NASA HECC Geometry and Performance Review Part I: Validation of a Computational Model for the Vaneless Diffuser Configuration with As-Manufactured Impeller Geometry

Gregorio Robles Vega, Alec J. Bosshart, Michael Ni and Ron-Ho Ni
AeroDynamic Solutions Inc

Herbert M. Harrison and Tammy Nguyen-Huynh
NASA Glenn Research Center
Outline

● Overview of Multipart Investigation
● HECC Description
● Geometry Description
● Modeling Approach
● Comparison against Data
● Observations
● Conclusions
Overview of Multipart Investigation

**Part I: Validation of a Computational Model for the Vaneless Diffuser Configuration with As-Manufactured Impeller Geometry**
- Description of the modeling approach used for all three parts
- Validate the model using the As-Manufactured impeller geometry against experimental data

**Part II: Geometric Differences between the As-Manufactured and Design-Intent Impeller Geometry and their Effects on the Vaneless Diffuser Configuration Performance**
- Comparison of predicted performance with both the As-Manufactured and Design-Intent impeller geometries
- Investigate the differences between the two geometries
- Explore the performance effect of the various geometry differences

**Part III: A Numerical and Experimental Investigation of Tip Clearance Effects on the Vaneless Diffuser Configuration**
- Introduce a new set of experimental data at various tip clearances
- Investigate the performance effects due to tip clearance using both CFD and experimental data
NASA High Efficiency Centrifugal Compressor (HECC)

- The HECC was designed in a joint project between NASA and UTRC
- Design Objectives:
  - Increase efficiency, work factor, and stall margin
  - Reduce maximum diameter
  - Maintain same rotational speed as CC3
- Design Approach:
  - Impeller blade lean, bow, and leading edge/trailing edge shaping
  - Diffuser fillets, elliptical leading and trailing edges and splitter vanes
- Design Outcome:
  - Pre-test CFD design assessment was promising and achieved goals relative to CC3

NASA High Efficiency Centrifugal Compressor (HECC)

- **Experimental Testing Outcome:**
  - Compressor fell short of the program goals
  - Both pre-test and post-test CFD tended to overestimate performance predictions and an adequate explanation for the reason had previously not been found

- **Follow-on efforts:**
  - Vaneless diffuser design and testing
    - Simplified problem, focused on impeller performance
    - Tested in 2018
    - Detailed experimental data and CAD were made publicly available in 2023
  - Same impeller as vaned diffuser configuration


Impeller Geometry Description: Design-Intent

- Until the present investigation only one publicly available impeller geometry was available
  - This impeller geometry definition was provided in the design report by Medic G. et al. [2] in 2017
    - 11 spanwise sections uniformly distributed along the span at increments of 10% span in X, RTheta, R coordinates
    - Did not include the fillets in the section data
  - This impeller geometry will be referred to as the Design-Intent
  - Further discussion of this impeller geometry will take place in Part II

---

Impeller Geometry Description: As-Manufactured

- As part of the present work new section data was extracted from the CAD model used for manufacturing
  - Fillets and cut-off trailing edge were included in sections
  - A verification was made to compare the CAD model matched the manufactured impeller in the lab
    - Scan confirmed a match within a maximum tolerance of +/- 0.005 in
  - This impeller geometry will be referred to as the As-Manufactured
  - Part I and Part III will use this geometry in the models
  - One of the new findings in this investigation is the differences between the Design-Intent and As-Manufactured which will be the focus of Part II
Modeling Approach

- Steady RANS
- Blade Count: 15 blades
- Rotational Speed: 21789 rpm
  - Corrected design speed
- Simulation Domain:
  - Inlet Duct | Stationary Frame
  - Impeller | Rotating Frame
  - Vaneless Diffuser | Stationary Frame
  - Exit Duct | Stationary Frame
- Tip clearance: 12 mils
- Adiabatic walls
- Fillets: Built into As-Manufactured section data extracted from CAD
- Aerodynamic Conditions
  - Standard Day conditions
    - PT=14.7psi | TT=518.7R
Meshing:

