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Performance estimation of supersonic impulse turbine at transient conditions

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Abstract

During startup as well as operational point changes, a supersonic impulse turbine can encounter gas dynamical conditions in which can result in excessive loads or immediate loss of performance. Effects such flutter [1], buzzing [2], under and over expanded flow and full gas blockage [3] can appear and induce high levels of stress, reducing the expected life of the turbine or deteriorating the expected efficiency.

Most performance prediction method for supersonic impulse turbine are restrictive for one single operational conditions and doesn't take into consideration the majority of effects in the system, as partial admission, leakage losses, etc. However, in a throttleable engine, the optimization must cover all operational envelope, as well as the transient conditions in between, as well as the startup, resulting in increase of performance in all expected conditions.

Different considerations need to be taken into account while evaluating the transient effects during performance estimation at such low load points. The most significant constrain is the evaluation of the das-dynamic condition and the boundary-layer effect during the analysis process in the pre-defined operation range.

The main models for design turbine systems applied for LRE are adjusted to engines with medium to high thrust levels (usually above 50-100kN), where various losses, as friction, leakage, non-uniform flow, partial admission and others are considerably smaller than the performance generated per rotor blade. With a decrease of nominal thrust at design conditions, especially during starting conditions or transient points, the turbomachinery size decreases considerably, result in losses outside of the well-known modelled ranges, making the performance estimation of such components imprecise.

The improvement of in house tools for off-design conditions prediction and its validations with experimental test cases allow to better estimate the effects of startup conditions and transient effects as well as its expected performance, increasing reliability on current tests and futures designs, with adequate precision for turbomachinery ranging from small sizes to standard high thrust models.

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1. Introduction

Turbopump fed liquid propellant rocket engines can be originally divided in two basic configurations: closed cycle and open cycle. In the former case, the full turbine mass flow rate is injected into the main combustion chamber, providing low adiabatic specific work, but enough mass flow rate to deliver the required power, which is characterized by a high turbine mass flow rate and a low expansion ratio. The required enthalpy for the expansion is provided either through the regenerative cooling circuit (expander cycle) or through pre-combustion of the propellants (staged-combustion). On the other side, for the open cycle, the turbine mass flow rate is not expanded through the main combustion chamber and the pressure ratio is supercritical, therefore supersonic turbines are the preferred choice. Due to the bleed mass flow rate, a major part of the engine performance is governed by the turbopump losses [4. It is therefore imperative to maximize the utilization of the available adiabatic specific work, by expanding the driver fluid at high levels, resulting in supersonic flow at this system. This motivates the optimization of turbine efficiency for the required operating conditions during its design phase.

Due to the optimization to operate at supersonic conditions, most turbine blades will show poor performance if the flow are outside its operational designed envelope. Considering that an usual design will provide adequate efficiency at off-design condition, where the engine are required to continuous operate, during the transient phase, the blades can experience conditions that may result in its non-operability due to the losses associated at such conditions are often order or magnitude higher than the available energy for the starting condition or operation point change.

2. LUMEN Demonstrator

LUMEN (Liquid Upper stage deMonstrator ENgine) [5 is a breadboard LOX/LCH4 engine [8 operating in an expander-bleed configuration. It is driven by two separate turbopumps (Oxidizer and Fuel TurboPump, resp. OTP and FTP) arranged in parallel configuration. In order to minimize the bleed mass flow rate, this demonstrator requires the utilization of supersonic impulse turbines in order to provide enough energy to drive its pumps. The OTP (Oxidizer turbopump) is used as the reference case for the current study. The following sections detail the relevant design features and approach..

2.1 Turbopump

The turbine design methodology applied for LUMEN OTP is mainly based on Ovsyannikov, Deych, Tschelikov and Belyaev [12[11[10[7[69), 6), 10), 11). Due power constrains, some modifications were required to comply with the reduced size inherent of such thrust class engine, where parameters were outside of the optimum statistical validity range.

Taking advantage of the elevated total pressure available provided by the engine cycle at the turbine inlet condition, the possibility to use the gas specific work resulted in an impulse turbine. The pressure ratio was maximized to a value of 13 while the turbine exhaust pressure was adjusted for no less than 250kPa at lowest load point as main design constrain. This constrain is needed to provide a sonic detachment between the turbine cavity and ambient, resulting in a constant operational donation in the turbine environment independent of the ambient pressure and temperature of the test. While considering a rotational speed around 25kRPM, the circular velocity at the meridional diameter was kept in the region of 180m/s. This resulted in a relative inlet Mach number of rotor of approximately 1.65. In the operational envelope, however, the relative Mach number could vary from 1.25 to 1.80.

The main characteristics of the OTP reference turbine are summarized in Table 1. The total inlet pressure and temperature (Poo and Too respectively) are obtained from the engine cycle analysis, whereas the rotation speed ω and the rotor tip diameter D_tip result from geometrical constrain from the design process associated to the material properties and manufacturability as well as compatibility with pump design requirements. The spouting velocity c_0, stator absolute exit velocity c_2 and Mach number M_2 result from the adopted expansion ratio of π=13.

