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Shape Optimization of an Air Turbo Rocket Hydrogen Turbine for Off-Design Performance Assessments

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Abstract

Reliable and efficient propulsion systems are critical for advancing civil hypersonic transportation. Air Turbo-Rocket (ATR) engines provide high specific thrust and impulse across a broad range of altitudes and Mach numbers, making them particularly effective for the acceleration phase. Furthermore, Expander-type ATRs extend the operational range by isolating the turbine from the hot airflow path associated with high flight Mach numbers, lifting a thermal constraint. Decoupling the turbine from the airflow path increases degrees of operational freedom. However, it leads to a more extensive variety of operating conditions in the turbines, making conventional scaling procedures for publicly available turbine performance maps impractical. This work performs a multi-fidelity design and optimisation of a hydrogen turbine to expand its feasible operational envelope. The approach combines a low-fidelity mean-line design with empirical loss correlations, which feeds a high-fidelity CFD optimisation using the in-house CADO optimisation. The optimised turbine geometry is evaluated across multiple operating conditions to generate a turbine performance map that is useable in thermodynamic engine simulations.

Keywords: *Air Turbo-Rocket, Mean Line Design, Differential Evolution, Hydrogen, Shape Optimisation*

Nomenclature

ATR – Air-Turbo Rocket
ESPSS – European Space Propulsion Simulation Toolkit
CADO – Computer-Aided Design Optimization
CFD – Computational Fluid Dynamics
DE – Differential Evolution

1. Introduction

Expander-type ATRs have a broad operational envelope by isolating the turbine from the hot airflow path, thereby eliminating traditional metallurgical limitations associated with high-temperature turbine operation. This design approach allows the turbine to operate under more controlled thermal conditions, enhancing its durability and efficiency while improving the overall cycle performance.

A schematic representation of the ATR studied in this work can be seen in Fig. 1. This figure shows how liquid hydrogen, stored cryogenically in the fuel tanks, is pumped through a network of heat exchangers in both the combustion chamber walls and the nozzle. These heat exchangers transfer waste thermal energy to the hydrogen, increasing its enthalpy before it is expanded through a two-stage turbine system. The first turbine stage powers the fuel pump, ensuring a continuous supply of pressurized hydrogen to the engine, while the second turbine stage drives a counter-rotating fan system. The compressed air from the fan is mixed with the exhaust hydrogen from the turbines and burned in the combustion chamber. The resulting high-energy mixture is expanded through a

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converging-diverging nozzle, generating thrust. This configuration was initially studied by Rodríguez-Miranda et al. [1], who developed a parametric ATR model which was subjected to a throttle parameter optimization for numerous points across the ascent phase of a given flight. Later, Fernàndez Villacé et al. [2] extended the study to include engine installation effects. For both these studies, however, the authors performed thermodynamic analyses of the ATR considering quasi-on-design operation for many of the engine's components. This includes the turbomachinery components, which are assumed to operate at a constant isentropic efficiency. Only a power-matching requirement is imposed, foregoing the more complex speed matching that is required to capture the engine off-design in more detail.

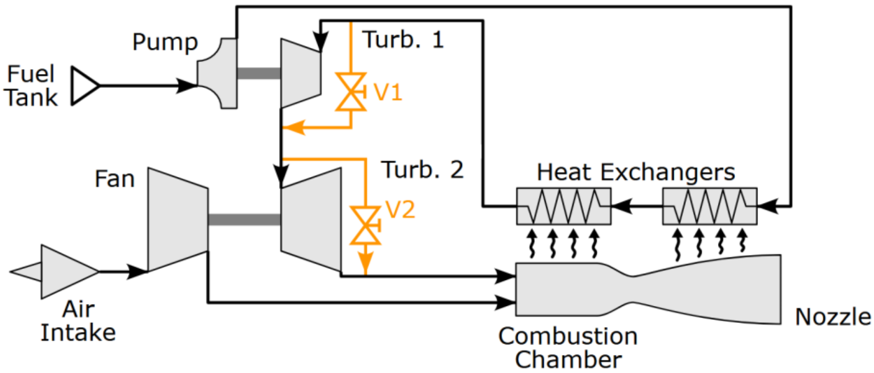

Fig 1. Schematic overview of the ATR engine used in the transient model simulations.

