Direct Integration of Axial Turbomachinery Preliminary Aerodynamic Design Calculations in Engine Performance Component Models

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**DEMOS**

**Developing advanced Engine Multi-disciplinary Optimization Simulations**
**DEMOS Objective**

The project DEMOS objective is to develop a modular, flexible and extensible multi-disciplinary framework to undertake design space exploration and multidisciplinary optimization assessments of novel aircraft engine concepts:

- Development of advanced modelling and simulation tools for preliminary design studies of novel aircraft engine concepts
- Integration of tools and design processes under the same, commercial, and user-friendly modelling and simulation environment
Research State of the Art

Research tools in existence today:

- **Modular** and **iterative** philosophy (e.g. EDS\(^1\), TERA\(^2\))
- 0D, 1D models from **disparate sources** and/or **proprietary nature**
- **Expert-level user** to set-up the engine model and calculation sequence

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Scope of Paper

In the context of DEMOS project, existing performance models for axial-flow, multistage compressors and turbines:

Aerodynamic Design  Flowpath Sizing  Weight Estimation  Thermodynamic Performance  New Turbomachinery Components

Same modelling level

HBR GTF with bypass VAN

Multi-Point Design @TO, CR, ToC

PROOSIS Simulation Environment

- Performance requirements
- Aerodynamic constraints
- Mechanical constraints
- Thermal constraints
Modelling Tool

- Object-Oriented
- Steady State
- Transient
- Mixed-Fidelity
- Multi-Disciplinary
- Distributed
- Multi-Point Design
- Off-Design
- Test Analysis
- Diagnostics
- Sensitivity
- Optimization
- Deck Generation
- Version Control

PROOSIS (PRopulsion Object-Oriented SImulation Software)
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2. Aerodynamic Design & Flowpath Sizing
3. Validation Cases

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Summary & Conclusions
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Summary & Conclusions
Performance–Aerodynamics Integration

- **Consistent and single-step preliminary design procedure**
- No need for continuous data interchange between 0D and 1D
- Mathematical models @component and @engine level remain unchanged
- Same level of robustness and speed of execution as for 0D models
Aerodynamic Design & Flowpath Sizing

The aerodynamic design is accomplished through:

- **Stage-by-stage, mean-line** calculation with variable gas properties
- Possibility for different mean-line distributions
- Possibility to specify different flow coefficient ($\phi$), stage loading ($\psi$), and stage reaction ($\Lambda$) distributions to establish velocity triangles @ $D_{m}$; To establish flow quantities @ $D_{h}$ + @ $D_{t}$ the free vortex flow assumption is used
- Aerothermodynamic calculations accounting for compressor bleeds
- Aerothermodynamic turbine design integrated with row-by-row cooling capability

After the aerodynamic design has been completed and the stagewise $D_{h}$ + $D_{t}$ are known:

- Axial sizing of component stages is performed assuming linear distribution of first and last stage blade $AR$ and axial gapping and a simple geometrical concept\(^3\)
- Component overall flowpath geometry is established by axial superposition of component stages

✓ Both aerodynamic design + flowpath sizing use only a small number of physical and geometrical inputs

### Calculation of stagewise isentropic efficiency ($\eta$):

#### Losses methods

**Lewis’**⁴ method for compressor stages:

$$
\eta = 1 - \frac{1}{2\psi} \left( \zeta_R \left[ \phi^2 + \left( \Lambda + \frac{\psi}{2} \right)^2 \right] + \zeta_S \left[ \phi^2 + \left( 1 - \Lambda + \frac{\psi}{2} \right)^2 \right] \right)
$$

**Glassman’s**⁵ method for uncooled turbine stages:

$$
\eta_{\text{uncooled}} = \frac{1}{1 + \frac{1}{2} A\psi}
$$

#### Semi-empirical methods

**Glassman’s**⁶ method for compressor stages:

$$
\bar{f}(\text{PR}, \eta_p, \eta) = 0
$$

**Aungier’s**⁷ method for uncooled turbine stages:

$$
\eta_{\text{uncooled}} = \text{TF} \times \left[ \eta_{\text{optimum}} - K (\phi - \phi_{\text{optimum}})^2 \right]
$$

**Glassman’s**⁸ correction for cooled turbine stages:

$$
\eta_{\text{cooled}} = (1 - \delta_R m_R - \delta_S m_S) \times \eta_{\text{uncooled}}
$$

