A New Integrated-Aerodynamic-Design Program of Multistage Axial Compressor MACADS ver.1.2

Part 1 : Meanline to 3D Design

Dr. Justin Jongsik Oh
Motivation & Objectives

- In general, the process of aerodynamic design of a multistage axial-flow compressor gets much more complicated than that of centrifugal compressors mostly because of,
  - Multiple stages, first of all, implying two blade rows per stage and plus extra rows such as IGV and/or EGV
  - Longer blade spans, requiring optimized blade design along the span (from the hub to the shroud)
  - Stage matching among front, mid and rear stage blocks, required to be a good design
  - Variable stator schedules of VIGV and VSVs, required to secure operability per operating speed
  - Interstage bleed schedules, for startup, turbine cooling and/or customer needs, per operating speed

- Even compared to that of a multistage axial-flow turbine, it is still more complicated requiring much longer design lead time and more resources, simply because of a significantly higher number of stages.

- As for public or commercial design programs, most of them are independently placed to work over the boundary users can reach out to, even with their capabilities short of expectation.

- Author has been dreaming of a design suite, which will integrate,
  - Meanline design
  - Meanline analysis
  - Compressor map → Cycle map predicted by meanline analysis
  - Throughflow design
  - Throughflow analysis → It will **not** be pursued because of poor convergences of the streamline curvature method at off-design
  - Blade row 3D design
  - Multistage 3D CFD effective → A simplified version of 3D multistage Navier-Stokes CFD, in order to be an efficient and rapid design tool, replacing the old-fashioned Throughflow Analysis
## Meanline Design – Input

### Design specifications, identical to NASA CR 165558 (1982)
- Speed and Flow
- PR and ETA (target)
- 10 stages
- R1 hub-to-tip radius ratio
- R1 prewhirl
- Aspect ratios
- CMD (but NASA has CID in rear stages)

### Main outputs are all stage geometry

### Very challenging efficiency (ETA) target with 10 stages for PR = 23

### Two unit system options
- US (inch, psi, °F, lbm, ft/s, ft lbf/lbm/°F)
- SI (mm, kPa, °K, kg, m/s, J/kg/°K)

### Project Title: Sample Design of a 10-stage Highly-loaded Axial Compressor with NASA CR 165558 (1982)

<table>
<thead>
<tr>
<th>Design Rotational Speed [rpm]</th>
<th>12303</th>
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</thead>
<tbody>
<tr>
<td>Overall Pressure Ratio (Total-to-Total) Target</td>
<td>23</td>
</tr>
<tr>
<td>Design Mass Flow Rate [lbm/s]</td>
<td>120,000</td>
</tr>
<tr>
<td>Total Number of Stages</td>
<td>10</td>
</tr>
<tr>
<td>Isentropic Efficiency (Total-to-Total) Target [%]</td>
<td>86</td>
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</tbody>
</table>

### Design specifications
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Meanline Design – Output

- My loss models say an 82% isentropic efficiency might be realistic from 10 stages.
- Flowpath diameters very close to NASA designs, despite incomplete CMD from NASA

NASA design
13.81 inch

7.01 inch

No IGV or EGV design yet

11.56 inch

10.78 inch
Meanline Design – Output

**Meanline Design of Multistage Axial-Flow Compressor**

Developed and Copyright by Dr. Justin Jongeik Oh

Sample Design of a 10-stage Highly-Loaded Axial Compressor with NASA CFD

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**Preliminary Design Results**

- **1ST-STAGE Tip Radius:** 351.49 mm
- **2ND-STAGE Tip Radius:** 313.38 mm
- **3RD-STAGE Tip Radius:** 265.37 mm
- **4TH-STAGE Tip Radius:** 210.26 mm
- **5TH-STAGE Tip Radius:** 157.62 mm
- **6TH-STAGE Tip Radius:** 112.27 mm
- **7TH-STAGE Tip Radius:** 70.57 mm
- **8TH-STAGE Tip Radius:** 39.09 mm
- **9TH-STAGE Tip Radius:** 22.52 mm
- **10TH-STAGE Tip Radius:** 16.48 mm
- **Total Temperature at Final Exit:** 779.67 K

