Numerical and experimental study for the prediction of the steady, three dimensional flow in a turbine nozzle vane cascade using OpenFOAM

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Outline

• Who we are
• Motivation & background
• Experimental and numerical setup
• Results and validation against measurements
• Conclusions & future developments
Who we are

**EST** - Energy Systems and Turbomachinery Group
Department of Engineering
University of Bergamo, Italy

**SCS Italy**

**CINECA**
Motivation

**Main goal**: exploring the potential of the OpenFOAM Toolbox to characterize the HP turbine section of a gas turbine engine

Air-cooled HP Turbine    Un-cooled LP Turbine

SGT-750 © Siemens AG 2010
Background

Experimental and numerical investigation of thermal and aerodynamic performance of linear vane cascade

- National Research Projects (PRIN) and Industrial research contracts
- Simulations by means of commercial CFD codes

Suction-type, open circuit wind tunnel
Current activity

CFD modelling supported by experiments

CFD open-source technology for industrial applications

HPC platforms for CAE applications:
http://www.fortissimo-project.eu/
http://www.prace-ri.eu/
Experimental setup

Solid Vane
- \( c = 142.1 \text{ mm} \)
- \( s/c = 1.04 \)
- \( H = 98 \text{ mm} \)
- \( H/c = 0.69 \)
- \( \beta_2 = 70^\circ \)
- \( \beta_1 = 0 \)

Operating conditions
- \( M_{2is} = 0.2 \)
- \( Re_{2is} = 6.5 \times 10^5 \)
- \( Tu_1 = 1.62\% \)

Inlet boundary layer \((X/c_{ax} = -1.6)\)
Experimental setup

Experimental data used for validation:

- vane loading at midspan \( z/H=0.5 \)
- wake total pressure \( P_{t2} \) \( z/H=0.5, \ x/C_{ax} = 1.50 \)
- kinetic energy loss coefficient \( \zeta \) \( \text{at } x/C_{ax} = 1.53 \)

\[
\zeta = \left( 1 - \frac{U_2^2}{U_{2is}^2} \right) \times 100
\]
Numerical workflow
Meshing

– Meshing CAD geometry
– Criteria: checkMesh output & experimental fidelity
– Hybrid mesh topology
– SW: Pointwise (Pointwise Inc.)
Mesh details

Different meshes were created to assess the sensitivity of the solver setup to the spatial discretization:

<table>
<thead>
<tr>
<th>Mesh name</th>
<th>y⁺ (min – max – average)</th>
<th>BL hexahedra block</th>
<th>BL – # of layers</th>
<th>Max Non-orthogonality</th>
<th>Average Non-orthogonality</th>
<th>Max Skewness</th>
<th>Max Aspect Ratio</th>
<th># of cells [Millions]</th>
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<tbody>
<tr>
<td>hybrid₁</td>
<td>15.1 – 113.7 – 60.2</td>
<td>yes</td>
<td>5</td>
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<td>6.1</td>
<td>0.7</td>
<td>6.2</td>
<td>1.6</td>
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<tr>
<td>hybrid₂</td>
<td>15.2 – 116.8 – 59.7</td>
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<td>5</td>
<td>37.1</td>
<td>6.1</td>
<td>0.7</td>
<td>6.4</td>
<td>2.4</td>
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<tr>
<td>hybrid₃</td>
<td>8.0 – 68.0 – 36.1</td>
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<td>5</td>
<td>36.9</td>
<td>6.2</td>
<td>0.6</td>
<td>4.6</td>
<td>3.5</td>
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## Boundary conditions

<table>
<thead>
<tr>
<th>Patch name</th>
<th>Patch type</th>
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<tr>
<td>inlet</td>
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<td>mid</td>
<td>symmetryPlane</td>
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<tr>
<td>outlet</td>
<td>patch</td>
</tr>
<tr>
<td>tip</td>
<td>wall</td>
</tr>
<tr>
<td>vane</td>
<td>wall</td>
</tr>
<tr>
<td>periodic*</td>
<td>cyclic</td>
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<table>
<thead>
<tr>
<th>Patch name</th>
<th>U</th>
<th>p</th>
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</thead>
<tbody>
<tr>
<td>inlet</td>
<td>timeVaryingMappedFixedValue</td>
<td>zeroGradient</td>
</tr>
<tr>
<td>outlet</td>
<td>zeroGradient</td>
<td>fixedValue</td>
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</tbody>
</table>
Numerical setup

- **Solver**: steady state *simpleFoam*
- **Discretization schemes**: 2\textsuperscript{nd} order
- **Advection term**: blended scheme (1\textsuperscript{st}/2\textsuperscript{nd} order)
- **Residual control**: ending criterion of $10^{-9}$
- **Monitoring**: 14 pressure and velocity probes
- **Two-equation turbulence models** with WallFunctions approach

<table>
<thead>
<tr>
<th>Mesh name</th>
<th>Turbulence model</th>
</tr>
</thead>
<tbody>
<tr>
<td>hybrid\textsubscript{1}</td>
<td>k-ε</td>
</tr>
<tr>
<td>hybrid\textsubscript{2}</td>
<td>k-ε</td>
</tr>
<tr>
<td>hybrid\textsubscript{3}</td>
<td>k-ε/realisable k-ε/SST k-ω</td>
</tr>
</tbody>
</table>
Results – Overview

Results will include the following:

• **Mesh sensitivity analysis** based on midspan flow features
  - Turbulence model: k-ε

• Evaluation of the **turbulence model** influence on the predictions of:
  - vane load
  - wake loss
  - secondary flows

• **Scalability** analysis over different HW configurations
Results – Mesh sensitivity

![Graph of vane load vs. Hybrid meshes]

![Graph of wake total pressure drop vs. Hybrid meshes]

Best mesh → Hybrid₃
Results – Vane load

Vane load predictions have a weak dependence on turbulence model
Results – Midspan velocity

(Turbulence model marginally affects midspan velocity)

$x/C_{ax} = 1.50$

$M_{2is} = 0.199$
Results – Midspan wake

Wake predictions have a strong dependence on turbulence model

\( x/C_{ax} = 1.50 \)
Results – Midspan wake

Wake predictions have a strong dependence on turbulence model $(x/C_{ax} = 1.50)$
Results – Secondary flows

\[
\zeta = \left( 1 - \frac{U_2^2}{U_{2is}^2} \right) \times 100
\]

\((x/C_{ax} = 1.53)\)

Hybrid$_3$ - Realisable \(k-\varepsilon\)
Scalability

Hybrid_3 mesh

Nehalem and Westmere cores are interconnected with Infiniband DDR

Sandybridge cores are interconnected with Infiniband QDR
Conclusions

• **Turbulence model**
  - The vane load prediction is satisfactory, especially on the pressure side.
  - *Realisable* $k-\varepsilon$ and *SST* $k-\omega$ are the closest to the measured wake loss, with an overestimation of 15% and 9%, respectively.
  - Simulations overpredicted the kinetic energy losses associated with the passage vortex and the corner vortex as well.

• **Computational efficiency**
  - The scalability of the study-case is effective on the tested cores range thanks to the **HPC platform (HW+Interconnection)**.
  - Setup shows a good efficiency (>80%) using up to **38k cells per computational core**. This cell density per computational core can be used as reference for the same setup on larger problems.
Future developments

• Pre-processing: Mesh topology based on native openFoam pre-processor
• Compressibility to match experiments at $M_{2is} = 0.4 – 0.6$
• Thermal modelling to simulate film cooling applications
• Unsteadyness for an accurate prediction of the thermal mixing between mainstream and coolant flow
Questions?

Thank you for your kind attention!