Van den Borre et al. [3] conducted an in-depth off-design performance evaluation of ATR engines using transient simulations. By scaling generic turbomachinery maps to fit the engine's working line, this study sought to improve the accuracy of performance predictions. However, the use of non-specific turbomachinery maps and the simple map scaling procedure used in conventional air-breathing engine performance simulations [4] is unsuited for the operational ranges required for the turbine. The limited applicability of existing turbomachinery databases underscores the need for a dedicated design and analysis framework capable of generating customized turbine maps for advanced propulsion systems.

This work focuses on developing a Mean Line Design tool for the preliminary analysis and optimization of an axial turbine for hydrogen-fueled ATR engines. A Differential Evolution algorithm is implemented to refine kinematic parameters, maximizing efficiency while ensuring physically feasible solutions. The optimized preliminary design provides a baseline 3D turbine geometry, which will be further refined using the in-house CADO optimization framework [5]. CFD simulations of the optimized geometry evaluate the turbine performance across a range of operating conditions, resulting in a turbine performance map that is required to perform off-design engine simulations.

2. Methodology

2.1. Mean Line Design tool

The Mean Line Design tool for preliminary turbine stage analysis has been developed in Python, leveraging various scientific computing libraries. Its development is guided by methodologies derived from academic textbooks [6], [7] and scientific literature [8]–[10], incorporating empirical correlations. The tool follows a modular, block-based structure, allowing flexibility in implementation and future expansion. It is built under the assumption of a repeating axial turbine stage, commonly used in high-speed propulsion applications. The tool is initialized with the required inputs, including kinematic parameters, efficiency estimates, and inlet conditions. The latter are sourced from fixed-point engine simulations conducted in EcosimPro [11] in combination with the European Space Propulsion Simulation Toolkit (ESPSS) [12], spanning a range of flight conditions, with Mach numbers varying from 0 to 3 and altitudes ranging from sea level to 23000 m. This wide operational envelope ensures that the turbine design remains robust across various flight regimes, accommodating both subsonic and supersonic operation. The considered operating points are summarized in Table 1.

Table 1. Inlet condition for three different Flight Mach numbers and altitudes.

M	Altitude [m]	Specific Power Output [kJ/kg]	Turbine Inlet Temperature [K]	Turbine Inlet Pressure [Pa]	Mass Flow Rate [kg/s]
0.2	2000	749.15	817.65	684402.13	11.23
1.5	12000	862.04	790.03	852361.99	10.11
3	23000	580.30	779.49	378918.43	8.19

Once the inlet conditions and kinematic parameters are established, the velocity triangles are constructed (see Fig. 2). These velocity triangles are critical in defining the flow characteristics throughout the turbine stage, dictating how energy is transferred between the working fluid and the rotor-stator system.