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**Final Optimized Meanline Design Results**

- **Stage Number:** 1
- **Rotor Tip Radius:** 351.10 mm
- **Rotor Tip Radius INC:** 1.78 mm
- **Rotor Tip Radius OUT:** 349.35 mm
- **Rotor Tip Radius OUT INC:** 1.78 mm
- **Rotor Tip Radius OUT TIP:** 349.33 mm
- **Rotor Tip Radius OUT TIP INC:** 1.78 mm
- **Rotor Tip Radius OUT TIP 2:** 349.31 mm
- **Rotor Tip Radius OUT TIP 2 INC:** 1.78 mm
- **Rotor Tip Radius OUT TIP 3:** 349.29 mm
- **Rotor Tip Radius OUT TIP 3 INC:** 1.78 mm
- **Rotor Tip Radius OUT TIP 4:** 349.27 mm
- **Rotor Tip Radius OUT TIP 4 INC:** 1.78 mm
- **Rotor Tip Radius OUT TIP 5:** 349.25 mm
- **Rotor Tip Radius OUT TIP 5 INC:** 1.78 mm
- **Rotor Tip Radius OUT TIP 6:** 349.23 mm
- **Rotor Tip Radius OUT TIP 6 INC:** 1.78 mm
- **Rotor Tip Radius OUT TIP 7:** 349.21 mm
- **Rotor Tip Radius OUT TIP 7 INC:** 1.78 mm
- **Rotor Tip Radius OUT TIP 8:** 349.19 mm
- **Rotor Tip Radius OUT TIP 8 INC:** 1.78 mm
- **Rotor Tip Radius OUT TIP 9:** 349.17 mm
- **Rotor Tip Radius OUT TIP 9 INC:** 1.78 mm
- **Rotor Tip Radius OUT TIP 10:** 349.15 mm
- **Rotor Tip Radius OUT TIP 10 INC:** 1.78 mm

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**Notes**

- Preliminary Design Results
- Final Optimized Meanline Design Results
- Data for future reference
Meanline Design – Output (when an optimal stage number is wanted)

85.2% efficiency will be feasible with total 14 stages according to my loss models, but it could be improved to 86% target in the detailed design steps.
Meanline Analysis

- All of stage geometry of meanline design outputs will be transferred as inputs.
- Stage-by-stage aerodynamic performance will be analysed from deeply choked flow to surge, from low to high speeds, to create a complete compressor map.
- VIGV (Variable IGV) and VSV (Variable Stator Vane) reset cases are included from reset schedule inputs varying with speeds.
- Interstage bleed cases are included from bleed % schedule inputs varying with speeds.
Meanline Analysis – Inputs (with no VSV resets and no interstage bleed)

Directly loaded from meanline design outputs,
Meanline Analysis – Outputs (Compressor Map with no VSV reset)

Surge-line kinks at lower speeds, preventing a smooth startup or shutdown.

Stagewise performance at a point (with a circle) on the map, selected by users.

A little better performance at DP was predicted.
Stage performance outputs still with SI units, for now
TAD-TP-2020-2

Meanline Analysis – Input (with VSV resets and interstage bleed)

- VIGV and VSV reset schedules are from NASA CR 165558.
- Interstage bleed % schedules are assumed as:
  - 10% bleed at S7 exit for a smooth startup and shutdown
  - 5% bleed at S5 exit for both turbine cooling and custom needs
Meanline Analysis – Output (Compressor Map with VSV resets and bleed)

A little reduced PR and ETA at DP due to interstage bleed.

Significantly enhanced operability and efficiency at lower speeds, thanks to VSV resets and interstage bleed.

Stage 4 efficiency is now down near DP, due to stator incidence mismatch.

R5 shows a large flow deviation near DP.

A need for EGV.
Operability at 75% Speed near PR = 8 as an example

Compared with Slide 10, flow is significantly shifted to the left, staying in a stable PR slope, thanks to VSV resets mostly.

