Turbine Design and Optimization Tool for LUMEN Expander Cycle Demonstrator

R. H. S. Hahn, J. Deeken, M. Oschwald, S. Schlechtriem

1 DLR - German Space Center. Im Langen Grund, 74239 Hardthausen am Kocher

Abstract. This paper describes the tool created for design and optimize supersonic partial admission impulse turbine for LRE [1] application, which is commonly used in open cycle applications, while focusing on the models used to better predict the operational conditions of turbines for small thrust range engines. Also, the tool for turbine blade profile generation and the main assumptions for its optimization are discussed and the preliminary results presented, showing the possibility to improve the turbine performance for LUMEN Demonstrator operational range

Nomenclature

\begin{align*}
\alpha_{\text{eff}} & \quad \text{Effective inlet flow angle} \\
\bar{\ell} & \quad \text{Pitch-Chord ratio} \\
M_{2t} & \quad \text{Mach number at blade inlet} \\
\theta_s & \quad \text{Local surface angle w.r.t. axial frame} \\
\text{TPF} & \quad \text{Fuel Turbopump} \\
\eta_{\text{TS}} & \quad \text{Total to Static efficiency} \\
\text{mMOC} & \quad \text{Modified Method of Characteristics} \\
\text{BRT} & \quad \text{Blade Runner Tool}
\end{align*}

1. Introduction

Recent studies have shown the feasibility in utilization of Methane as fuel for expander bleed engine, resulting in the development of various thrust class engine, going from cycle demonstrator to operational flight versions. However, the elevated molecular mass of CH4, combined with low temperature at turbine inlet condition results in possible performance degradation.

LUMEN [2] (Liquid Upper stage deMonstrator ENgine) is a breadboard engine operating in an expander-bleed configuration, driven by two separate turbopumps (oxidizer and fuel turbopump). As an open cycle, this demonstrator requires utilization of supersonic impulse turbines in order to provide enough energy to drive its pumps, while minimizing the amount of required bleed mass flow in the system. In order to achieve the best performance possible, the turbine shall use a blade geometry which is compatible with the system requirements. Therefore, the use of standard geometry from open literature is limited. Thus, a turbine optimization tool was created and implemented in the turbopump design model in use by DLR Lampoldshausen.

2. Turbine requirements and design constrains

During the design procedure, the requirement for turbine performance could accept a relatively low efficiency design. Thus, the use of blade geometry from catalogue was could be suitable for this application. Taking advantage of the elevated total pressure available at the turbine inlet interface according to the engine architecture, the possibility to use the gas specific work resulted in an impulse turbine with stator pressure ratio of 12,5. This value was adopted to maximize the pressure ratio while the turbine exhaust pressure was adjusted for no less than 250kPa at lowest load point. The stator consists in an axisymmetric conical nozzle with convergent and divergent section design to provide the required expansion ratio with minimum losses. At the end of conical section of divergent part, the flow is directed through a truncated cylindrical path in order to maintain the homogeneous flow at the designed exhaust Mach number.

While considering a rotational speed in the range of 50kRPM, the circular velocity at the meridional diameter was kept in the range of 350m/s. This resulted in a relative inlet Mach number at rotor of around 1,35. In the operational envelope, however, the relative Mach number could vary from
1.25 to 1.8, limiting the options of blade geometry available for such application, as presented at the Table 1.

### Table 1. Supersonic blade profile from Deych [3]

| Blade Profile | α_{eff} | t | M_{2t} |
|---------------|---------|---|--------|
| R2118V        | 18-20   | 0.60-0.70 | 1.30-1.90 |
| R2522V        | 20-24   | 0.54-0.65 | 1.35-1.60 |
| R2926V        | 23-27   | 0.53-0.63 | 1.35-1.60 |
| R3330V        | 28-32   | 0.51-0.61 | 1.35-1.60 |
| R3025V        | 23-27   | 0.48-0.58 | 1.35-1.75 |

Considering the operational envelope, the blade R2118V was chosen as standard configuration for the LUMEN TPF. Using data from literature and at operational condition the design performance can be seen in the paper [4], where the CFD simulation of this configuration operating at the first operational condition was performed. The quasi-2D analysis, taking the main losses for small size turbines as presented at [5], was performed with similar results.

The logical next step was a design optimization for the turbine in order to increase its efficiency. Since the amount blade profile available in the literature was small and not necessary compliant with the all requirements from the cycle, the current design was modified in order to provide the maximum power for the system, while keeping the main requirements for the project.

### 3. Optimization

In this analysis, the stator design and conditions was kept as the original. Thus the inlet boundary conditions, as pressure, temperature and its geometry were unchanged.