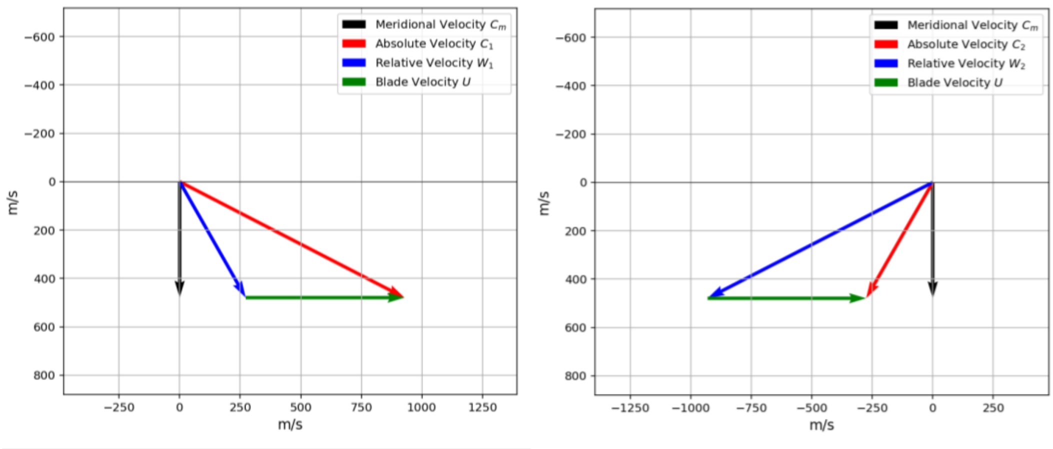

Fig 2. Graphical outputs of the MLD code for flight Mach 1.5, with the rotor inlet (left) and outlet (right) velocity triangles.

The computed velocity triangles serve as input for subsequent calculations, enabling the evaluation of thermodynamic states and geometric properties for both the stator and the rotor. To accurately determine thermodynamic properties, the tool employs CoolProp [13], an open-source library for thermodynamic fluid properties such as enthalpy, entropy, density, etc. CoolProp enables an accurate representation of the thermodynamic behaviour of hydrogen close to the triple point and in the supercritical region. To quantify aerodynamic losses within the turbine stage, an updated version of the Ainley Mathieson [14], [15] loss model is implemented. This model accounts for various loss mechanisms, including profile, secondary flow, tip clearance and trailing edge losses, computed separately for the stator and rotor, ensuring a comprehensive assessment of the turbine stage efficiency. The calculated losses are subsequently converted into efficiency. An iterative convergence process is employed to refine the initial estimates. The efficiency assumption is compared against the computed efficiency value, and the process repeats until the difference falls below a predefined convergence threshold. This iterative approach ensures that the final efficiency value accurately reflects the impact of aerodynamic losses and flow characteristics within the turbine.

2.2. Optimization

The optimization methodology employed in this work is Differential Evolution [16], a population-based optimization algorithm well-suited for complex, non-linear problems. The choice of DE is driven by its ease of implementation within Python-based computational frameworks and its ability to navigate highly non-linear objective functions, such as those encountered in turbine loss models, without requiring gradient information. The DE algorithm operates by iteratively evolving a population of candidate solutions, where each individual solution represents a design vector consisting of kinematic parameters.

At each iteration, three randomly selected individuals from the population undergo mutation, generating a trial vector through a weighted combination of their components. This process introduces diversity into the population, preventing premature convergence to local optima. The recombination step follows, wherein components of the trial vector are randomly exchanged with the original design vector to generate a candidate solution. The final selection process evaluates the objective function and determines whether the new candidate is retained in the next generation. The optimization process continues until a convergence criterion is met, ensuring that the final turbine design parameters achieve optimal performance within predefined physical constraints.