A much higher efficiency

Acceptable D-factor limits
Throughflow Design

- Based on Meanline Design & Analysis outputs defined at RMS, the key parameters of blade geometry in the spanwise direction are determined with empirical loss and deviation modelings considered.
- Row-by-row the simple radial equilibrium equation is iteratively solved until meeting overall performance targets of PR and ETA, through changing those key parameters of geometry.
Initially no IGV or EGV, but they will be added if wanted.
# Throughflow Design – Initial Output

### Axial Compressor Throughflow Design

Developed and Copyrighted by Dr. Justin Jeong on 5/6/2020

# Output View

**Stage 1: Rotor with 57 Blades of Aspect Ratio 1.149**

<table>
<thead>
<tr>
<th>Span</th>
<th>R-inlet</th>
<th>U</th>
<th>Cml</th>
<th>Cml</th>
<th>Cu1</th>
<th>Cu2</th>
<th>M1</th>
<th>Alph1</th>
<th>Beta1</th>
<th>LER</th>
<th>TER</th>
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<tbody>
<tr>
<td>0.000</td>
<td>268.44</td>
<td>180.0</td>
<td>90.6</td>
<td>56.44</td>
<td>46.64</td>
<td>1.808</td>
<td>5.645</td>
<td>0.166</td>
<td>0.130</td>
<td></td>
<td></td>
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<tr>
<td>0.125</td>
<td>264.30</td>
<td>190.33</td>
<td>91.16</td>
<td>55.02</td>
<td>56.99</td>
<td>1.729</td>
<td>5.777</td>
<td>0.197</td>
<td>0.121</td>
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<tr>
<td>0.250</td>
<td>260.16</td>
<td>200.66</td>
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<td>1.750</td>
<td>5.903</td>
<td>0.150</td>
<td>0.132</td>
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**Stage 2: Stator with 76 Blades of Aspect Ratio 1.440**

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<tr>
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<th>Cml</th>
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<th>M1</th>
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<tr>
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<td>320.58</td>
<td>170.58</td>
<td>80.46</td>
<td>56.62</td>
<td>40.71</td>
<td>0.926</td>
<td>2.052</td>
<td>0.126</td>
<td>0.147</td>
<td></td>
<td></td>
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<tr>
<td>0.125</td>
<td>316.07</td>
<td>180.13</td>
<td>80.90</td>
<td>56.62</td>
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<td>0.926</td>
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<tr>
<td>0.250</td>
<td>311.53</td>
<td>190.66</td>
<td>81.34</td>
<td>56.62</td>
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<td>0.926</td>
<td>2.052</td>
<td>0.126</td>
<td>0.147</td>
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### Stage 3: Rotor with 49 Blades of Aspect Ratio 1.071

<table>
<thead>
<tr>
<th>Span</th>
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<th>Cml</th>
<th>Cml</th>
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<th>M1</th>
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<tr>
<td>0.000</td>
<td>303.90</td>
<td>170.58</td>
<td>80.46</td>
<td>56.62</td>
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<td>0.926</td>
<td>2.052</td>
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<td>0.125</td>
<td>309.35</td>
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<td>0.926</td>
<td>2.052</td>
<td>0.126</td>
<td>0.147</td>
<td></td>
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</tr>
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</table>

**Note:** Inlet or Exit is not considered in the program, but for IGV you can control prewhirl and inlet total pressure.
IGV Added – Initial Design

 MACADS ver:1.2 - Multistage Axial Compressor Aerodynamic Design Suite (Developed by TurboAeroDesign.com)

Module File Edit CFD Tool Help
-4.003353E+00 3.212217E Program Setup
Add IGV or EGV (an initial basic one) Map Flow Variables
R1 R2 R3 R4 R5

IGV
S1 S2 S3

Throughflow Design Flowpath
Sample Design of a 10-stage radial compressor

Add IGV or EGV as an initial basic profile

- IGV
- EGV

Chord on the hub
Chord on the shroud
Blade Inlet Metal Angle on the hub
Blade Inlet Metal Angle on the shroud
Blade Exit Metal Angle on the hub
Blade Exit Metal Angle on the shroud
max Thickness / Chord on the hub
max Thickness / Chord on the shroud
Solidity on the hub

50 % of Chord on the hub of a Neighboring Row
130 % of Chord on the hub of itself
0 deg, from a meridional reference (*)
0 deg, from a meridional reference (*)
20 deg, from a meridional reference (*)
10 deg, from a meridional reference (*)
5 %
10 %
1.5

(*) Negative angle acts against the direction of rotor rotation. Both hub and shroud diameters will be assumed as those of LE or TE of a neighboring row. Geometry needs a refined design in the next steps.

