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FLEXIBLE, FAST AND HIGH FIDELITY APPROACH TO GTU PART-LOAD AND OFF-DESIGN PERFORMANCE PREDICTIONS

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Introduction

Gas turbine (GT) engines are the primary engines for modern aviation. They are also widely used as power propulsion engines at power stations.

It is a characteristic feature of GT engines to work at off-design/part load modes. This can occur for due to:

- Different modes of aircrafts:
    - Ground idle mode
    - Take off
    - Maximum continuous mode
    - Cruising mode
    - Etc.
- Different ambient conditions
- Grid demands (for power generation engines and gas pumping (compressor) stations)

Introduction

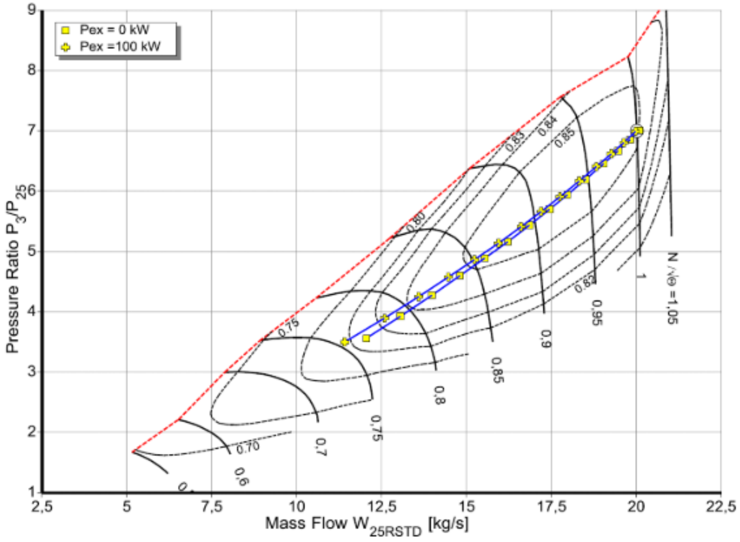
The main element present in every GT engine is the gas generator (compressor, turbine and combustor).

Due to off-design/part load operating conditions, the parameters of a gas generator might change significantly, which influences not only the engine efficiency, but also the reliable work of the turbine (high temperature at turbine inlet) and compressor (surge zone) at joint operational points.

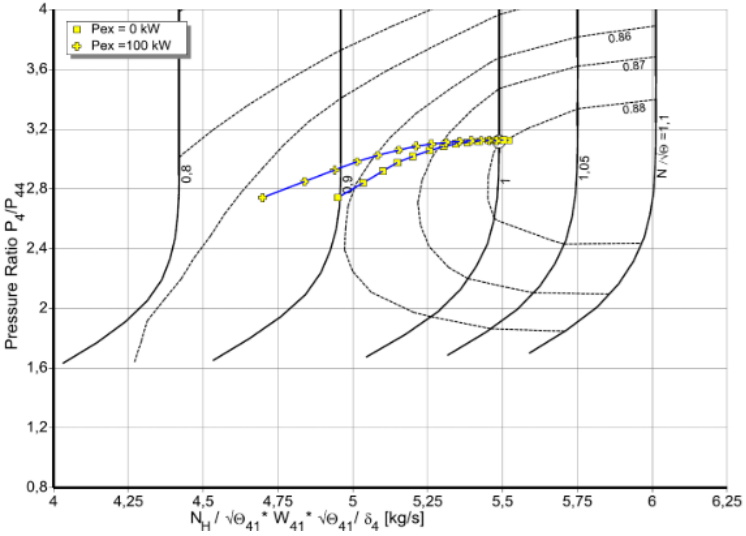
With this in mind, accurately determining the gas generator parameters at every off-design mode is of crucial importance.

Introduction

Utilization of compressor and turbine maps is a **common approach** to GT engine off-design calculations



Compressor map*



Turbine map*

[* source](#)

Introduction

There are different complex systems that allow simulation of GT engines, such as:

- GasTurb [1]
- GSP [2]
- EcosimPro [3]
- NPSS
- Etc.

These tools use simplified mathematical models for basic GT components (compressor, combustor, turbine, etc.), which when combined with their maps do not account for the physical processes of turbine and compressor flow paths, and, thus, have certain limitations.

1. GasTurb
2. GSP
3. EcosimPro

Introduction

A more detailed simulation of the GT engine can be done with 1D/2D/3D calculations of the turbine and compressor flow paths.

Such an approach can decrease time of engine refinement, allowing optimization of the GT engine.

The influence of compressor air bleed from the intermediate stages to the first stages and restaggering of the compressor guide vanes can also be accounted for during engine simulation.

Presentation Content

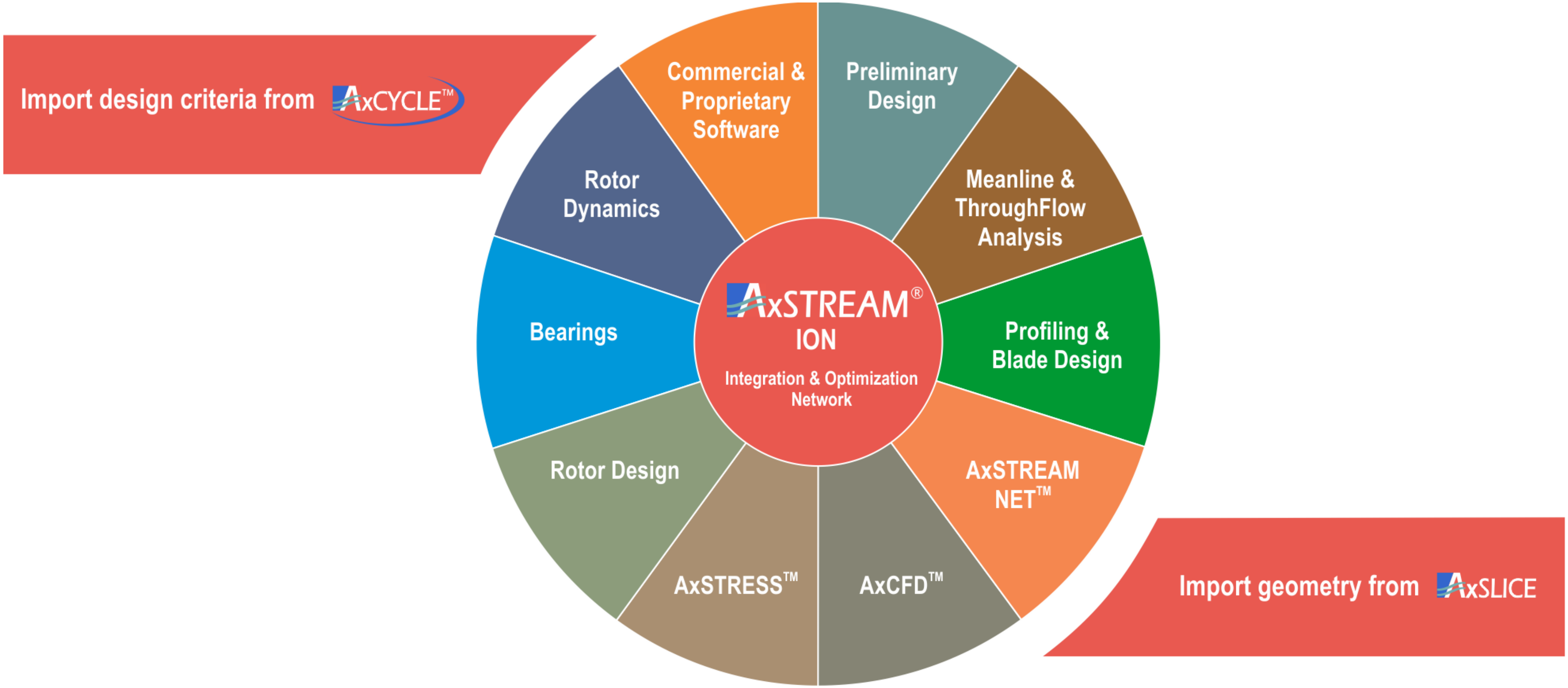
The main part of the study is devoted to calculation of aircraft turboprop engine parameters and performance at typical modes of engine operation.