For the blade optimization tool, was evaluated different method of blade profiling implemented in the Blade Runner Tool, as Bezier curves, modified Method of Characteristics, Polynomial curves, multi-arc, etc. This work, however, focus on the first two methods in order to simplify the options and amount of time available for the optimization.

Using a Smith chart [6], was possible to calculate the expected performance according to the stage flow factor and stage loading factor of current design as being η_{TS} = 0.747. However, the current design result is well below the performance obtained using the Smith chart. The main reason is related to the leakage losses and other performance degradation phenomena as described at [5]. Using the current blade profile, the first step was modeling it using the parameter tools in order to have it as starting point.

For the profiling generation using Bezier method was adopted 4 control points, divided as 2 main points for the suction surface and 2 for the pressure surface. The inlet and outlet angle for both surfaces as adopted as variable, while the inlet and outlet angle of Camber line was adjusted to match the inlet flow at relative frame. A second general consideration was that the angle of camber line at trailing edge was equal to the leading edge of the profile. This consideration was adopted in order to simplify the optimization model and reduce the total integration time for each step. During the optimization, the flow path was evaluated, in order to minimize the local \( \frac{\partial \theta}{\partial x} \). Also, the next step was reducing the flow path area ratio in order to reduce the chance of flow blockage at blade channel and keep the design inside the Kantrowitz limit [7]. Finally, the pressure and suction surface can be analyzed with a modified method of characteristics in order to have an initial glance about the flow at the blade surface.

The program also allows to select the leading and trailing edge design. In this work, all models was adjusted to circular corners with 0.05mm radius. This radius was adopted in order to comply with the manufaturability, without have possible weakening of these surfaces. Thinner edges would be desirable in this geometry, but due to stress and loads, smaller radius could become unfeasible.

Another possibility was the use of sharp edge, where the suction and pressure surface meet each other creating a very thin edge. This design most common in the standard MOC is unfeasible and is omitted for the optimization. An alternative for the sharp edge would be the “y” or “x” curvature
displacement, where the corners are shifted accordingly in order to make the profile feasible, while taking the supersonic flow into consideration. The last alternative possible for this tool, despite not being implemented in the optimization is the combination of curvature displacement, where the geometry is shifted in “y” direction, while the chord is modified to accommodate a flat surface.

4. Results

For the optimization, was selected the result with smaller variation in all parameters for the design cycle. Changing the control points while evaluating the main results of the flow path, the expected gas-dynamical behavior (when considering the mMOC) and geometry, allows obtaining the first group of profiles. From this group, were selected two geometries, which are presented below.

4.1. Original blading – R2118V

The results of the original design, as mentioned above, were presented at [4]. In order to perform the optimization, a simplified analysis was made, considering similar boundary conditions. The main difference was reducing the computational size of model by using a periodic region equivalent to 1/5th of total circumference. Also, a simple frozen rotor was chosen in order to reduce the processing time for each simulation.

The blade profile was generated using the design parameter in the Blade Runner Tool in order to increase the fidelity of the optimization starting point. In the Figure 1, is shown the pitch representation for this design and is possible to verify the small blade rotation to match the required flow incidence angle.

![Figure 1. Left: Pitch versus chord. Right: Area ratio of flow passage](image)

As the result, the BRT provide the area ratio at the flow path, presented at the graph of Figure 1. This parameter is used to evaluate the Kantrowitz limit and reduce the possibility to have a flow blockage at the blade inlet.

Using the results presented at [4], the simulation was adjusted and the results compared. For the simulation presented in this paper, the efficiency obtained was $\eta_{TS} = 0.516$, which is very similar to [4]. The Static enthalpy and Static Entropy distribution in this design configuration is presented in the Figure 2.
As the result, the simulation boundary conditions were kept constant for all analysis and the only difference was the blade geometry, despite the meshing settings being similar.

4.2. First optimization – RO2222BV

The first result for the optimization had mostly of the inlet and outlet angles changed in order to accommodate the flow and minimize the normal shock. The $\frac{\partial \theta}{\partial x}$ was minimized at the location of previous flow detachment while increased in the next adjacent section, resulting a profile with equal solidity and slightly bigger total turning angle. This allows also minimizing the flow incidence angle in this design.

This optimization was also aiming to keep the geometry symmetric as much as possible. In this design the area ratio of flow passage was kept almost constant, with a small expansion at the middle point, as shown at Figure 4.
This design has a $\eta_\text{T} = 0.535$, showing an increase of efficiency from the standard design. The Static enthalpy and entropy are presented at the Figure 5, where is still possible to see the high entropy region at the suction surface.

