Advanced Turbomachinery Methods

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Presentation Overview

1. Turbomachinery challenges
2. ANSYS TurboSystem
3. Blade row fluid dynamics solution methods
   – Available methods
   – Description of the ANSYS Transformation methods
4. Transient Blade Row applications
5. Other ANSYS blade row design tools
6. Summary
Turbomachinery manufacturers are challenged to develop advanced machines and deliver them to market quickly

- Efficient
  - Turbines: low fuel burn
  - Compressors: high efficiency
- Low emissions (carbon, others) or “green”
- Durable (safe, reliable, long and predictable life)
- High performance (loading, range, power density, compact etc.)

High-fidelity, industry-specific simulation tools are required to enable developers to develop machines that perform as promised

- ANSYS continues to expand the scope of its Turbo Tools, as described on the following slides
ANSYS TurboSystem

Complete turbomachinery design and analysis in ANSYS Workbench

- Geometry
- Throughflow
- Meshing
- CFD
- Thermal
- Combustion
- Structural mechanics
- Rotordynamics
- Post-processing
- Optimization

This presentation will focus on ANSYS blade row fluid dynamics tools
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Blade Row Fluid Dynamics: Steady

Blade Row Methods

Stage (Mixing-Plane)

Frozen Rotor

Transient Rotor/Stator

Steady Methods
Single (or few) blade passages per row

+ Proven, industry-standard workhorse tools
+ Fast and efficient
+ Good at design point
- Do not account for unsteady phenomena
Blade Row Fluid Dynamics: Transient

Blade Row Methods

Stage (Mixing-Plane)

Frozen Rotor

Transient Rotor/Stator

- Accurately captures unsteady interactions
- Unequal pitch dictates full or partial wheel modeling
- Requires large computing resource

unequal pitch

Phase-shifted boundaries a consequence of pitch change
Blade Row Fluid Dynamics: Transient

• Problem: How to obtain the full-wheel transient solution, but at low cost?

• Solution: The ANSYS TBR Transformation family of methods
  + New models minimize number of simulated passages, providing enormous efficiency gains and reduced infrastructure requirements
Blade Row Fluid Dynamics Solutions

Blade Row Methods

- Stage (Mixing-Plane)
- Frozen Rotor

Steady Methods
Single (or few) blade passages per row

Transient with Pitch Change

- Transient Rotor/Stator
- Full Domain Modeling

TBR Transformation Methods

- Profile Transformation
- Time Transformation
- Fourier Transformation
- Harmonic Transformation

Transient methods with pitch change
Single or few blade passages
Profile Transformation Method

• Performs an interface profile transformation (stretching)
  • Maintains true blade geometry
  • Accuracy increases as ensemble pitch ratio approaches unity
• Efficient and fast
• Available in CFX for many years

The ANSYS
TBR Transformation Methods
Fast Blade Row Solutions
Time Transformation Method

• Transforms equations so that instantaneous periodicity applies
• Fast, low memory
  – Fully implicit + turbulent (unlike earlier methods)
  – Ideal for inlet disturbance or single stage
• R14: released for single disturbance
  – R14 (beta): combine with PT or Stage

\[
\frac{\partial Q}{\partial t} + \frac{\partial E}{\partial X} + \frac{\partial G}{\partial Y} = 0
\]

\[
X' = X
Y' = Y
\]
\[
t' = t - \lambda Y
\]

\[
\frac{\partial (Q - \lambda G)}{\partial t'} + \frac{\partial E}{\partial X'} + \frac{\partial G}{\partial Y'} = 0
\]

\[
\Delta T = \frac{P_s - P_r}{V_r}, \quad \lambda = \frac{\Delta T}{P_r}
\]

Based on “Time-Inclining” (Giles, 1988)
Fourier Transformation Method

- Fourier Series reconstructs solution on periodic/interface boundaries
- Efficient data storage
- No restriction on pitch-ratio/compressibility
- R14: released for inlet disturbance only
  - R14 (beta): single stage
  - Future: multiple perturbations/stages

Based on L. He (1989) and Gerolymos et al. (2002)
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LPT – Description (more details in GT2011- 46635)

• Low pressure turbine stage designed by PCA Engineers (UK)
• Typical of stages sometimes used in the low pressure section of an aircraft engine
• High loading
  – Work coefficient ($\Delta H/U^2$) = 2.8
• High lift coefficient
  – Rotor Zweifel coefficient = 1.35
• 88 stators : 76 rotors
  – Quarter wheel periodicity
• Flared casing
• Shrouded rotor blades

• No tip gap or leakage flows
• Hexahedral meshes from ANSYS TurboGrid

<table>
<thead>
<tr>
<th>Mesh Type</th>
<th>Nodes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse</td>
<td>478K</td>
</tr>
<tr>
<td>Medium</td>
<td>1.2M</td>
</tr>
<tr>
<td>Fine</td>
<td>2.3M</td>
</tr>
</tbody>
</table>

# of nodes for one stator + one rotor passage
LPT – Computational Methods

• Stage calculation
  – **Transient**: PT, TT and FT methods
  – **Steady**: “Stage” model (circumferential averaging)
  – **Periodic** reference solution on ¼ wheel with 23.9M nodes

• **Turbulence model**
  • Fully turbulent: SST turbulence model (Menter)
  • Transition: SST + Γ-Θ transition model (Menter et al.)

