Direct Coupling of a Two-Dimensional Fan Model in a Turbofan Engine Performance Simulation

by

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INTRODUCTION
  - Zooming Approaches
  - Motivation & Objectives

HIGH FIDELITY FAN MODELLING
  - Empirical Models
  - Comparison with Experimental Data

0-D ENGINE PERFORMANCE MODELLING

MIXED FIDELITY ENGINE PERFORMANCE MODEL
  - PROOSIS 2-D Fan Component
  - Test Case

SUMMARY & CONCLUSIONS
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SUMMARY & CONCLUSIONS
Component Zooming: execution of higher order analysis code and integration of its results back in the 0-D engine cycle allows for:

- more accurate physics & geometry based estimates of component performance
- complex phenomena & component design change studies

Different methods exist:
1. De-Coupled Approach
2. Semi-Coupled Approach
3. Fully-Coupled Approach
De-Coupled Zooming Approach

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Run multi-point steady-state simulation to generate map data

Construct appropriate map format

Repeat for new design

Select maps at component level & perform 0-D engine calculation

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Semi-Coupled Zooming Approach

Run 0-D engine model → Pass 0-D component information to 2-D component → Run 2-D component model → Correct 0-D component performance accordingly through scalars

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Fully-Coupled Zooming Approach

Remove 0-D component from engine model
Add 2-D component in its place
Connect 2-D component with engine model

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Motivation & Objectives

- Have in hand a tool that can efficiently be used to address:
  - gas turbine installation effects (e.g. distorted inlet flow)
  - compressor/fan design optimization
  - engine health monitoring (through simulation of fouling/erosion/tip clearance)

- Build a computational tool combining an in-house Streamline Curvature (SLC) through flow solver with a commercial 0-D performance simulation tool.

- Follow the fully-coupled approach between the two solvers without affecting conventional model construction and simulation case definition.
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SUMMARY & CONCLUSIONS
Through Flow Solver

SOCRATES: Synthesis Of Correlations for the Rapid Assessment of Turbomachine Engine Systems

Produces two dimensional flow solution based on Streamline Curvature (SLC) method.

Boundary Conditions

Inviscid solution core

Empirical models

= Viscous equivalent flow solution

Compressor Geometry
SOCRATES details

Inviscid Solution
✓ Full radial equilibrium equation considered along quasi-normal curves.
✓ Pseudo force terms included.
✓ Incorporation of dynamic convergence schemes with variable tolerance.

Empirical Models
✓ Profile loss: Bucket shaped curves (incidence vs profile loss) positioned based on flow Mach number level (Aungier)
✓ Shock loss: Simplified loss model based on frozen shock pattern (Swan).
✓ Deviation angle: Separate individual components considered due to off–design operation superimposed on the minimum loss value (Aungier)
✓ Boundary layer: Simplified end wall boundary layer model. Boundary layer shape parameters are defined from an integral approach based on meridional velocity along the boundary layer edge (Jansen & Moffatt)
Validation – Geometry

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Validation – Performance Maps

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Validation - Velocity Profiles

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Socrates – Input/Output

**Input**
- number of flow stream lines.
- number of points when defining a radial profile of a property at component inlet.
- number of stages.
- number of stator and rotor blades of each stage.
- radial location (as a percentage) of points in a profile.
- the stator/rotor stagger angle radial distributions.
- the inlet air mass flow rate. / outlet static pressure
- the fan rotational speed.
- the inlet flow temperature, pressure and angle radial distributions.