Since the flow path of the considered aircraft engine does not have any cooled blades, the applicability of the approach to simulation taking into account a sophisticated cooling system is demonstrated based on the industrial cooled gas turbine, since fundamentally they are the same.

AxSTREAM® Platform and AxSTREAM ION™

AxSTREAM® Platform

Integrated platform for design, analysis and optimization of turbomachinery and off-design performance estimations



Import design criteria from AxCYCLE™

AxSTREAM® ION

Integration & Optimization Network

Commercial & Proprietary Software

Preliminary Design

Meanline & ThroughFlow Analysis

Profiling & Blade Design

AxSTREAM NET™

AxCFD™

AxSTRESS™

Rotor Design

Bearings

Rotor Dynamics

Import geometry from AxSLICE

AxSTREAM ION™

AxSTREAM ION™ is SoftInWay's newest software tool which performs optimization tasks and helps structure and accelerate the overall design process. It also permits the user to input their own personal criteria and modeling rules for intuitive use.

Primary Benefits and Capabilities:

- Automates the design process
- Performs multi-criteria and multi-parameter optimization tasks
- Option of inputting of in-house modeling rules results in ease of use for even junior-lever engineers
- Performs off-design tasks

Features

AxSTREAM ION™ Features:

- Used to integrate commercial and proprietary software products and customize their interaction based on different problem formulations
- Presence of scripts enable user functionality
- Enables the integration of software systems without the need to write additional program codes
- Allows for the control of process execution at every calculation stage

Aircraft Engine Digital Twin

Digital Twin General Specification

Goal of Digital Twin Development

- Aircraft engine performance calculation for different flight modes and comparison of the results with the conventional approach

Considered Engine

- Walter M601 turboprop aircraft engine

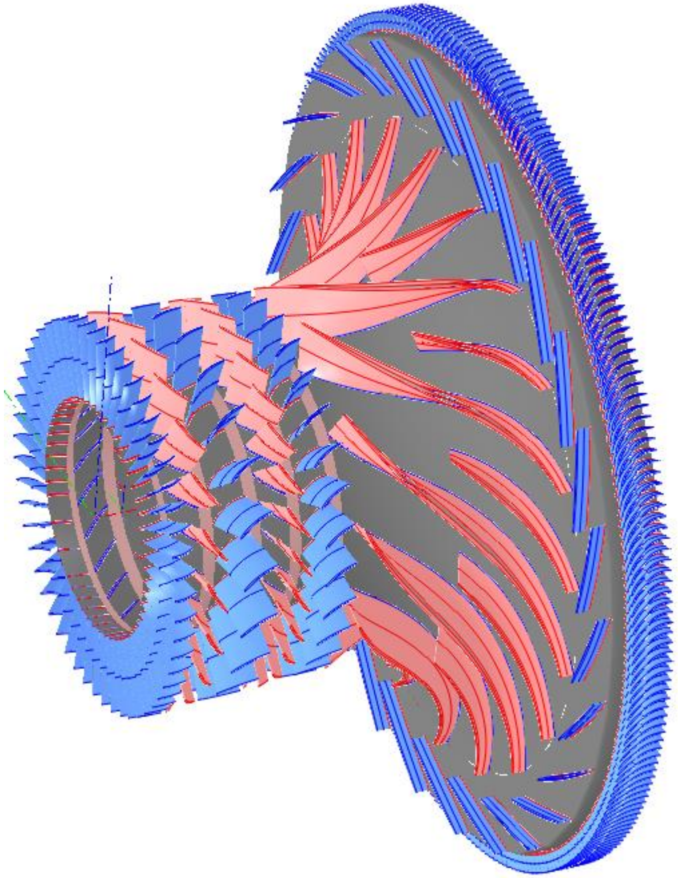
Digital Twin Flight Modes

- Ground idle mode (80 kW)
- Take off (529 kW)
- Maximum continuous rating (465 kW)
- Cruising mode (385 kW)

Digital Twin Output

- Aircraft engine performance at flight modes, including the whole set of internal thermodynamic and kinematic parameters for compressor and both turbines

Compressor Flow Path at the Design Mode in AxSTREAM®[4]



Parameter	Unit	Value
Total-to-total pressure ratio	-	6.560
Inlet MFR	kg/s	3.579
Shaft rotational speed	rpm	28652
Efficiency	-	0.8015
Power	kW	922
Type	Axial-centrifugal	

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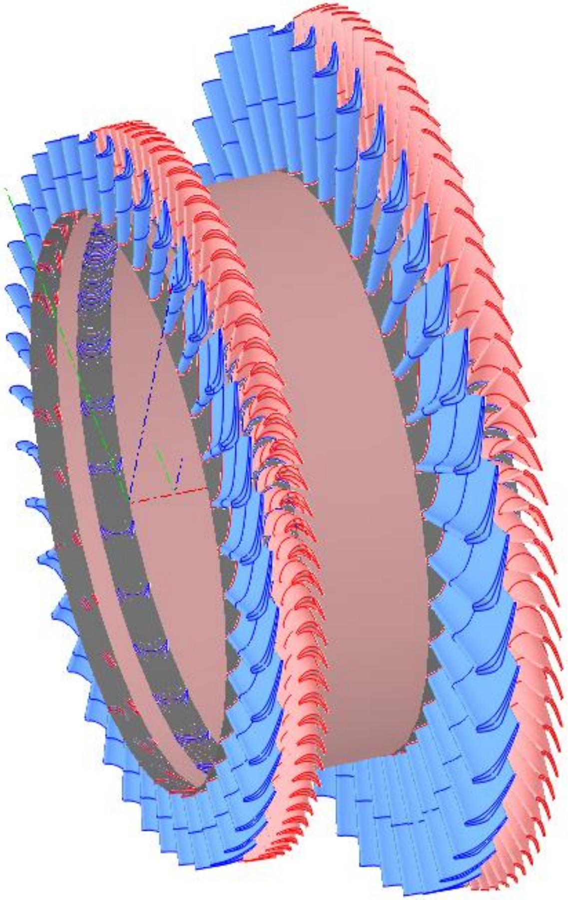
[4] L. Moroz, Yu. Govoruschenko, P. Pagur, A uniform approach to conceptual design of axial Turbine / compressor flow path, The Future of Gas Turbine Technology. 3rd International Conference, October 2006, Brussels, Belgium.

Compressor Turbine and Free Turbine Flow Paths in AxSTREAM®



Parameter	Unit	Value
Inlet temperature	K	1050
Inlet pressure	kPa	645
Shaft rotational speed (compressor turbine)	rpm	28652
Shaft rotational speed (free turbine)	rpm	21079
Power (compressor turbine)	kW	922
Power (free turbine)	kW	529
Efficiency (compressor turbine)	-	0.893
Efficiency (free turbine)	-	0.919
Type	Axial	

Loss Models for Performance Prediction

Compressor Calculation

- Meanline and streamline calculation approaches were used to predict compressor performance [4]. Profile losses were determined utilizing the Lieblein's test data [5] approximated by Aungier [6]. Given loss model based on NACA 10-stage compressor test data.