- Mesh generator: Code Wand
  - Automated turbomachinery structured multiblock mesh generator
- Structured multiblock with tip cap clearance mesh
- Wall integration with y+ approximately 1
- A mesh family consisting of four mesh levels was created by increasing the number of planes uniformly in all directions
  - Spanwise planes:
    - 37 planes - 49 planes
  - Tip clearance spanwise planes:
    - 9 planes - 21 planes
  - Points around main blade:
    - 233 points - 257 points
  - Points around the splitter blade:
    - 161 points - 177 points

<table>
<thead>
<tr>
<th>Mesh Level</th>
<th>Inlet Duct</th>
<th>Impeller</th>
<th>Vaneless Diffuser</th>
<th>Exit Duct</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse</td>
<td>132,349</td>
<td>442,072</td>
<td>117,845</td>
<td>74,333</td>
</tr>
<tr>
<td></td>
<td>124,416</td>
<td>383,232</td>
<td>110,592</td>
<td>69,120</td>
</tr>
<tr>
<td>Medium</td>
<td>242,433</td>
<td>706,308</td>
<td>218,489</td>
<td>146,657</td>
</tr>
<tr>
<td></td>
<td>230,400</td>
<td>632,320</td>
<td>207,360</td>
<td>138,240</td>
</tr>
<tr>
<td>Fine</td>
<td>388,485</td>
<td>1,036,748</td>
<td>353,565</td>
<td>146,657</td>
</tr>
<tr>
<td></td>
<td>371,712</td>
<td>945,792</td>
<td>337,920</td>
<td>138,240</td>
</tr>
<tr>
<td>Very Fine</td>
<td>537,089</td>
<td>1,404,732</td>
<td>492,793</td>
<td>248,805</td>
</tr>
<tr>
<td></td>
<td>516,096</td>
<td>1,297,152</td>
<td>473,088</td>
<td>236,544</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mesh Level</th>
<th>Inlet Duct</th>
<th>Impeller</th>
<th>Vaneless Diffuser</th>
<th>Exit Duct</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>766,599</td>
<td>687,360</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medium</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1,313,887</td>
<td>1,208,320</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fine</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2,027,603</td>
<td>1,891,968</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Very Fine</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2,794,519</td>
<td>2,630,400</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Copyright © Aerodynamic Solutions Inc 2024
Solver Settings

- Solver:
  - Solver: Code Leo
    - GPU accelerated, compressible, density based, explicit-time marching using the Ni-Scheme distribution formula finite volume approximation that is 2nd order accurate in both time and space
  - Turbulence model: Wilcox kw 98
  - Variable gamma
  - Speedlines were generated using an automated iterative tool that moves the simulations towards stall with consecutively smaller backpressure changes
    - Tries to within 0.1% of numerical stall back pressure
Mesh Convergence Study

Fine level was deemed to have reached mesh convergence
Mesh Convergence Study: Fine Convergence

- Fine
- Convergence Tail

Stage Adiabatic Efficiency, %

Inlet Corrected Flow Rate, lb/hr/seg

Stage Adiabatic Efficiency, %

Iteration
Mesh: Fine | 2.0M Nodes | 1.9M Elements

- Completion time:
  - Laptop with 1 Nvidia RTX A5000 mobile GPU
    - Single point convergence time: ~7min 42sec
    - 8-points speedline run serially: ~1hr
  - 8 Nvidia V100 GPUs
    - Four cases in parallel: ~7min 16sec
    - 8-point speedline: ~14min 30sec
Experimental Data

- Measurement stations:
  - Station 3 | Impeller exit
  - Station 7 | Stage exit
- Baseline metal inlet configuration experimental data measured in 2018
- Total temperature rakes at the impeller exit failed early in the experimental test campaign, thus they are not available for comparison
- Experimental averaging approach: Area averaged
- Simulation averaging approach: Mass averaged
  - A comparison was made between area and mass averaged results
  - Differences were deemed small enough to proceed

