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

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John Clark, D Phil, PE
Turbine Engine Division
Propulsion Directorate
Air Force Research Laboratory
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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 total-total</td>
</tr>
<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>$AN^2$ (in² rpm²)</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>
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</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 related flow patterns.](image)
Reverse-Bowed 2V Leads to a Significant Change in Distribution of 46E Unsteadiness

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

HIT RT With Steady 2V Blowing

1113 holes, $P_{t_{cool}} = 28$ psia, 0.8% 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

1113 holes, Pt_{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 Pt_inlet

HIT RT

With Steady 2V Blowing

1113 holes, Pt_{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

HIT RT

With Steady 2V Blowing and Bowed 2V

1113 holes, Pt_{cool} = 28 psia, 1.7% Flow, \( \alpha = 90^\circ \)
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.