Turbine Calculation

- Meanline and streamline calculation approaches were used to predict turbine performance [4]. Craig and Cox profile loss model [7] was utilized to predict profile losses of the turbine nozzles and blades at design and off-design modes. According to Ning Wei Craig and Cox loss model is one of the most accurate empirical loss models for axial turbines [8].

5. S., Lieblein, 1959. “Loss and Stall Analysis Of Compressor Cascades”, Trans., Journal of Basic Engieneering, ASME, Vol.81, Sept., 1959, pp. 387-400
6. Ronald H. Aungier, 2003. “Axial –Flow compressors: a strategy for aerodynamic design and analysis”, The American Society of Mechanical Engineers, New York, 2003, 363p.
7. H. R. M. Craig; H. J. A. Cox, 1970 “Performance Estimation of Axial Flow turbines,” Proc. Instn. Mech. Engrs. 1970-71, ol.185 32/71.
8. Ning WEI, 2000. “Significance of Loss Models in aerothermodynamics Simulation for Axial Turbines”, Doctoral Thesis, Department of Energy Technology Division of Heat and Power Technology Royal Institute of Technology, 2000, 164p.

Combustor Model

Combustor calculation is based on thermodynamic equations.

$$I_{in\_turb} = f(P_{turb\_turb}, T_{turb\_in}, AEF)$$

where

I_{turb_in} – turbine inlet enthalpy;
P_{turb_in} – turbine inlet pressure;
T_{turb_in} – turbine inlet temperature;
AEF – air excess factor.

Combustor Model

Combustor calculation is based on thermodynamic equations.

$$G_{fuel}=(G_{comb\_out}*I_{turb\_in} - G_{comp\_out}*I_{compr\_out})/LHV$$

where

G_{fuel} – fuel MFR;
G_{comb_out} – combustor outlet MFR;
G_{comp_out} – compressor outlet MFR;
I_{comp_out} – compressor outlet enthalpy;
LHV – lower heating value.

$$G_{comb\_out} = G_{comp\_out} + G_{fuel}$$

$$AEF = G_{comb\_out} / (G_{fuel} * l_{0)}$$

where

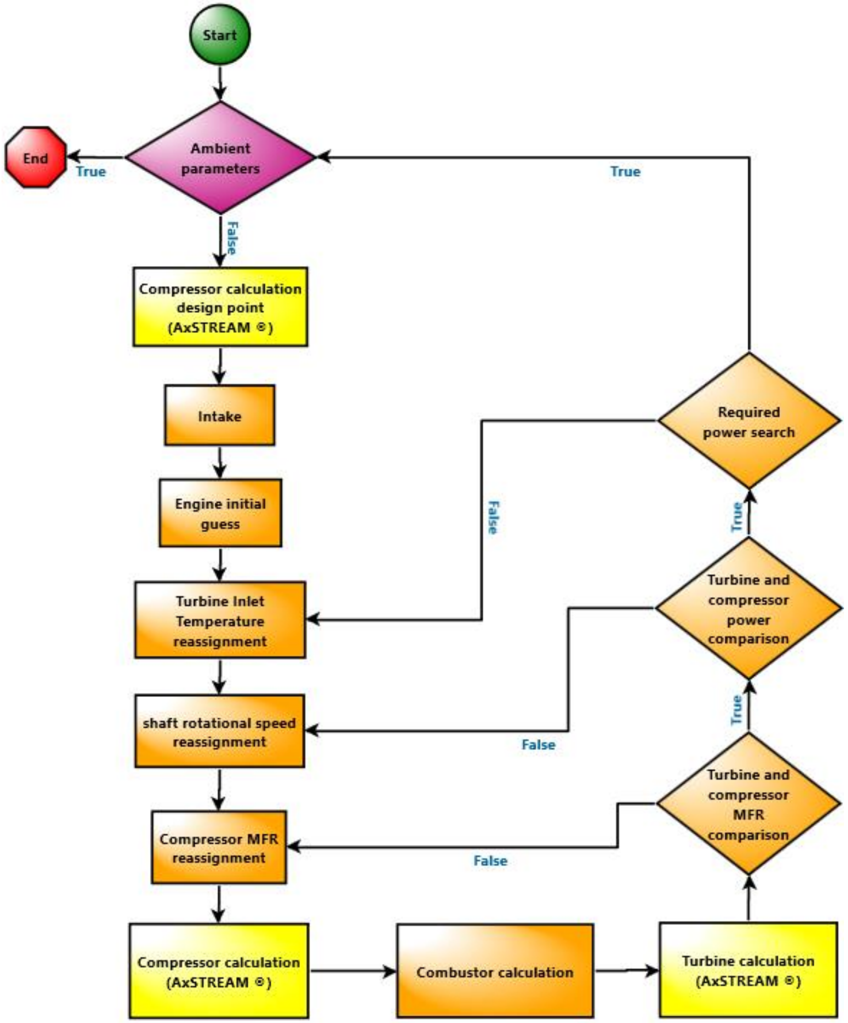
l_0 – stoichiometric air-fuel ratio.

Fuel – Jet A-1

Data Transfer

Block	Inputs	Outputs
Ambient parameters		Nreq, Pamb, Tamb, M
Intake	Pamb, Tamb, M	P_{compr_in}, T_{compr_in}
Engine initial guess		G_{compr_in}, n_{compr}, T_{turb_in}
Compressor calculation	P_{compr_in}, $T_{compr\_in,}$ $n_{compr,}$ G_{compr_in}	N_{compr}, eff_{compr}, P_{compr_out}, T_{compr_out}
Combustor calculation	P_{compr_out}, T_{compr_out}, G_{compr_out}, T_{turb_in}	AEF, G_{fuel}, $G_{comb\_out,}$ P_{turb_in}
Turbine calculation	P_{turb_in}, T_{turb_in}, AEF, $P_{turb\_out,}$ n_{turb}	N_{turb_compr}, N_{turb_free}, eff_{turb_compr}, eff_{turb_free}, G_{turb_in}, etc.
MFR_c&MFR_t comparison	$G_{compr\_in,}$ G_{turb_in}	G_{compr_in}
Compressor and turbine 1 power comparison	$N_{compr,}$ $N_{turb\_compr,}$ n_{compr}	n_{compr}
Required power search	Nreq, N_{turb_free}, T_{turb_in}	T_{turb_in}

