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

Wasn't there someone who used to run this?

The USER GUIDE to UNHELPFUL USER GUIDES
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

1. Flow area
2. Machine area
3. Flow mean radius
4. 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**
  - $m_2$
  - $h_{t2}$
  - $p_{t2}$
  - $\alpha_2$
  - $radius_2$
  - $MN_2$

- **BladeRow Dependents**
  - continuity
  - conservation of energy/Euler
  - non-ideal process loss
  - non-ideal process turning
  - geometry constraint (radius)
  - geometry constraint (area)

  - $m_{m2} = m_{m1}$
  - $h_{t2} - h_{t1} = \omega (r_2 V_2 - r_1 V_{01})$
  - $P_{t2} = P_{t2ideal} - \Delta P_t$
  - $\beta_2 = \beta_{blade} + \delta$
  - $radius_2 = r_{machine}$
  - $A_{flow2} = A_{machine} - A_{blockages}$
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

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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)

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

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

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

\[ \beta_{2} = \beta_{blade} + \delta \]

\[ r_{2} = r_{machine} \]

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

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. \( \frac{1}{\rho} \frac{dp}{dr} = \frac{\theta_i^2}{r} \)
\( 1 \)  geometry constraint

\( m_{m2i} = m_{m1i} \)
\( h_{t2i} - h_{t1i} = \omega (r_{2i} \theta_{2i} - r_{1i} \theta_{1i}) \)
\( p_{t2i} = p_{t2\text{ideal }i} - \Delta p_{t_i} \)
\( \beta_{2i} = \beta_{\text{blade }i} + \delta_i \)
\( r_{2\text{inner}_{i+1}} = r_{2\text{outer }i} \)
\( r_{2\text{sum}} = r_{\text{machine}} \)

\( \frac{1}{\rho_i} \frac{\Delta p_i}{\Delta r_i} = \frac{\theta_i^2}{r_i} \)
\( A_{\text{flow}_{2\text{sum}}} = A_{\text{machine}} - A_{\text{blockages}} \)

\( n = \) number of streams
\( i = \) stream number, 1 to \( n \)
\( \text{sum} = \) aggregate value
 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
responsible for differences between BladeSegments

holds blade row specific variables: annulus areas, number of blades, blade angles, power, etc.
Slide Master