4.3. Second Optimization – RO2623BV

The second optimization was intended to minimize the total load, while the stage flow factor was kept constant. The angle of camber line at leading and trailing edge was equal as the previous model, also allowing achieving zero incidence angles for this design. The $\frac{d\theta}{dx}$ was reduced at the blade middle point to minimize the possibility of flow separation. For this geometry, the location of control point for the suction and pressure side was decoupled, allowing the surfaces change independently, resulting in a profile smaller than the standard configuration, as shown in the Figure 6.
Figure 6. Comparison between the profile RO2623BV geometry with the original design

Also, in order to comply with the Kantrowitz limit, the pitch ratio was reduced, resulting in an increasing number of blades (change of solidity), while the area ratio where kept within limits, as shown in Figure 7.

Figure 7. Area ratio at the meridional flow path for the RO2623BV design

The result is a design with a $\eta_{TS} = 0.554$, showing an improvement from the previous configuration. The analysis of static enthalpy and entropy are presented at the Figure 8.
Figure 8. Left: Result of Static enthalpy using RO2623BV blade design. Right: Static entropy from the same simulation.

The results for this model were the basis for the evaluation of changing in solidity using BRT, as presented in the section below.

4.3.1. Optimization of RO2623BV

One further step was change the area ratio constrains from previous design. While keeping the geometry similar, the solidity was changed in order to alter the axial area ratio profile for this configuration, as show at Figure 9.

Figure 9. Area ratio at the meridional flow path for the optimization of RO2623BV geometry

A minimum efficiency improvement was achieved with this optimization. The Figure 10 show the optimization of solidity in this configuration has an efficiency increase of around 0,3% while the flow conditions are similar.
4.4. Third variant – RO2011MV

Adopting the same design conditions and using as initial basis the RO2623BV geometry as well as the imposed restriction previously defined, the last variant was design using the mMOC, which the original method is presented at [8] and [9]. In this configuration, in order to reduce the blade loading, the Mach number at suction and pressure surface was chosen to be 1.10 and 2.00 respectively. The main modification from the traditional MOC design consists in taking the lading and trailing edge into consideration. The comparison of this profile with the standard and the previous design is presented at Figure 11.

The results for this optimization, as presented at the Figure 11 show the highest performance until now, with $\eta_{TS} = 0.577$. Taking into consideration the same boundary conditions as the previous design, the mMOC method together with the optimization routine from BRT can provide reasonable results in this range of application, as shown.

5. Conclusion

The current optimization model implemented in the blade design tool has performed well for the current conditions adopted, as possible to verify at Table 2.
Table 2. Optimization results

| Profile        | $\eta_{TS}$ | $\eta_{TT}$ | $\Delta\eta_{TS}$ | $\Delta\eta_{TT}$ | $\bar{t}$ |
|---------------|-------------|-------------|-------------------|-------------------|----------|
| R2118V        | 0.516       | 0.520       | ---               | ---               | 0.682    |
| R2222V        | 0.538       | 0.546       | 0.022             | 0.026             | 0.682    |
| R2623V1a      | 0.554       | 0.562       | 0.038             | 0.042             | 0.591    |
| R2623V2a      | 0.557       | 0.568       | 0.041             | 0.048             | 0.521    |
| MOC01         | 0.577       | 0.589       | 0.061             | 0.069             | 0.521    |

Despite the flow separation expected to be eliminated with the optimization methodology, in all cases evaluated it was present, despite being minimized. An increase of approximately 6% in efficiency using this tool was representative and will be further investigated.

Through all the performed analysis, the performance increase was identified as a combination between reductions of multiple losses contributors as follows. The adjustment of local turning angle $\theta$ at region just before the flow separation together with redirection of the reflected shock wave helped to minimize the degree of flow detachment at the blade surface, which causes a significant deceleration of the flow, resulting in the reduction of the local energy available for the rotor. However, the adjustment of the local turning angle change the interaction between the compression and expansion lines, resulting in a flow with high transition of local direction. Last, but not least, the adjustment of the local turning angle at compression and expansion lines interception also was aimed to reduce regions with high speed friction losses without reduce the integral transferred impulse for the rotor.

The next step for this work will be the design optimization of stator, following by the coupled optimization model. This may increase the improvement range by allowing more efficient subcomponents together.

Despite this work was done for partial admission supersonic impulse turbine, this tool also can design full admission and subsonic/transonic reaction turbines. Furthermore, the optimization method for this second type will be investigated in future works.

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7. References

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