Cancel Apply

5/6/2020 TurboAeroDesign.com
EGV Added – Initial Design

Engine Axis

5/6/2020

TurboAeroDesign.com
Blade 4 corner points can be changed in BLADE3DR mode which will be in the next steps.
Axial Gaps – Bleed Ports

- 10% bleed at S7 exit for a smooth startup and shutdown
- 5% bleed at S5 exit for both turbine cooling and custom needs
Blade 3D Geometry Design per Row

It will call BLADE3DR (ver.5.1B) to join which is a stand-alone design program of a single blade-row 3D design.
Blade 3D Geometry Design – Stator of the 2\textsuperscript{nd} stage, for example
Top Menu of BLADE3DR ver.5.1B
Total 5 types of flow analysis in a single row are available.

CFD-NSC is now under construction.
Geometry Edit – Example of S02 : Hub Thickness

- Full blade means a normal blade in axial-flow machines
- Splitter blades refer to tangential splitters in radial-flow machines. (Max. 3 splitter blades available)

- Total 21 spanwise sections are created by default, but the number can be increased up to max. 51 sections with arbitrary spanwise locations.

![Blade Design Interface](image-url)
Geometry Edit – Example of S02 : Hub Thickness

A single large screen for any edits is what author has been looking for at aerodynamic design tasks.

Showing all of 3 spans, i.e., hub, midspan and shroud at any edits is also what author has been looking for at aerodynamic design tasks.
Geometry Edit – Example of S02 : Spanwise Beta1b

Spanwise Edit of Blade inlet metal angles, for example, which is also what author has been looking for at aerodynamic design tasks.

Very critical in controlling optimal incidence profiles.
Geometry Edit – Example of S02: Blade Sweep and/or Lean

Edit Blade Stacking Curves

Stacking Axial Blade in Spanwise Sections

1. Stacking Point per span
   - CG (Center of Gravity, or Centroid)
   - Leading edge
   - Trailing edge
   - Mid Throat
   - Point on camberline at %Axial from LE

2. Axial Stacking Curve
   (Axial-coordinate of stacking point per span will be moved as specified, but anchored at Hub)
   - Move to Hub-Axial of stacking point
   - Custom Curve
   - None

3. Tangential Stacking Curve
   (Theta-coordinate of stacking point per span will be moved as specified, but anchored at Hub)
   - Move to Hub-THETA of stacking point
   - Custom Curve
   - None

Note that the custom axial stacking curve will build the meridional sweep, while the custom tangential stacking curve will do the tangential lean.
Note that if "None" is selected for both (2) and (3), no stacking action will be made, no matter what is chosen in (1).
Geometry Edit – Example of S02 : Blade Sweep and/or Lean

Forward Sweep

Tangential Lean
Geometry Edit – Example of S02 : Throat Area

Throat area estimated
Geometry Edit – Example of S02 : Restagger Rotation (VSV)
Geometry Edit – Example of S02 : Restagger Rotation (VSV)
Updated rows compared to Slide no.20

NASA CR 165558 Final Design Flowpath (ver.1)
- Axial length shorter than my design → Very aggressive design
- EGV is not shown
- CID design in the rear stage block
- It will be hard to say which design would be better, because this first design failed to achieve design goals from rig tests.
In Part 2, the followings will be covered:

- **Multistage CFD effective**
  - Multistage 3D compressible Navier-Stokes flow analysis
    - But simplified to be effectively utilized in MACADS
  - Checking overall compressor performance at design point
  - Investigating interstage performance details
  - Investigating row-by-row matching of aerodynamics
  - Finding optimal incidence and deviation profiles per row
  - Off-design flow and speed performance