100% Speed Impeller Exit Performance

- Speedline resolved numerical stall within 0.05% backpressure change
  - 14-points converged
  - Speedline completion: ~1hr 48min
- Overall simulations compare well with data
- Simulations showed good agreement between data and simulation at higher flow rates
  - At the design flow rate (11lb$_m$/s) TPR only varied by 0.024 (0.46% error)
- Towards stall the simulations under predicted the impeller pressure rise relative to data
  - At inlet flow rate ~9.44lb$_m$/s TPR varied by 0.063 (1.17% error)
- Stall margin prediction compared well to data
  - Simulation: 32.7% | Data: 30.8% | 1.9% difference
100% Speed Stage Performance

- Stage TPR: Data=5.091 | Leo=5.115 | Percent error=1.90%
- Stage TTR: Data=1.637 | Leo=1.648 | Percent error=0.69%
- Stage Efficiency: Data=83.81% | Leo=84.09% | Percent error=0.33%
- Stage Stall Margin: Data= 28.7% | Leo=30.1% | Difference= 1.4%
Compressor map consists of 35 points
- Completion time: Laptop RTX A5000 ~4hr 30min | 8 V100 ~1hr 5min
- At both 95% and 90% speeds the simulations compared well with the data
- The numerical stall prediction from the steady simulations compares well with the data
- The modeling approach used in all parts of the investigation was deemed validated compared to the 1D data
Spanwise Profiles: Impeller Exit Total Pressure Ratio

- Data was measured at two different circumferential stations
- Simulations show excellent agreement in both shape and magnitude at the impeller exit
  - Shape changes accordingly as simulation moves from choke to stall
  - Observed differences are of a similar magnitude as differences between the measurements at the two probes
Stage Spanwise Profiles

- Data was measured at three different circumferential stations.
- Stage spanwise profiles show good agreement on magnitude.
- Differences are observed in the shape:
  - CFD shows a bias towards shroud while data shows the opposite bias.
  - Hints at some missing loss mechanism in experiment that is not present in model.
- Overall, the models magnitude prediction was deemed validated for spanwise profiles at the stage exit.
Spanwise Profiles: Impeller Exit Total Pressure Ratio

- As a last step in the validation process, spanwise comparisons were made at off-design conditions.
- Model adequately predicts both magnitude and shape at various speeds for the impeller exit.
Contour Observations
Loading Observations

70% Span | Design Point | 100% Speed

Static Pressure, psi

Meridional Distance, %

70% Span | Design Point | 100% Speed

Isentropic Mach Number

Meridional Distance, %
Loading Observations

![Graphs showing loading observations for different blade sections at 100% speed]

Design Point | 100% Speed

- Static Pressure, psi
- Meridional Distance, %

- 30% MainBlade
- 30% SplitterBlade
- 50% MainBlade
- 50% SplitterBlade
- 70% MainBlade
- 70% SplitterBlade

- Isentropic Mach Number
- Meridional Distance, %

- 30% MainBlade
- 30% SplitterBlade
- 50% MainBlade
- 50% SplitterBlade
- 70% MainBlade
- 70% SplitterBlade
Part II: As-Manufactured vs Design-Intent
Vaned Diffuser Configuration: As-Manufactured vs Design-Intent
Conclusions

- An extensive validation of the HECC vaneless diffuser model to data has been conducted
  - 35-point As-Manufactured compressor map completed
  - ~4hr 30min on a laptop and 1hr and 5min on a 8V100 system
- 1D and spanwise profiles comparison show the model can reasonably predict the measured performance
- Loading and contours profiles showed a non-ideal performance in the As-Manufactured impeller geometry
- Design-Intent predicted significantly higher performance than As-Manufactured for both vaneless diffuser and vaned diffuser configurations
- Why are Design-Intent and As-Manufactured performing differently?