### Other ways to establish component overall efficiency:

- Directly imposed
- **Samuelsson et al.**’s⁹ method for overall polytropic efficiency ($\eta_p$) estimation:

$$
\eta_p = f \left( \text{Component Size}, \text{Entry Into Service Year}, \text{Reynolds Number}, \text{Stage Loading} \right)
$$

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Validation Cases

Compressor component

- NASA/GE E³ HP Compressor was used\textsuperscript{9,10}
- 10-Stage
- High-speed
- High-aerodynamic loading
- Efficiency goal: 85.7%

Turbine component

- NASA/GE E³ LP Turbine Block II Scaled Air-Model was used\textsuperscript{11}
- 5-Stage
- High-aerodynamic loading
- Measured efficiency: 92.0%


Compressor component

<table>
<thead>
<tr>
<th>Method</th>
<th>Calculated Efficiency</th>
<th>Relative Error from Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lewis (Losses)</td>
<td>85.01%</td>
<td>-0.81%</td>
</tr>
<tr>
<td>Glassman cur.</td>
<td>84.41%</td>
<td>-1.51%</td>
</tr>
<tr>
<td>Glassman adv.</td>
<td>86.51%</td>
<td>+0.95%</td>
</tr>
</tbody>
</table>

Turbine component

<table>
<thead>
<tr>
<th>Method</th>
<th>Calculated Efficiency</th>
<th>Relative Error from Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glassman (Losses)</td>
<td>91.38%</td>
<td>-0.68%</td>
</tr>
<tr>
<td>Aungier (TF=1)</td>
<td>89.02%</td>
<td>-3.24%</td>
</tr>
</tbody>
</table>

✓ Sufficient agreement, using existing turbomachinery components that have been through all the stages of the development course.
Application Example

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Summary & Conclusions
The HBR GTF Engine Model with Bypass VAN

1. Constant $D_h$
2. Constant $\psi$
3. Linear $\phi$
4. Specified $\alpha_1 \rightarrow \Lambda$
5. Losses method for $\eta$

- 1. Constant $D_m$
- 2. Specified stage $\Delta h_t$
- 3. Linear $\phi$
- 4. Specified $\alpha_1 \rightarrow \Lambda$
- 5. Losses method for $\eta$

- Linear $D_m$
- Constant $\psi$
- $\Lambda = 0.5$ (symmetrical velocity triangles)
- Aungier’s method for $\eta$

- $\eta_p = f(FPR)^{12}$

- ✓ 1_G_4_8_2_3
- ✓ Fixed fan diameter
- ✓ Fixed sFN @ToC
- ✓ Off-design performance from suitable maps scaled accordingly during design calculation

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The MPD Structure

**ENGINE MODEL** → **MULTI-POINT DESIGN (MPD)** → **DEFINE OPERATING POINTS** → **SELECT VARIABLES TO BE DESIGNED** → **FORMULATE CLOSURE EQUATIONS** → **SOLVE EXTENDED MATHEMATICAL PROBLEM**

**Mathematical model boundaries at every OP (e.g.):**
- Fuel mass flow rate (to match specified engine thrust) @ToC, TO, CR
- VAN % area change (to match VAN operability criterion) @ToC, TO, CR

**Component attributes at individual OPs (e.g.):**
- Scaling factors of all turbomachinery maps @ToC
- HPT cooling flow fractions for all blading rows @TO
- FN = Specified FN @ToC, TO, CR
- BPR, FPR, OPR, nPR = (Calculated or specified) BPR, FPR, OPR, nPR @ToC
- For compressors: $\eta_p = $ (Calculated or specified) $\eta_p$ @CR
- For turbines: $\eta = $ (Calculated or specified) $\eta$ @CR

ToC, TO, CR (set flight and ambient conditions)
Turbomachinery efficiencies $@CR$ are established through three different methods:

- **Method-1**: Aerodynamic design
- **Method-2**: Samuelsson et al.
- **Method-3**: Constant values

### Constraints

- **OPR**:
  - $\text{HPC CDT} @ToC \leq \text{CDT}_{\text{max}} = 950 \text{ K}$
  - $\text{HPC LSBH} \geq \text{LSBH}_{\text{min}} = 13 \text{ mm}$