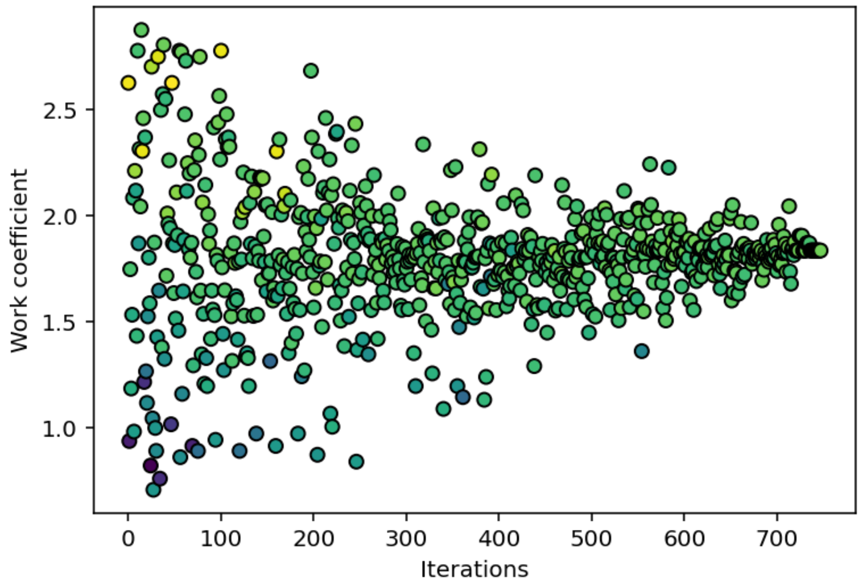

Fig 3. Optimization of the work coefficient for Flight Mach number 1.5.

For this application, the design vectors encapsulate kinematic parameters such as flow angles, velocity ratios, and loading coefficients, all bounded within ranges established through state-of-the-art turbine design considerations. Additional constraints are implemented to eliminate non-physical solutions, ensuring that the optimized parameters remain feasible within a real-world ATR engine configuration. An example of the optimization progress can be seen in Fig. 3.

2.3. 3D shape optimisation

The results obtained from the optimization routine serve as the foundational design parameters for a repeating axial turbine stage. These results include kinematic parameters, thermodynamic state properties, and efficiency values, collectively defining the baseline turbine geometry. The tool provides an initial estimate of critical geometric attributes, such as the metal angles of the turbine blades, the stagger angle, and the overall blade shape. Blade height, chord length, and aspect ratio are computed based on aerodynamic and structural considerations, while blade solidity is used to determine pitch and the required number of blades per stage. Additional geometric properties such as maximum blade thickness, trailing edge thickness, and tip clearance are evaluated to refine the aerodynamic and mechanical design of the turbine. The stage geometry is further defined by computing hub and tip diameters, enabling a full characterization of the turbine's flow path. These parameters collectively establish the initial 3D geometry of the turbine stage, as illustrated in Fig. 4. The optimized turbine geometry serves as the baseline for subsequent 3D design refinements, which will be performed using VKI's internal optimization tool, CADO. While the Mean Line Design tool provides essential first-order approximations of turbine geometry, the thickness distribution of the blades remains an open design parameter requiring further refinement. Integrating 3D optimization techniques will allow for improved aerodynamic shaping, enhanced efficiency, and the mitigation of secondary losses.

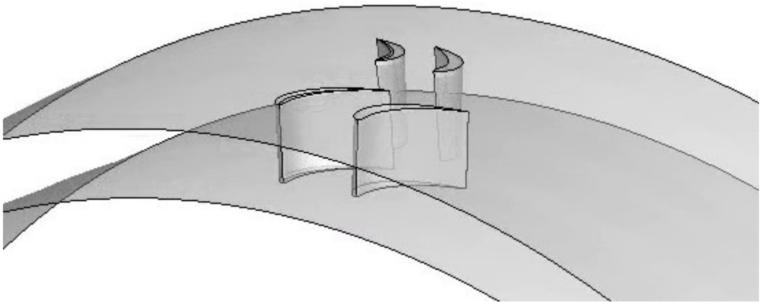

Fig 4. Baseline geometry of the mean line optimized turbine stage.

3. Conclusion and outlook for the final paper

A mean-line design tool is developed to facilitate the preliminary design and analysis of a repeating axial turbine stage for hydrogen-fuelled ATR engines. The tool employs a Differential Evolution optimization routine to determine optimal kinematic parameters, thermodynamic states, and geometric properties, ensuring maximum efficiency while maintaining physically feasible solutions. The final study aims to extend this framework by incorporating a 3D optimization process using the in-house CADO tool, refining the turbine stage geometry for improved aerodynamic and structural performance. Additionally, a comprehensive characteristic map will be generated to evaluate turbine behaviour under off-design conditions, providing valuable data for integration into broader thermodynamic cycle simulations.

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