Aerodynamic Performance of a Compact, High Work-Factor Centrifugal Compressor at the Stage and Subcomponent Level

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Aerodynamic Performance of a Compact, High Work-Factor Centrifugal Compressor at the Stage and Subcomponent Level

- Background and Scope
- Test Article and Facility Description
- Key Instrumentation
- Stage and Subcomponent Results
- Performance Assessment vs. Pre-test CFD
- Summary
Background and Scope

- **NASA/UTRC High Efficiency Centrifugal Compressor (HECC)**
  - NRA cost-share contract
  - Develop HPC technologies for advanced turboshaft engines for rotorcraft
  - Challenging goal set for centrifugal compressors
  - Maintain similitude between engine scale and rig scale hardware
  - Design/Analysis, fab, assembly, test

<table>
<thead>
<tr>
<th>Metric</th>
<th>Intent (rig scale, 2x engine scale)</th>
<th>CFD*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exit-corr. flow</td>
<td>$2.1 &lt; \dot{m}_{c,ex} &lt; 3.1 \text{ lb}_m/s$</td>
<td>2.98</td>
</tr>
<tr>
<td>Work factor</td>
<td>$0.60 &lt; \Delta H_0/U_2^2 &lt; 0.75$</td>
<td>0.7905</td>
</tr>
<tr>
<td>$\eta_{p,tt}$ (poly)</td>
<td>$\geq 0.88$</td>
<td>0.888</td>
</tr>
<tr>
<td>Diam. ratio</td>
<td>$D_{max}/D_2 \leq 1.45$</td>
<td>1.45</td>
</tr>
<tr>
<td>Design SM</td>
<td>13%</td>
<td>12%</td>
</tr>
<tr>
<td>$M_{ex}$</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>$\alpha_{ex}$</td>
<td>15°</td>
<td>14°</td>
</tr>
</tbody>
</table>

HECC Stage Overview

Design speed = 21,789 ft/s   (Exit tip speed = 1615 ft/s)

- **Impeller:** 15 blade/splitter pairs, spanwise varying backsweep, lean, elliptical leading and trailing edges
- **Diffuser:** 20 vane/splitter pairs, with splitters offset to maximize pressure recovery
- **EGVs:** 60 cascade-style airfoils
Small Engine Component Test Facility (CE-18)

- 6000 hp / 60,000 rpm / 30:1 PR / Max 20" diameter
- Inlet pressures 2-45 psia / Inlet air -20 ºF to ambient
- Inlet flow 60 lbₘ/s / Exhaust to ambient or 26 in-hg
Tip Clearance System

- 4 rub probes at each station used for tip clearance calibration/alignment
- $\varepsilon/b = 2\%$ (0.012") design tip clearance, no step in flowpath at impeller/diffuser interface

Tip Clearance Variations @ $N_c = 100\%$

$\Delta \varepsilon/b$ of 0.5%, $\rightarrow$ 0.12 pt. impact on $\eta_{tt}$
Diffuser LE and “Rake” Instrumentation

- **Vane Leading Edge (2.4)**
  - Two vanes with 7 Kiel head $p_0$ ports
  - Key measurements for impeller and diffuser performance

- **Vane Trailing Edge (2.7)**
  - 6 locations resolve one main-to-main diffuser passage
  - Miniature Cobras at immersions of 15-85%, calibrated for $\alpha$ and $p_0$
Surveys
3-Port Cobra Probe

- Vaneless Space (2.2) & Diffuser Exit (2.7)
  - Traversable spanwise, manually aligned to flow
  - Calibrated to M=0.84 (Cal. Facility limit)
EGV Exit/Stage Rating (Station 3)

- 12 Rakes indexed to resolve one main-to-main diffuser pitch
- Kiel head $p_0$ and $T_0$ ports on area centroids
- 3 adjacent EGVs have LE Kiel head $p_0$ (25-75% span)
Stage and Subcomponent Results

- Compressor Maps
- Design point performance - comparison of measured vs. predicted
- Representative subcomponent measurements at $N_c = 100\%$
Stage Pressure Ratio vs. Inlet Corrected Mass Flow Rate