**Output**
- Radial distribution of pressure.
- Radial distribution of temperature.
- number of stages.
- Radial distribution of meridional velocity component.
- Radial distribution of absolute velocity.
- Radial distribution of axial Mach number.
- Radial distribution of absolute Mach number.
- Radial distribution of density.
- Radial distribution of flow angle.
- Streamtube mass flow rate
- Streamtube cross sectional area.
- A convergence flag is also returned to warn the user in case of non-convergence.
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Turbofan Engine Model

Mathematical Model

820 equations + 410 input data
1 boundary variable (fuel flow rate)
8 algebraic variables (inlet flow rate, BPR, BETA/ZETA)
2 dynamic variables (shaft rotational speeds)
10×10 Jacobian matrix
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SUMMARY & CONCLUSIONS
SOCRATES from executable stand-alone application → subroutine with specific interface as static library

SOCRATES defined in PROOSIS as external FORTRAN function

"FORTRAN" FUNCTION NO_TYPE SOCRATES_SLL (  
  IN INTEGER NoOfBoundaryPointsIn,  
  IN INTEGER NoOfTimeStepsIn,  
  IN REAL SplitterRadiusIn,  
  ...  
  OUT REAL StrlineRadialPositionOut[],  
  OUT REAL CompressorAbsTotPressureRatioOut,  
  OUT REAL CompressorIsentrEffOut,  
  ...  
) IN "SOCRATES_SLL.lib"
Simple 2-D component definition based on PROOSIS abstraction and inheritance capabilities

Component Fan2D IS_A Fan

SOCRATES_SLL(…)
MassAverage (…)

END COMPONENT

Use component to:
- Generate map
- Parametric studies
- Optimize geometry
Parametric Study – Effect of Streamline Number

NASA TP1493 1st stage
SLS conditions
Win = 30 kg/s
N = 14505 rpm

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Mixed Fidelity Turbofan Model Construction

Mathematical Model
1 boundary variable
7 algebraic variables
2 dynamic variables
9×9 Jacobian matrix

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<table>
<thead>
<tr>
<th>Component</th>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>InEng</td>
<td>W [kg/s]</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>N [rpm]</td>
<td>14500</td>
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<tr>
<td>CmpFan</td>
<td>BPR</td>
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<tr>
<td></td>
<td>Inner fan eff [-]</td>
<td>0.914</td>
</tr>
<tr>
<td></td>
<td>Inner fan PR [-]</td>
<td>1.492</td>
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<tr>
<td></td>
<td>Outer fan eff [-]</td>
<td>0.900</td>
</tr>
<tr>
<td></td>
<td>Outer fan PR [-]</td>
<td>1.500</td>
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<tr>
<td>CmpL</td>
<td>PR [-]</td>
<td>1.3</td>
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<tr>
<td></td>
<td>eff [-]</td>
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<td>PR [-]</td>
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<td>N [rpm]</td>
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<td>Brn</td>
<td>eff [-]</td>
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<tr>
<td></td>
<td>Pressure loss [%]</td>
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<tr>
<td>TrbH</td>
<td>eff [-]</td>
<td>0.86</td>
</tr>
<tr>
<td>TrbL</td>
<td>eff [-]</td>
<td>0.88</td>
</tr>
<tr>
<td>Perf</td>
<td>FN [N]</td>
<td>9000</td>
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</tbody>
</table>
### Test case Design Point Selected Results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>TrbH PR [-]</td>
<td>3.1</td>
</tr>
<tr>
<td>TrbL PR [-]</td>
<td>2.4</td>
</tr>
<tr>
<td>WF [kg/s]</td>
<td>0.115</td>
</tr>
<tr>
<td>TET [K]</td>
<td>1292</td>
</tr>
<tr>
<td>SFC [g/(kN·s)]</td>
<td>12.82</td>
</tr>
</tbody>
</table>
Operating Line for 0-D and 2-D Models

SFC [gr/(kN·s)]

FN [N]

SFC-0D
SFC_2D

1%
Stator = 34 blades

Rotor = 22 blades
Operating Line for Different Rotor-Stator Blade Numbers

![Graph showing operating line for different rotor-stator blade numbers.](image)

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Summary & Conclusions

- The integration of a stand-alone higher fidelity code in a 0-D engine performance simulation environment was presented through design point and off-design studies. The potential of the tool for advanced types of analysis is exemplified with a parametric study that calculates engine performance for different fan geometry settings.
- The proposed approach does not affect the model building procedure and the logic of the established mathematical formulation in existing performance simulations.
- The method presented does not depend on the fan geometry and type of engine or performance and can be extended to cover other engine components in an engine performance simulation.
감사합니다 – THANK YOU