- **BPR**:
  - $\text{TET} @ToC \leq \text{TET}_{\text{max}} = 1850 \text{ K}$

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<table>
<thead>
<tr>
<th>Parameter</th>
<th>Method-1</th>
<th>Method-2</th>
<th>Method-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPR [-]</td>
<td>52.00</td>
<td>53.55</td>
<td>55.05</td>
</tr>
<tr>
<td>BPR [-]</td>
<td>12.22</td>
<td>13.07</td>
<td>13.27</td>
</tr>
<tr>
<td>FPR [-]</td>
<td>1.427</td>
<td>1.460</td>
<td>1.453</td>
</tr>
<tr>
<td>nPR [-]</td>
<td>0.443</td>
<td>0.383</td>
<td>0.500</td>
</tr>
<tr>
<td>EP13 [-]</td>
<td>0.948</td>
<td>0.950</td>
<td>0.924</td>
</tr>
<tr>
<td>EP25 [-]</td>
<td>0.914</td>
<td>0.919</td>
<td>0.920</td>
</tr>
<tr>
<td>EP3 [-]</td>
<td>0.905</td>
<td>0.917</td>
<td>0.925</td>
</tr>
<tr>
<td>E45 [-]</td>
<td>0.924</td>
<td>0.920</td>
<td>0.921</td>
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<tr>
<td>E5 [-]</td>
<td>0.933</td>
<td>0.952</td>
<td>0.946</td>
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<tr>
<td>Transfer Efficiency [-]</td>
<td>0.874</td>
<td>0.882</td>
<td>0.859</td>
</tr>
<tr>
<td>Core Efficiency [-]</td>
<td>0.559</td>
<td>0.567</td>
<td>0.572</td>
</tr>
<tr>
<td>Propulsive Efficiency [-]</td>
<td>0.804</td>
<td>0.817</td>
<td>0.816</td>
</tr>
<tr>
<td>SFCi [g/kNs]</td>
<td>15.932</td>
<td>15.329</td>
<td>15.578</td>
</tr>
<tr>
<td>CDT [K]</td>
<td>950.0</td>
<td>950.0</td>
<td>950.0</td>
</tr>
<tr>
<td>TET [K]</td>
<td>1760.6</td>
<td>1790.9</td>
<td>1850.0</td>
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<tr>
<td>VAN change [%]</td>
<td>8.24</td>
<td>6.68</td>
<td>6.98</td>
</tr>
<tr>
<td>W [kg]</td>
<td>2594</td>
<td>2622</td>
<td>2496</td>
</tr>
<tr>
<td>Gear ratio [-]</td>
<td>2.80</td>
<td>2.60</td>
<td>2.65</td>
</tr>
<tr>
<td>HPC LSBH [mm]</td>
<td>16.2</td>
<td>13.9</td>
<td>16.4</td>
</tr>
</tbody>
</table>
Design Space Exploration Results

Engine design space is explored through **parametric MPD runs** varying (FPR, OPR) @ToC, and each time (BPR, nPR) @ToC are again optimized for minimum SFCi @CR:

- Design spaces of similar shape
- Boundaries and optimum solution depend on method to establish turbomachinery efficiencies @CR
- Installed performance differences up to ~3% between different methods
Engine Flowpath Visualization

Through the aerothermodynamic design is possible to visualize the engine flowpath geometry:

- Method-1: Geometry calculated for optimum (OPR, FPR, BPR, nPR) @ToC = (52.00, 1.427, 12.22, 0.443)
- Method-3: Geometry calculated for optimum (OPR, FPR, BPR, nPR) @ToC = (55.05, 1.453, 13.27, 0.500)
- Method-1 to establish turbomachinery efficiencies @CR

Constrained MPD and flowpath sizing calculations < 3 seconds in a typical home desktop PC
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Summary & Conclusions
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- A consistent, single step modelling process was presented that combines turbomachinery 0D thermodynamic performance with 1D aerodynamic design and flowpath sizing, at the same modelling level and under the same user-friendly simulation environment.

- Design point efficiency of turbomachinery components can be established using losses or semi-empirical correlations, through a stage-by-stage design approach.

- Constrained MPD Optimization and Parametric runs were then carried out on a HBR GTF with bypass VAN, allowing performance requirements and aerodynamic, thermal, and structural constraints to be accounted for simultaneously at three different operating conditions.

  - MPD runs showed that the optimum design in terms of installed performance as well as engine geometry depend on the method for obtaining the turbomachinery design-point efficiencies.

  - MPD runs also showed that installed performance could present significant differences between the different methods used to establish turbomachinery design-point efficiencies.

- Future work includes the integration of modules for noise, emissions, lifing, and maintenance calculations, and the simultaneous optimization of both aircraft and engine at mission level.
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