Total Pressure Ratio, $P_{0,3.0}/P_{0,0}$

Inlet Corrected Mass Flow Rate, $lb_{m}/s$

Design Point
Stall Boundary
3.0 lb$_{m}$/s op line

70%
75%
85%
90%
95%
100%
105%
Efficiency vs. Inlet Corrected Mass Flow Rate

- Polytropic
- Adiabatic

Design Intent

Efficiency vs. Inlet Corrected Mass Flow Rate, lbm/s

- 70%
- 75%
- 85%
- 90%
- 95%
- 100%
- 105%
# Measured vs. Predicted Performance

($N_c = 100\%$, $\dot{m}_{c,ex} = 3.0$ lbm/s, design tip clearance)

<table>
<thead>
<tr>
<th>Metric</th>
<th>Design Goal</th>
<th>Rig Scale Design Intent $p_{0,0}=14.7$ psia</th>
<th>Rig Scale Design Intent $p_{0,0}=11$ psia</th>
<th>Measured $p_{0,0}=11$ psia ± Uncertainty (95% Confidence)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure ratio, $p_{0,3}/p_{0,0}$</td>
<td>4.85</td>
<td>4.80</td>
<td>4.68 ± 0.0074</td>
<td></td>
</tr>
<tr>
<td>Inlet flow rate, $\dot{m}_{c,\text{in}}, \text{lb}m/s$</td>
<td>11.2</td>
<td>11.1</td>
<td>10.85 ± 0.1</td>
<td></td>
</tr>
<tr>
<td>Exit flow rate, $\dot{m}_{c,\text{ex}}, \text{lb}m/s$</td>
<td>2.1 &lt; $\dot{m}_{c,\text{ex}}$ &lt; 3.1</td>
<td>2.98</td>
<td>2.98</td>
<td>2.98</td>
</tr>
<tr>
<td>Adiabatic efficiency, $\eta_{tt}$, %</td>
<td>0.862</td>
<td>0.8495</td>
<td>0.822 ± 0.011</td>
<td></td>
</tr>
<tr>
<td>Polytropic efficiency, $\eta_{p,tt}$, %</td>
<td>≥ 0.88</td>
<td>0.888</td>
<td>0.879</td>
<td>0.855</td>
</tr>
<tr>
<td>Adiabatic, total pressure to static pressure, $\eta_{ts}$, %</td>
<td>0.852</td>
<td>0.8396</td>
<td>0.805</td>
<td></td>
</tr>
<tr>
<td>Exit Mach number, $M_{\text{ex}}$</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
<td>0.18</td>
</tr>
<tr>
<td>Exit flow angle, $\alpha_{\text{ex}}$, deg</td>
<td>15°</td>
<td>14°</td>
<td>14°</td>
<td>34.3°</td>
</tr>
<tr>
<td>Stability Margin, SM, %</td>
<td>13</td>
<td>12</td>
<td>12</td>
<td>7.5</td>
</tr>
<tr>
<td>Work factor</td>
<td>$0.60 &lt; \Delta H_0/U_2^2 &lt; 0.75$</td>
<td>0.7905</td>
<td>0.793</td>
<td>0.81</td>
</tr>
<tr>
<td>Diameter ratio $D_{\text{max}}/D_2$ ≤ 1.45</td>
<td>1.45</td>
<td>1.45</td>
<td>1.45</td>
<td></td>
</tr>
</tbody>
</table>

$\Delta H_0 = H_0 - H_2$, $H_0 = H_2 + \frac{1}{2} \dot{m}_{c,\text{ex}} U_2^2$. 

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$\Delta H_0/U_2^2$ is the specific enthalpy drop across the nozzle.  

$H_0$ and $H_2$ are the stagnation enthalpies at the nozzle entry and exit, respectively.  

$U_2$ is the exit velocity.  

$\dot{m}_{c,\text{ex}}$ is the mass flow rate at the exit.  

$D_{\text{max}}/D_2$ is the ratio of the maximum diameter of the nozzle to the throat diameter.  

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$N_c$ is the nozzle compression ratio.  

$\dot{m}_{c,\text{ex}}$ is the exit mass flow rate.  

$\eta_{tt}$ is the adiabatic efficiency.  

$\eta_{p,tt}$ is the polytropic efficiency.  

$\eta_{ts}$ is the adiabatic, total pressure to static pressure efficiency.  