Algorithm Implementing Digital Twin



Process

- Represents an available computational tool

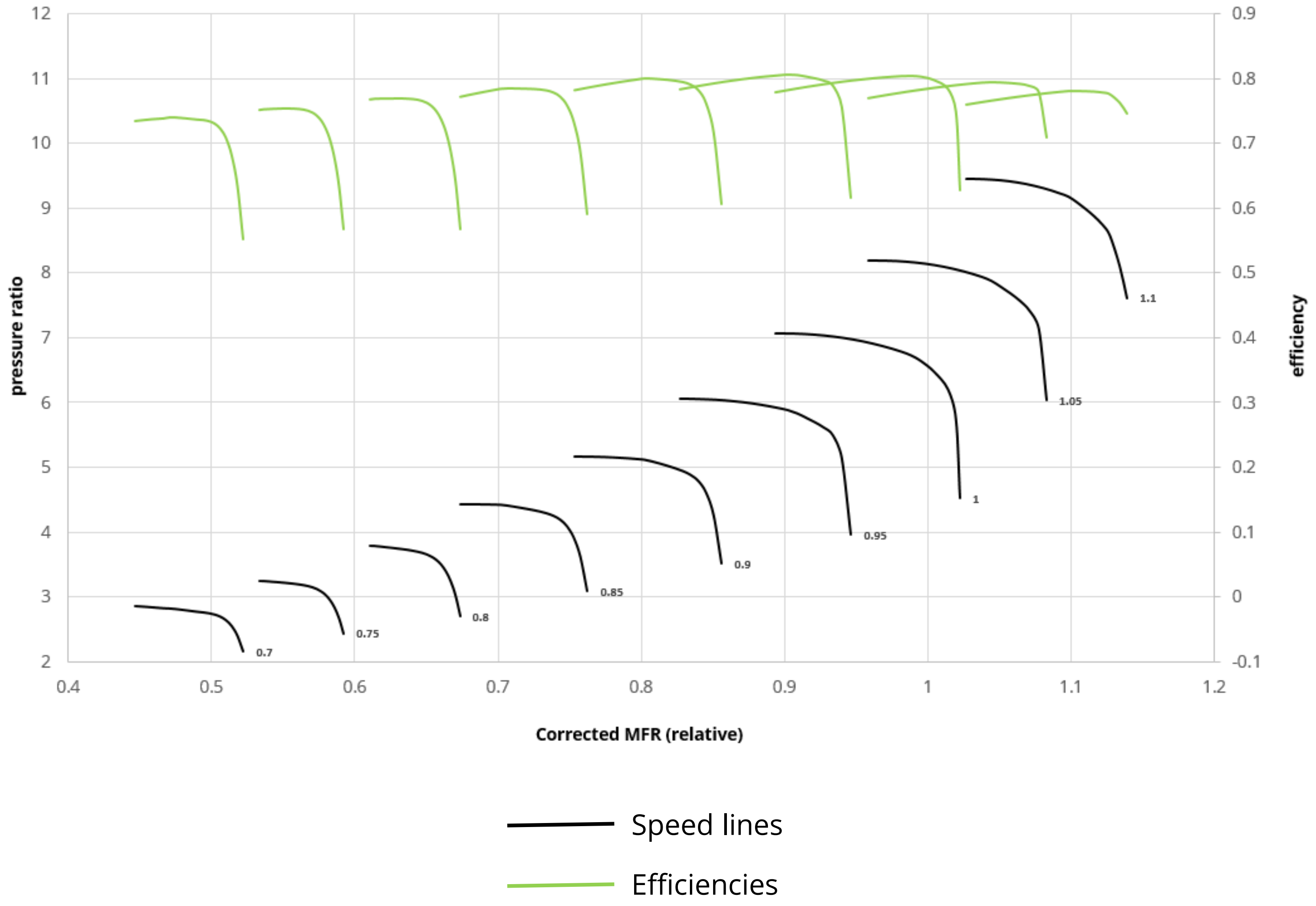
Script

- Represents custom scripts to perform additional calculations not available among off-the-shelf tools (intake calculation, combustor calculation)

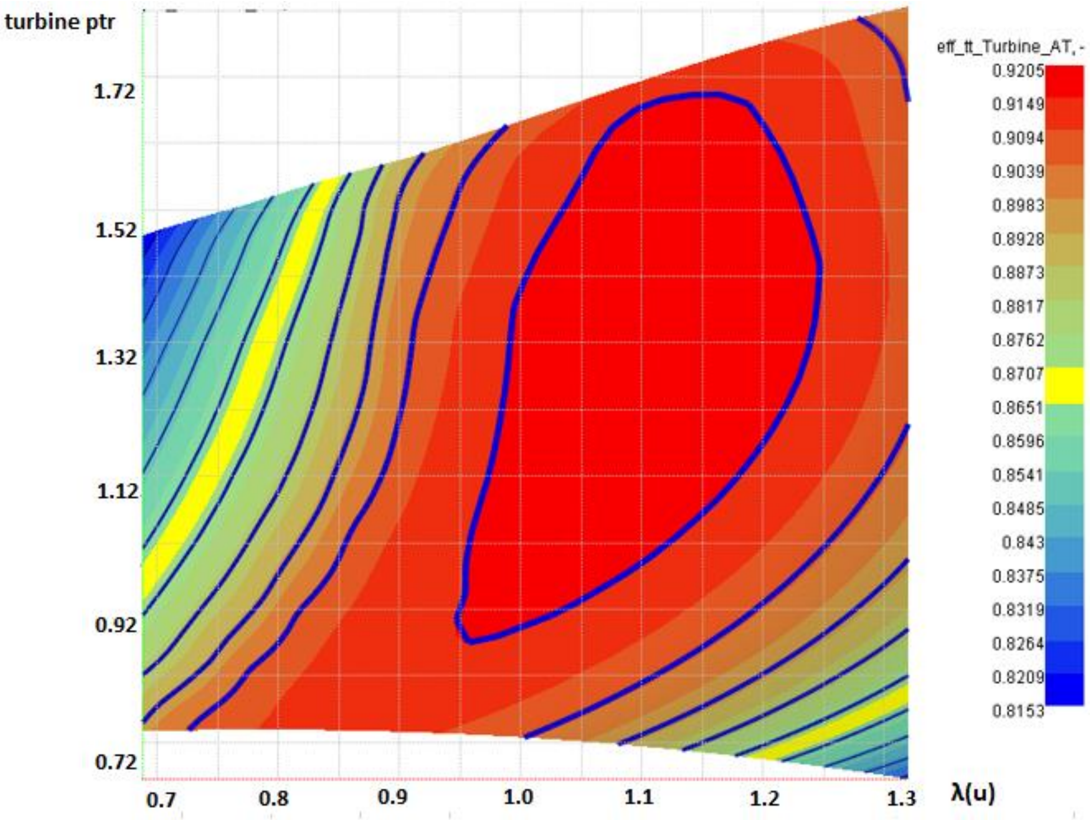
Condition

- Represents conditional statements for process control according to a predefined condition. Allows implementation of loops required to converge required parameter

Compressor Map (Calculated in AxSTREAM®)



Free Turbine Map (Calculated in AxSTREAM®)



Maps Based Approach Description[9]

With assumption that turbine pressure ratio is constant at off-design modes, the line of joint modes can be calculated as:

$$\frac{\pi_c^*}{q(\lambda_c)} = C\sqrt{\frac{e_c^* - 1}{\eta_c^*}} \qquad (1)$$

where

π_c^* - compressor pressure ratio
$q(\lambda_c)$ - function of flow density at compressor inlet
C - constant (is determined based on one calculated point)
η_c^* - compressor efficiency
$e_c^* = {\pi_c}^{\frac{k-1}{k}}$
k - isentropic exponent

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9. Nechaev Yu., Fedorov R., Kotovsky V. The theory of aviation engines (part 2), Moscow, 2006, 448p.

