR: SOURCE CODE NOT FOUND

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

Element object
flow connection
mechanical connection
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 mean radius
flow mean radius

flow area
machine area

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
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

\[ A \text{ Method of Performance Estimation for Axial-Flow Turbines, D.G. Ainley and G.C.R. Mathieson, 1957} \]
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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*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
\[ m_{m2} = m_{m1} \]

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

\[ \begin{align*}
  n & \quad \text{continuity} \quad \dot{m}_{m2i} = \dot{m}_{m1i} \\
  n & \quad \text{energy/Euler} \quad h_{t2i} - h_{t1i} = \omega (r_{2i} V_{\theta2i} - r_{1i} V_{\theta1i}) \\
  n & \quad \text{loss condition} \quad P_{t2i} = P_{t2\text{ideal}i} - \Delta P_{ti} \\
  n & \quad \text{flow follows blade} \quad \beta_{2i} = \beta_{\text{blade}i} + \delta_{i} \\
  n-1 & \quad \text{geometry constraint} \quad r_{2i\text{inner}i+1} = r_{2i\text{outer}i} \\
  1 & \quad \text{geometry constraint} \quad r_{2i\text{sum}} = r_{\text{machine}} \\
  n-1 & \quad \text{spanwise eq.} \quad \frac{1}{\rho} \frac{dp}{dr} = \frac{V_{\theta}^2}{r} \\
  1 & \quad \text{geometry constraint} \\
\end{align*} \]

n = number of streams
i = stream number, 1 to n
sum = aggregate value

\[ \frac{1}{\rho_i} \frac{\Delta p_i}{\Delta r_i} = \frac{V_{\theta i}^2}{r_i} \]

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

responsible for differences between certain flow states 

entrance

ext - actual

ext - ideal $h_t$

ext - 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.