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The table shows the measured and predicted performance metrics for the nozzle under different conditions. The predicted performance is based on design intent, with $p_{0,0}$ representing the static pressure at the nozzle entry. The measured performance is presented with uncertainty bounds at a 95% confidence level. The table includes metrics such as pressure ratio, flow rates, efficiencies, Mach number, flow angles, and stability margin, among others.
Impeller Exit (2.2) and Diffuser Vane LE (2.4)  
\( (N_c = 100\%, \dot{m}_{c,ex} = 3.0 \text{ lbm/s}) \)

- Measured swirl angle in relatively good agreement

Vane to vane agreement very good
Vane LE and CFD in good agreement
Probe \( p_0 \) (at 2.2) lower than vane LE, probe does not adequately resolve the pressure flow field
Probe (2.2 vaneless space) data only used qualitatively

\( 100\% N_c \)

\( \text{Local } p_{0,2.2}(z)/p_{0,0} \)

\( \text{Fraction of span from hub} \)

\( \text{Swirl angle } \alpha_{2.2}, \text{ deg.} \)

\( \text{Fraction of span from hub} \)
Diffuser Exit Probe Survey Data (2.7)

\( (N_c = 100\%, \ \dot{m}_{c,ex} = 3.0 \text{ lb}_m/\text{s}) \)

### Flow Angle, Deg.

<table>
<thead>
<tr>
<th>Flow Angle</th>
<th>60</th>
<th>68</th>
<th>76</th>
<th>80</th>
<th>84</th>
<th>92</th>
</tr>
</thead>
</table>

### TE Mean Camber Angle
- Main = 51 deg
- Splitter = 52 deg

### % Pitch, Main to Main

\[ \Omega \]

### % Span

- Hub to Tip

#### % Span Hub to Tip

- 0%
- 100%

#### PS

- main

#### SS

- splitter

- main
Diffuser Exit Survey Results vs. Operating Condition ($N_c = 100\%$, Choke, Design, Near-Stall)

- Flow redistributes as stage is throttled
- High swirl angles at SS main vane could indicate separated flow
Pressure Contours at Stations 2.7, 2.8, 3.0

\( N_c = 100\%, \; m_{c,ex} = 3.0 \text{ lb}_m/\text{s} \)
Diffuser Vanes Loading Diagrams-Shroud
Static Pressures ($N_c=100$, near design point CFD)

- Overall pressure rise lower than predicted
- Negative loading on splitter indicates operating at large negative incidence vs. lightly loaded design intent
Stage and Impeller Adiabatic Efficiency

- Impeller CFD
- Stage CFD

Impeller and stage efficiency, %

Inlet corrected flow, lbm/s

- Impeller (Sta. 0 to 2.4)
- Stage (Sta. 0 to 3)
- Impeller - pre-test CFD
- Stage - pre-test CFD

100% Nc
Diffusion System Static Pressure Rise

\[ c_p = \left( \frac{\bar{p}_{ex} - \bar{p}_{in}}{\bar{p}_{0,in} - \bar{p}_{in}} \right) \]

- Static pressure rise increases from choke to stall (Diffuser and Diffuser+Bend+EGV)
- Static pressure rise across 90° bend and EGV is relatively constant
Test results show a minimum loss at a lower flow rate than design intent.
Diffuser Corrected Flow Characteristic

Diffuser processes flow as per design intent \( \dot{m}_{c,ex} = 3.0 \text{ lb}_m/\text{s} \)

- NASA HECC 12 mil - coarse grid - mixing-plane
- NASA HECC 12 mil - fine grid - mixing plane
- HECC test data

Impeller exit corrected flow, \( \text{lb}_m/\text{s} \)

Stage exit corrected, \( \text{lb}_m/\text{s} \)

Design-intent

100% \( N_c \)
Impeller Corrected Flow Characteristic

- Impeller is operating at a lower $\dot{m}_{c,\text{in}}$ at the design intent impeller exit corrected flow rate.

**Design-intent** ($\dot{m}_{c,\text{ex}} = 3 \text{ lb}_m/\text{s}$)

**Data**

**CFD**

100% $N_c$
Summary

- Aerodynamic performance of an advanced, compact, high work-factor centrifugal compressor stage was presented.
- Stage performance and stability were lower than design intent
  - Adiabatic Efficiency by 2.75 pts., mass flow by 2.25%, and Stability Margin by 4.5 pts.
- Differences in predicted and measured impeller efficiency, impeller flow characteristics, and diffuser loss buckets were observed.
- Root-cause-analysis of the performance shortfall was initiated within the NRA contract. Analyses continue with intent to guide future design efforts.

Comprehensive data sets and geometry to be made publically available.
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