Maps Based Approach Description[9]

$$C = {}^{A}\!/\!_{\sqrt{B}}$$

where

$$A = \frac{a m_a F_a}{m_g q(\lambda_n) F_n \sigma_n \sigma_{ch}}$$

a – coefficient that accounts for fuel and extraction MFRs

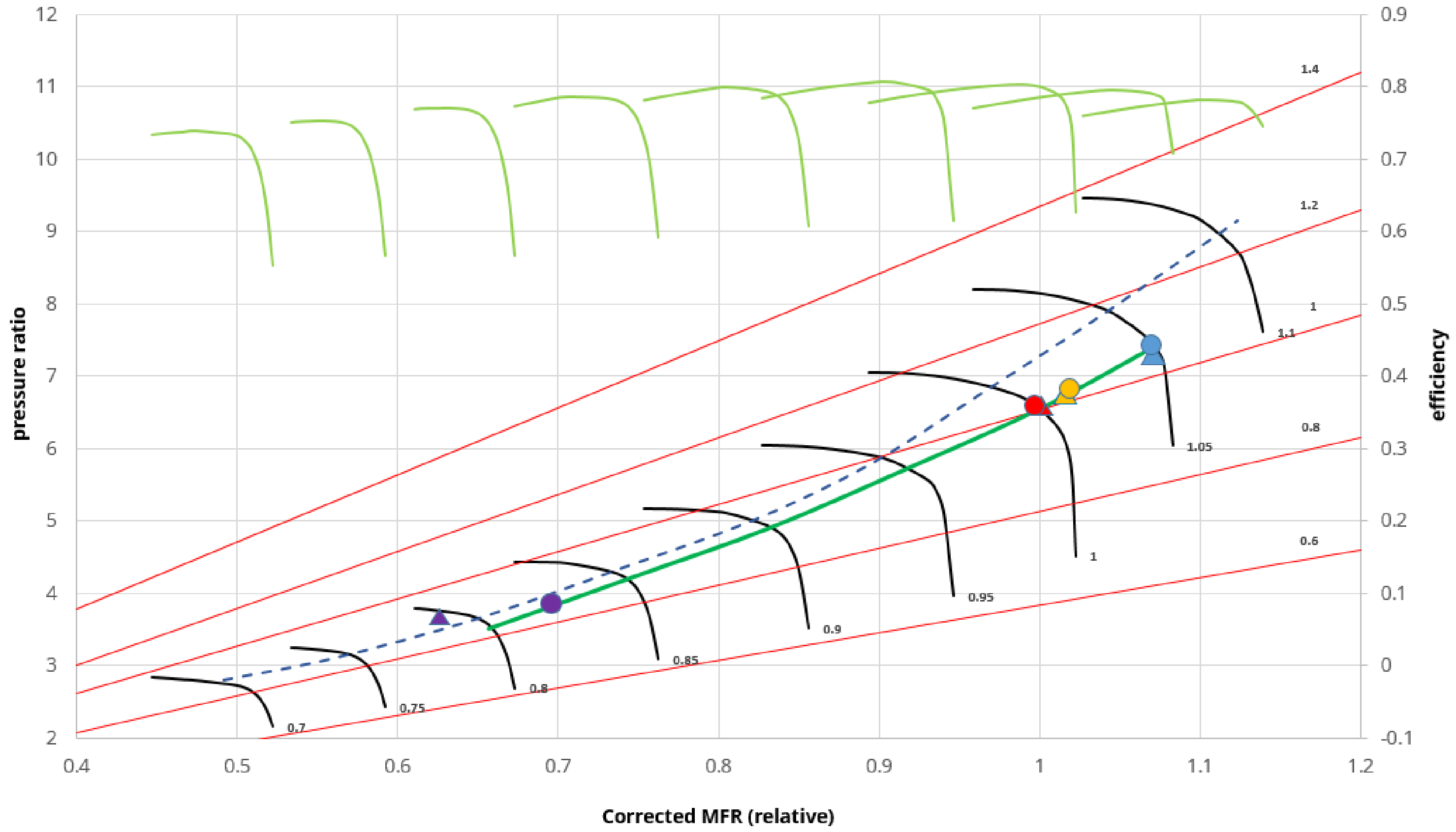
F_a - compressor inlet area
$q(\lambda_n)$ - function of flow density at turbine inlet
F_n - turbine inlet area
σ_n - efficiency of turbine inlet
σ_{ch} - efficiency of combustor chamber

$$\mathrm{B} = \frac{a C_{pg}}{C_{pa}} \left(1 - \frac{1}{e_t^*}\right) \eta_t^*$$

C_{pa}, C_{pg} - constant pressure specific heat of air and combustion products
η_t^* - turbine efficiency

9. Nechaev Yu., Fedorov R., Kotovsky V. The theory of aviation engines (part 2), Moscow, 2006, 448p.

Results of Calculations



— — — - Surge margin line

━━ - Lines of constant T_3/T_1

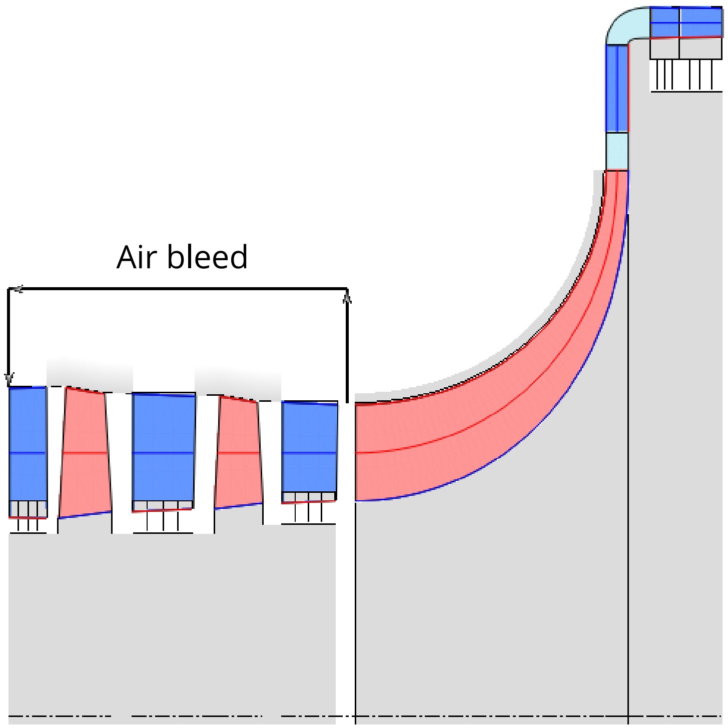
━━ - Theoretically calculated line of joint modes (according to Slide 21, Slide 22)

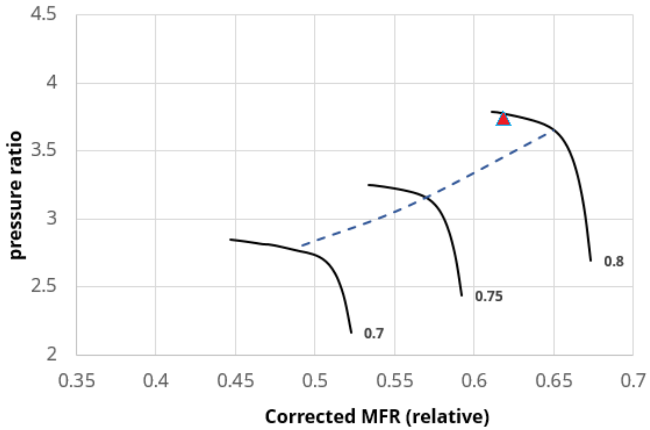
▲▲▲▲- Calculated by AxSTREAM ION™ (the ground idle, take off, cruise and maximal continuous modes respectively).

●●●●- Calculated by maps (the ground idle, take off, cruise and maximal continuous modes respectively).

