Reduction of Unsteady Forcing in a Vaned, Contra-Rotating Transonic Turbine Configuration

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Acknowledgements and Collaborations

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The AFRL High Impact Technologies Research Turbine (HIT RT)

Meanline Design Parameters: HIT RT

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PR</td>
<td>3.75</td>
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<tr>
<td>Reaction</td>
<td>49.5%</td>
</tr>
<tr>
<td>Flow Coefficient</td>
<td>0.71</td>
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<tr>
<td>Work Coefficient</td>
<td>2.11</td>
</tr>
<tr>
<td>$AN^2$ (in$^2$ rpm$^2$)</td>
<td>$573 \times 10^8$ (Engine)</td>
</tr>
<tr>
<td>Turning</td>
<td>77°, 116°, 11°</td>
</tr>
<tr>
<td>$M_{exit}$</td>
<td>0.88, 1.30, 0.89</td>
</tr>
<tr>
<td>Airfoil Count</td>
<td>23, 46, 23</td>
</tr>
</tbody>
</table>
Unsteadiness due to Downstream Interaction is Dominated by First Harmonic of Vane Passing

1B Suction Side, Percent Signal Power

Cross-Passage Shock
Turbine Design And Analysis System: Created to Enable Design of the HIT Research Turbine

Iterative Turbine-Design Loop

- **1D**: Turbine size and velocity triangles were set with a 1D meanline code (HuberLine, FTT)
- **2D**: Airfoil-section design, analysis, and optimization was conducted in MATLAB
  - HuberFoil (FTT) profile algorithm
  - GUI-based flowfield interrogation
  - Optimization via SQP, genetic algorithms, and DoE
- **4D**: Time-resolved 3D analysis
  - DSP-based convergence-monitoring and unsteady post-processing
  - Enables investigation of unsteady shock interactions and instrumentation design for code validation

A range of solvers are integrated with the system:
- Corsair (Dorney, NASA MSFC)
- LEO (Ni, Aerodynamic Solutions, Inc.)
- MBFLO (Davis, UCDavis)
Cascade Experiments are Underway to Validate Design and Analysis Tools

• Match to predictions gives confidence that the source of 1B-2V interaction is controllable via aerodynamic shaping.
HIT RT Blade was Re-Designed in an Attempt to Reduce Levels of Unsteadiness at 46E

- Design-space exploration was performed to equalize strengths of the double-shock pair.
- Peak-to-peak circumferential distortion in exit static pressure was reduced of order 25%.
Small Decrease in 46E Unsteadiness Despite ≈25% Reduction in Peak-to-Peak Ps Variation

1B Suction Side, DFT Magnitude, Percent Pt_{inlet}

HIT RT

With Low dP 1B
Additional Means to Reduce 1B-2V Interaction: Steady 2V Blowing and 3D Vane Shaping

**Present Situation**

- 2V geometry leads to shock reflections for vaned contra-rotating turbines.
- These arise because induced-flow components due to moving shocks must be cancelled at no-slip surfaces.
- Injection of a small amount of flow equal and opposite the induced velocity should reduce the strength of reflected shocks.
- Bowing of the 2V should affect unsteadiness levels on the 1B surface.

*Diagram showing HPT Blade, LPT Vane, Incident Shocks, Reflected Shocks, and flow visualization.*

2V With Blowing, Bowed 2V, HIT RT 2V, Reverse-Bowed 2V.
Reverse-Bowed 2V Leads to a Significant Change in Distribution of 46E Unsteadiness

1B Suction Side, DFT Magnitude, Percent Pt\text{inlet}

HIT RT

Reverse-Bowed 2V
Bowed 2V Also Leads to a Significant Change in Distribution of 46E Unsteadiness

1B Suction Side, DFT Magnitude, Percent Pt_{inlet}

HIT RT

Bowed 2V
Small Decrease in 46E Unsteadiness Due to Steady Blowing on 2V Pressure Side

1B Suction Side, DFT Magnitude, Percent Pt_{inlet}

HIT RT

With Steady 2V Blowing

1113 holes, Pt_{cool} = 28 psia, 0.8% Flow, α = 90°
Reduction in 46E Unsteadiness Increases with Increasing Mass Flow

1B Suction Side, DFT Magnitude, Percent Pt$_{\text{inlet}}$

HIT RT

With Steady 2V Blowing

1113 holes, Pt$_{\text{cool}}$ = 28 psia, 1.7% Flow, $\alpha = 90^\circ$
Reduction in 46E Unsteadiness Increases with Increasing Mass Flow

1B Suction Side, DFT Magnitude, Percent Pt_{inlet}

HIT RT

With Steady 2V Blowing

450 holes, Pt_{cool} = 28 psia, 2.8% Flow, \( \alpha = 90^\circ \)
Reduction in 46E Unsteadiness Increases with Increasing Mass Flow

1B Suction Side, DFT Magnitude, Percent \( P_{t_{\text{inlet}}} \)

HIT RT

With Steady 2V Blowing

1113 holes, \( P_{t_{\text{cool}}} = 28 \) psia, 6.8% Flow, \( \alpha = 90^\circ \)
A Combination of 2V Pressure-Side Blowing and 2V Bow Looks Promising

1B Suction Side, DFT Magnitude, Percent Pt_inlet

HIT RT

With Steady 2V Blowing and Bowed 2V

1113 holes, Pt_{cool} = 28 psia, 1.7% Flow, α = 90°
HIT RT is Intended to Assess 1B-2V
Unsteady Interaction in Great Detail

- Variable Stagger 2V (±10% A45 variation)
  - Also enables the investigation of vane asymmetry and re-stagger to reduce unsteady loading
- Vane-row clocking to affect phase of unsteadiness

Full-Scale Testing in Turbine Research Facility, Spring 2010
Summary

• HPT blade unsteadiness in the presence of a downstream vane consistent with contra-rotation is characterized by strong interaction at the first harmonic of downstream vane passing.

• An existing stage-and-one-half transonic turbine rig design was used as a baseline to investigate means of reducing such a blade-vane interaction.

• Methods assessed included:
  ➢ Aerodynamic shaping of HPT blades
  ➢ 3D stacking of the downstream vane
  ➢ Steady pressure-side blowing

• Of the methods assessed, a combination of vane bowing and steady pressure-side blowing produced the most favorable result.

• Transonic turbine experiments are planned to assess predictive accuracy for the baseline turbine and any design improvements.