• “Medium” grid solutions presented here
LPT - Overall predictions

<table>
<thead>
<tr>
<th>Method</th>
<th>Relative Work Coeff.</th>
<th>Relative Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PT</td>
<td>0.00</td>
<td>0.2</td>
</tr>
<tr>
<td>TT</td>
<td>0.00</td>
<td>-0.2</td>
</tr>
<tr>
<td>FT</td>
<td>0.00</td>
<td>-0.3</td>
</tr>
<tr>
<td>¼ wheel</td>
<td>0.00</td>
<td>0.0</td>
</tr>
</tbody>
</table>

(Nominal: $\Delta H/U^2 \approx 2.8 \quad \eta \approx 90\%$)

- Solutions with transition
  - (Almost) identical work coefficients
  - Efficiencies $\pm 0.3\%$

- Larger differences between transition and fully turbulent than among PT/TT/periodic solutions. For fully turbulent:
  - $\Delta H/U^2 \approx 0.2 - 0.3$ lower
  - $\eta \approx 1\%$ lower

(relative to the ¼ wheel case)
LPT - Flow details (1)

**Instantaneous midspan entropy**
almost identical (with transition)

**Time-averaged mid-span Mach #**
after identical (no transition)
LPT - Flow details (2)

Instantaneous entropy in rotor, looking upstream

Shows loss development near suction side, especially near shroud and hub

Shows loss development, especially near hub & shroud, & suction side boundary layer (red)
### LPT - Computational Effort

<table>
<thead>
<tr>
<th>Method</th>
<th>Stator/Rotor Passages</th>
<th>Relative effort</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage (steady)</td>
<td>1/1</td>
<td>1.0</td>
</tr>
<tr>
<td>PT</td>
<td>1/1</td>
<td>22.0</td>
</tr>
<tr>
<td>TT</td>
<td>1/1</td>
<td>36.7</td>
</tr>
<tr>
<td>FT</td>
<td>2/2</td>
<td>48.0</td>
</tr>
<tr>
<td>¼ wheel</td>
<td>22/19</td>
<td>440.0</td>
</tr>
</tbody>
</table>

- **Transformation methods**
  - Require 20 to 50 times the effort of steady solutions
  - Require about one order magnitude less effort than periodic solution (¼ wheel, reference solution), and machine/disk requirements an order of magnitude lower
Modified Hannover Axial Compressor

Beta at R14: combined usage of PT and TT

Courtesy of TFD Hannover
Modified Hannover Axial Compressor:
2Pt + 2TT solution .vs. full domain solution

Reference (1/4 wheel)

Time Transformation

Courtesy of TFD Hannover
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ANSYS VISTA Design and Analysis tools

- **R13: WB integration**
  - Meanline design tools VISTA-CCD (compressors), VISTA-RTD (radial turbines) and VISTA-TF (throughflow solver)

- **R14: more WB integration**
  - VISTA-AFD (axial fans)
  - Includes a throughflow solver in inverse design or analysis mode
ANSYS BladeModeler

• **R13: Airfoil Design Mode**
  – Enabled axial turbo design
  – Also: auxiliary view plots, blade parameterization in WB (for DOE)

• **R14: Arbitrary flow path layers**
  – Using sketch curves, layers don’t need to be at constant span

- Improved workflow
- Camberline and airfoil design modes more consistent
- Auxiliary view for blade/flow path curvature
• R13: Release of ATM method
  – Automated, very high quality hex meshes for blade rows
  – Rounded or cut-off LE or TE
  – Parameters in WB

• R14: ATM for splitters
  – No manual positioning req’d.
• R14: New templates added to improve mesh resolution near rounded leading and trailing edges

• R14: “Double-herringbone” template added to improve mesh resolution for cut-off blades with lower blade angles
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Summary

ANSYS is advancing the availability of high-fidelity, industry-specific simulation tools which assist in the development of advanced turbomachines that are

- Efficient
- “Green”
- Durable
- High performance

Significant advances, to be delivered at ANSYS R14, in transient blade row simulation and blade row design tools have been presented.

ANSYS plans to continue with significant advances to its turbomachinery-specific tools beyond R14.