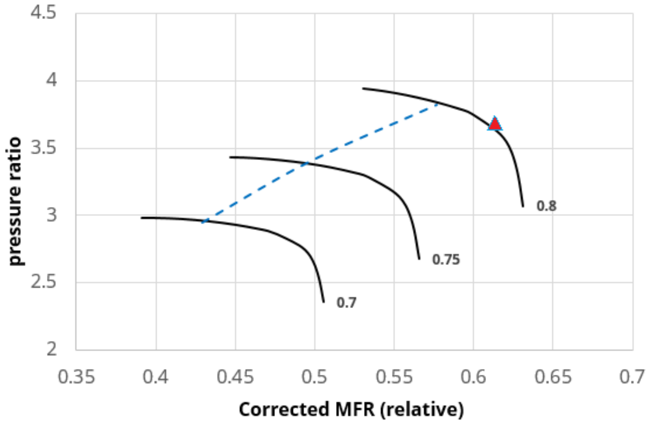
Air Bleed Influence at Ground Idle Mode

Compressor air bleed was performed to satisfy surge margin factor





Without air bleed



With air bleed

Preliminary Conclusions on Turboprop Aircraft Engine Analysis

1. The received results using digital twin model are in good agreement with those based on theoretical principles with maps utilization at high power modes.

2. The results at ground idle mode found using digital twin model show a significant change in the compressor turbine pressure ratio that does not allow correct determination of the GT engine condition at low power modes using equation (1) at slide 23. That is why the significant difference in results at ground idle mode takes a place.

3. Calculated results show a decrease in the surge margin factor at ground idle mode.

Preliminary Conclusions on Turboprop Aircraft Engine Analysis

4. Digital twin model allowed determining that the compressor is beyond the safe operation margin without any hardware performance testing, while conventional maps-based approach showed that the compressor is in safe area at ground idle mode.

5. The latter allows taking special actions to move the compressor operation point to a safe operation area. In particular, the compressor safety margin to surge was increased from 2.5% to 24% applying bypassing of air in axial compressor part.

Industrial Gas Turbine Cooling Air MFR Control

Digital Twin General Specification

Task Formulation

- Augmentation of GTU performance by cooling air MFR control

Engine Prototype

- 170 MW industrial gas turbine unit

Digital Twin Part Load Modes

- 40-100% of design mode power

Digital Twin Output

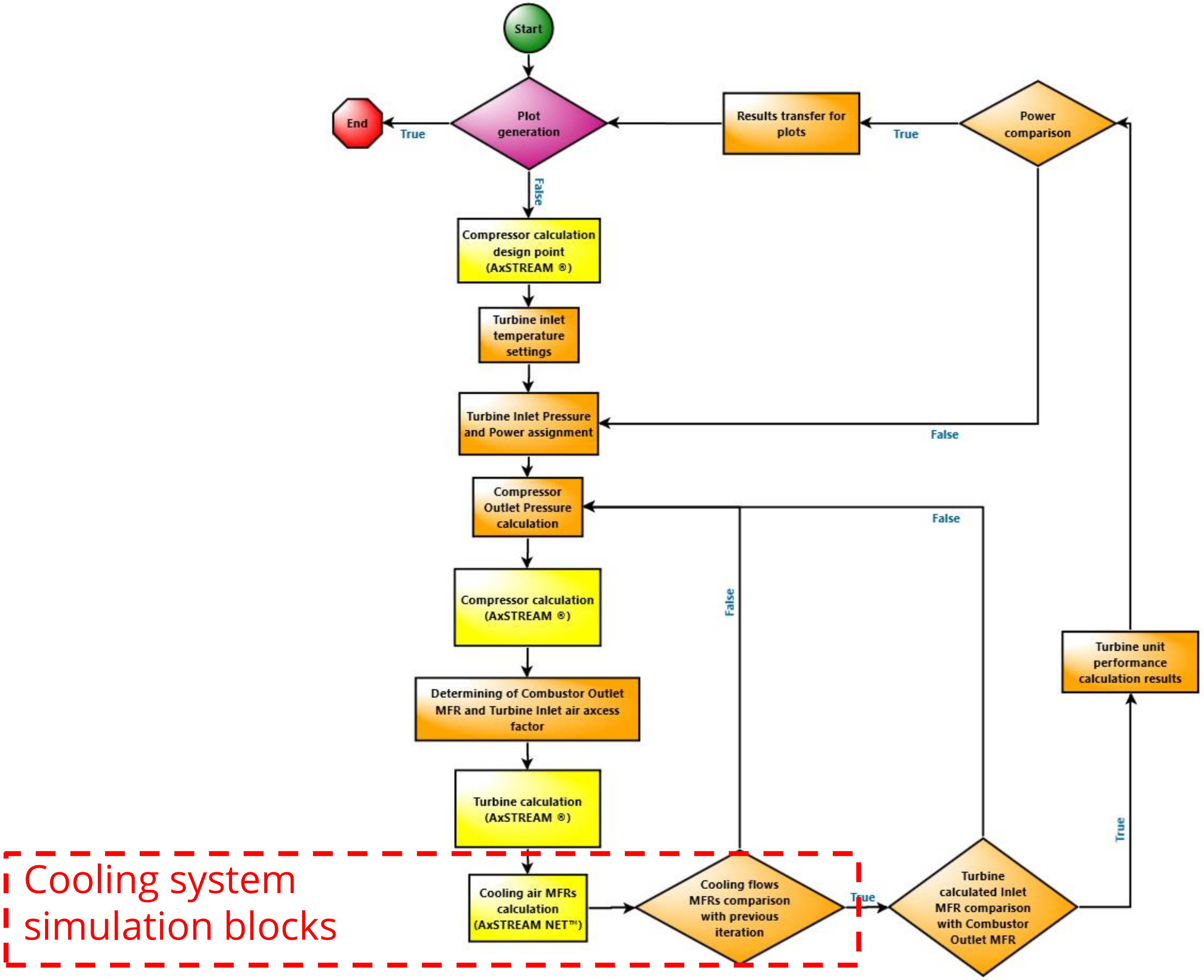
- GTU performance at part-load modes

Assumption

- Cooling air MFR is controlled at first stator only
- The part-load modes are achieved by turbine inlet temperature varying

Note: The rationality of appropriate cooling air MFR control should be considered in every single case as it leads to design complexity and weight increment of GT engine.

Digital Twin with Cooling System Simulation



Cooling system simulation blocks

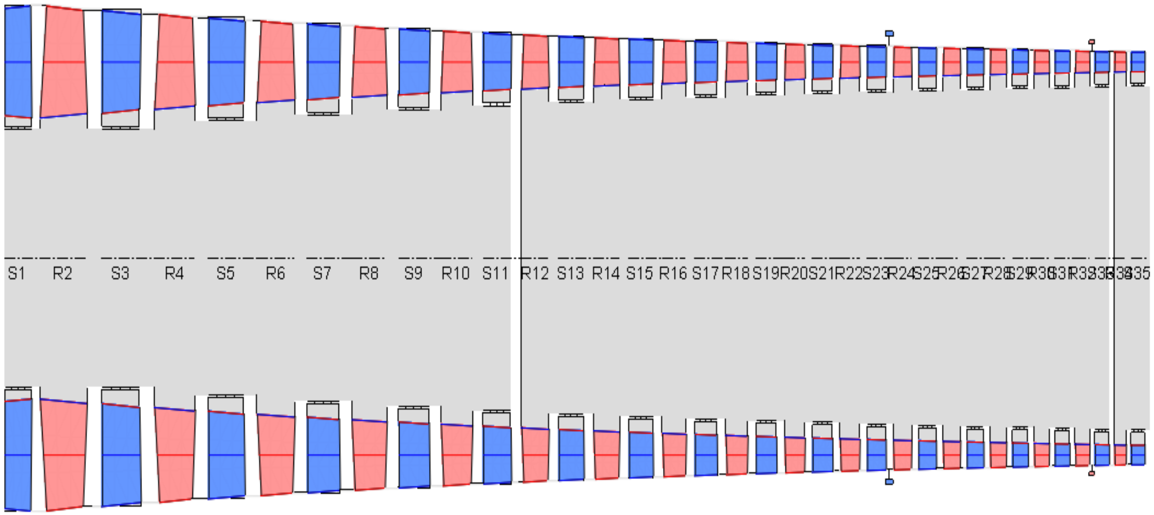
170 MW Industrial Cooled GTU Analysis

Compressor

The compressor is a 17 stage machine with an IGV and 3 extractions to the cooling system. Extractions occur:

- After nozzle of the 11th stage
- After rotor of the 16th stage
- At the compressor outlet

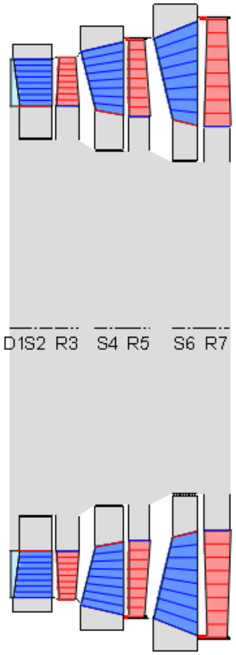
The power of compressor at design mode is 137 MW

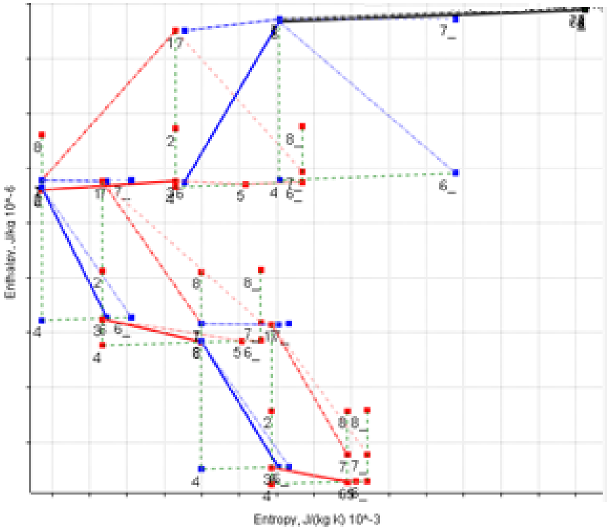


170 MW Industrial Cooled GTU Analysis

Turbine

The turbine is a three-stage axial machine with 14 cooling inductions including the cooled duct at the turbine inlet

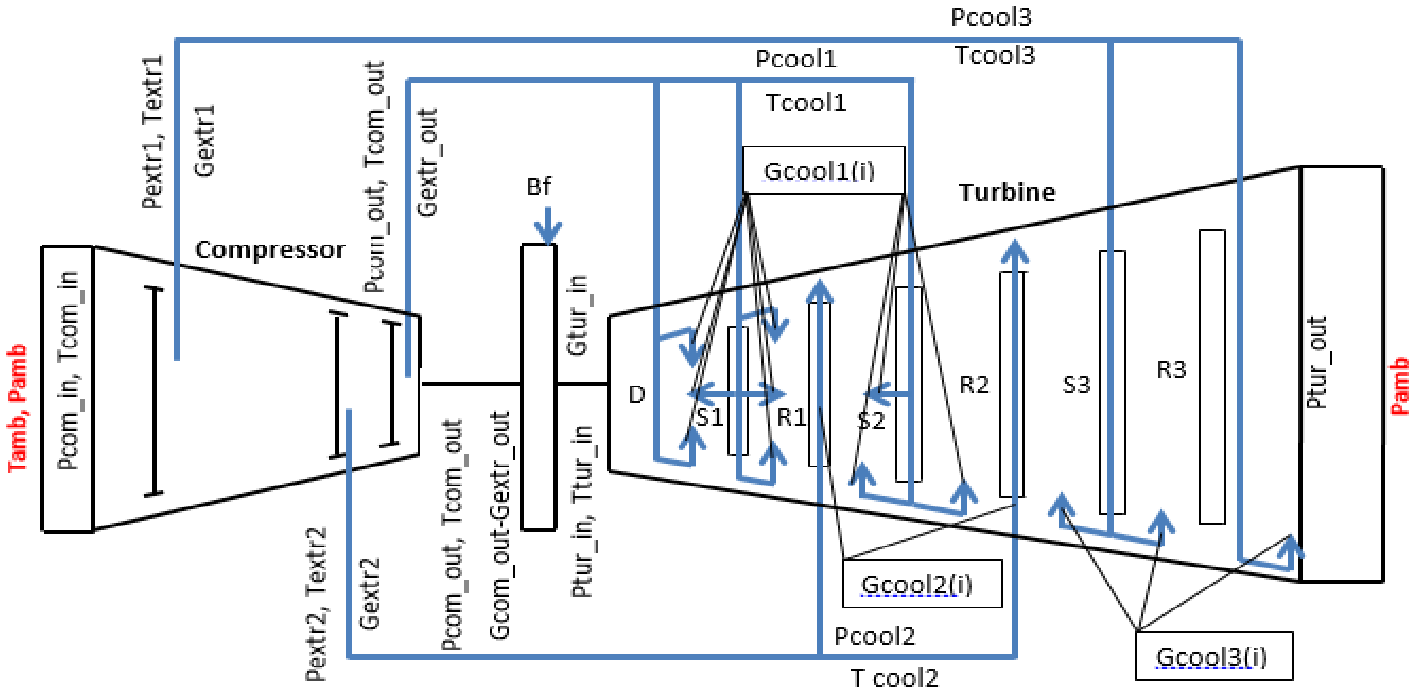




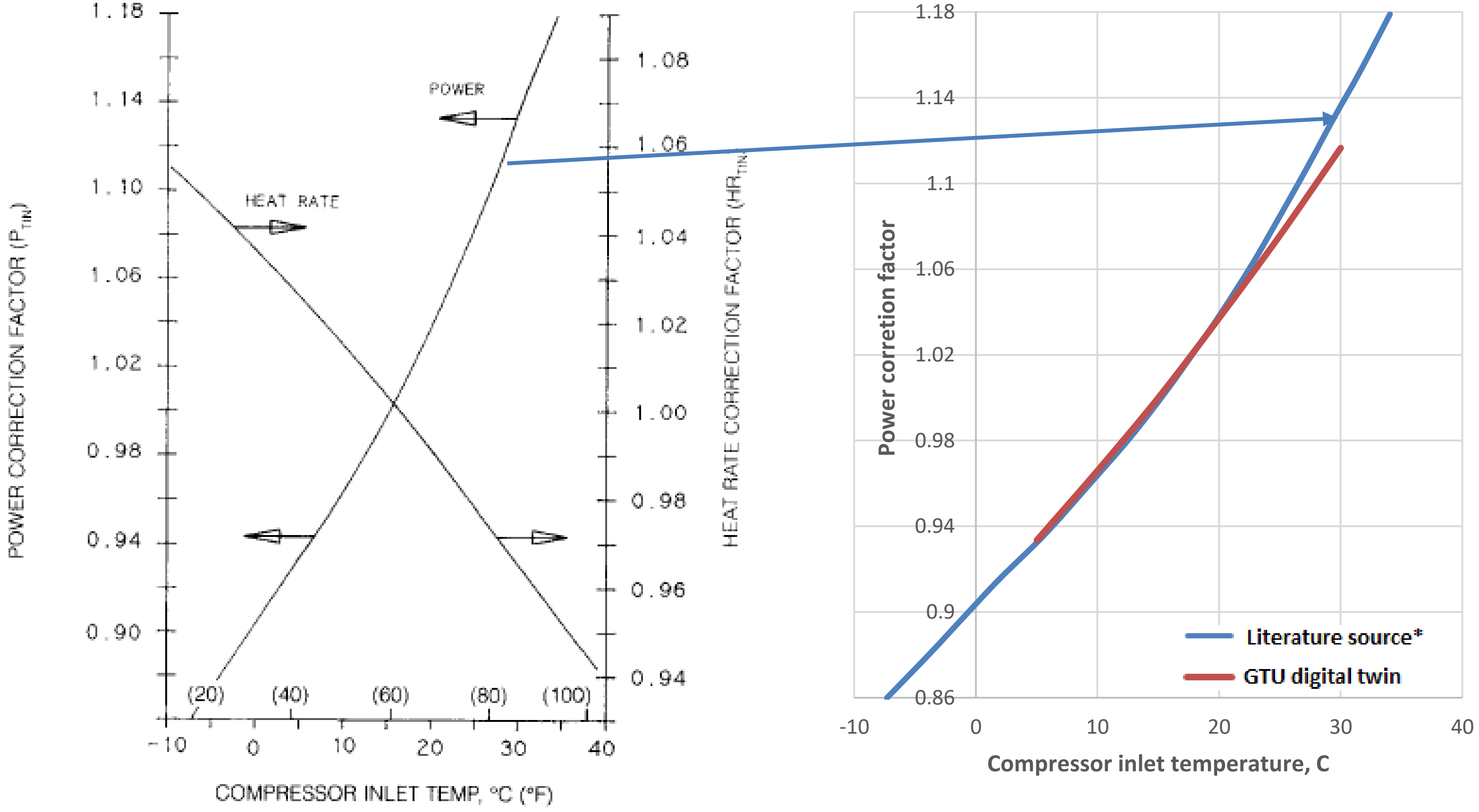
Cooling System Sketch

Cooling System

- Three extractions from the compressor:
  - One rotor extraction to provide the cooling flow to the first and second stage rotor blades of the turbine
  - Two casing extractions which provide the cooling flow to the inlet duct and all stator blades of the turbine

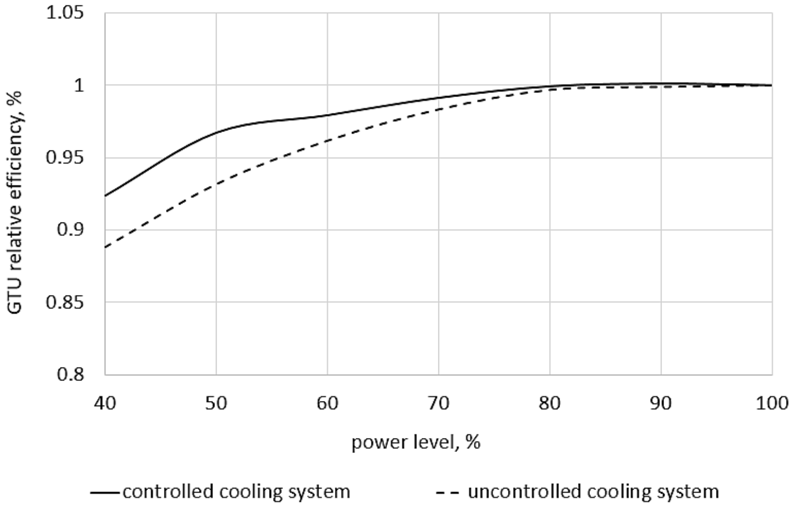


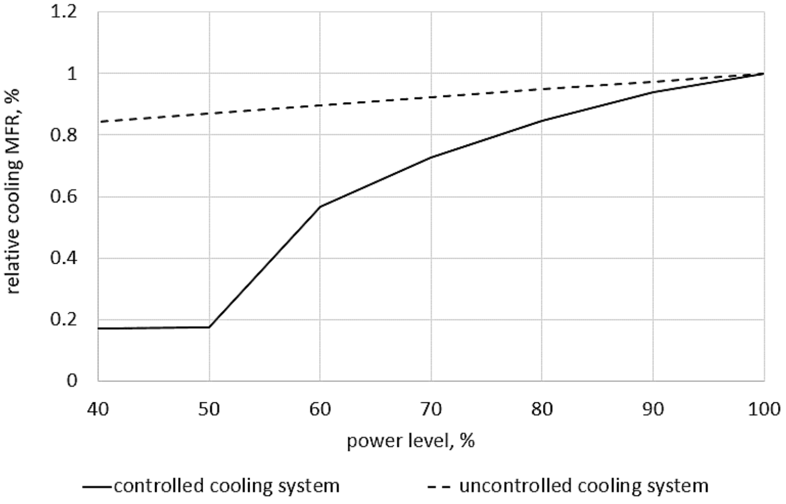
Simulation of Ambient Temperature Influence on GTU Performance



* IHOR S. DIAKUNCHAK and DAVID R. NEVIN, 1989. “Site Performance Testing of CW251 B10 Gas Turbines”, ASME, 89-GT-142, 8p.

Results of Cooling Air MFR Control





- The efficiency of the digital twin with a controlled cooling system is higher than the digital twin with an uncontrolled cooling system.
- The efficiency increment at 40% power is about 3.5% in relative values while at 70% power, it is about 1%.
- The decrement of the cooling air mass flow rate is much more significant considering the controlled cooling system.
- A preliminary economics analysis shows that the annual savings are in the range of $154,000-$387,000 per year.

Conclusions

1. The received results on turboprop aircraft engine using its digital twin model are in good agreement with those based on theoretical principles with maps utilization at take-off, cruise and maximum continuous modes.

2. The results at ground idle mode found using digital twin model show a significant change in the compressor turbine pressure ratio that does not allow correct determination of the GT engine condition at low power modes using equation (1) at slide 23. That is why the significant difference in results at ground idle mode takes a place.

3. Digital twin model allowed determining that the compressor is beyond the safe operation margin to surge without any hardware performance testing, while conventional maps-based approach showed that the compressor is in safe area at ground idle mode.

Conclusions

4. Using digital twin model of the engine, the special actions to move the compressor operation point to a safe operation area were taken. In particular, the compressor safety margin to surge was increased from 2.5% to 24% applying bypassing of air in axial compressor part.

5. The validation of the proposed digital twin of cooled turbine with the test data for the case of different ambient temperature values was done. The validation showed good agreement of the digital twin performance data with the real test data.

6. The assessment of possibility of cooling mass flow rate control and its influence on turbine performance was performed. The efficiency increment at 40% of power is about 3.5% in relative values, at the 70% it is about 1%.

7. The proposed digital twin approach is a flexible, fast and high fidelity tool for gas turbine engines parameters analysis and performance estimation at different operation modes including idle ones.

Thank You for Your Attention