Table 1. Supersonic blade profile from Deych

Design	α_{1eff}	$\bar{t}$	M_{2t}
R2118V	16-20	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

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R3330V	28-32	0,51-0,61	1,35-1,60
R3025V	23-27	0,48-0,58	1,35-1,75

The meridional contour for the LUMEN turbine was defined according to recommendations by Ovsyannikov. It suggests geometric constrain for the blade height and chord based on the meridional diameter and radial gap in case of an unshrouded rotor. These constrains are defined in accordance with losses models for supersonic impulse turbines, aiming to minimize the performance degradation due to friction, leakage and reaction degree variation along the blade span.

Since LUMEN OTP uses axisymmetric stators, the blade height and chord ratio are limited according to the number of stators used as shown in the Table 3. An increase of blade height h_1 reduces the radial gap ratio $\bar{\Delta}$. This minimizes the leakage but at the same time also increases the velocity ratio between hub and tip U_(h/t). This in turn results in an increase of losses due to the reaction degree variation along the blade span. A span wise variation of u/c_0 would require a complex rotor and stator geometry. This would be impractical for such a small size turbine. Furthermore, the performance recovery could easily vanish compared to the losses induced by the partial admission degree (ε), in particular for such high span ratio blades. Based on these considerations, three stator nozzles resulted in good compromise in performance and feasibility for the current application. It agrees with recommendations by Ovsyannikov and Deych.

3.Transient operation

During the starting transient, the rotor inertia results in a mismatch of input power through stator and shaft power. This will result in a high initial relative inlet Mach number in the rotor frame of movement. According to the rotor design, the consequence can be a performance loss above the maximum available for a self-starting condition of the turbine.
The starting transient can be divided in two main classes as follows.

3.1. Slow starting

With a slow starting condition, the rotor speed can be kept close to the expected relative inlet Mach number, resulting in a minimization of friction and shock losses that ultimate will contribute to the increase of performance degradation. Depending on the inertia of the rotating part of the turbine, this option can result in a long starting transient time, which will require a large amount of propellant for such inefficient phase of the engine. Also, during the transonic phase of the stator and/or rotor, there is a possibility of instability region caused by the shock formation at the throat of the stator and/or the stator blading, according to the designed condition of such component.

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3.2. Fast Starting

In the opposite side of the presented starting transient, the fast start can minimize the instability caused by the shock formation at the throat of the stator and/or the stator blading, resulting in lower blading loading during this phase. This also minimize the propellant consumption required for a full start and by consequence, the optimum performance can be quickly achieved.

On the other hand, the fast starting transient can produce conditions that are adequate for a “buzzing” effect to start. The fast increase of inlet pressure with the slower acceleration of the rotor will create a relative inlet Mach number at the rotor that can be outside the design limits. It also can completely choke the rotor blade, producing a supersonic instability at this part of the turbopump.

The compromise between both options need to be asserted according to the rotor inertia and power delivered to the turbine in combination with the expected performance of the system at off-design condition

3.3. Operation point change

Less critical than the stating, the operation point chance can also provide mismatch between the power delivered and consumed in both directions as stated. The decrease of inlet power will provide conditions to reduce the relative inlet Mach number, while the pumping effect of blade passage can create a reduction of the pressure between stator and rotor, which can result the possibility of flow separation at the stator.
This last condition can be also identified during shut-down procedure. However, the shut-down conditions will not affect the overall performance and therefore can be ignored for the purpose of this work.

4. Calculation method

In order to calculate the performance during the transient conditions, the stator is initially analyzed as a single nozzle. Such approach is valid for a supersonic impulse turbine and in case of reaction design, the stator need to be aerodynamically evaluated ate each point of the transient and will not be part of this work.

Since the thermal inertia of the measurement system may not coincide with the starting dynamic, the outlet conditions were calculated using gas-dynamic conditions as presented by [7[10 using the total inlet pressure and temperature. Considering the test approach used to validate this model, the inlet total temperature can be considered constant, while the total inlet pressure was measured close to the stator inlet. The result of steady state condition, where the thermal inertia can be neglected, allowed having a good precision of the calculation method.

5. OTP Test results

During second half of 2021, a test campaign was carried at test bench P6.2 in order to characterize the assembled turbopump performance (Fig. 4). The chosen operating fluid was water and GN2 for the pump and turbine side respectively. The performance analysis was carried out using similarity models.
Later in 2021 and most of 2022, test campaigns at the new P8.3 test stand at DLR Lampoldshausen were conducted. During these test campaigns, the initial starting transient was evaluated, from slow to fast conditions. It allowed also to verify the performance at operation conditions far from the expected design of LUMEN, which resulted in precise identification and a refinement of the losses in the OTP Turbine.
Inlet pressure between 1.5bar until approximately 60bar were tested, with starting conditions from 0.3s to long slow ramp of above 30s also took part of the test during the OTP investigation.
For this work, most of the evaluations of turbine performance were conducted at the first second, while the rotor inertia was not following the gas-dynamic condition of the stator. Two main starting transient profiles allowed identifying and validating the model, as shown as follows.
For the first analysis, the adopted starting point was approximately 60bar, which was assumed to be achieved below 2 seconds. The stator pressure was supplied at a rate of around 140bar/s at constant temperature of around 270K, as shown in the graph of Figure 1.

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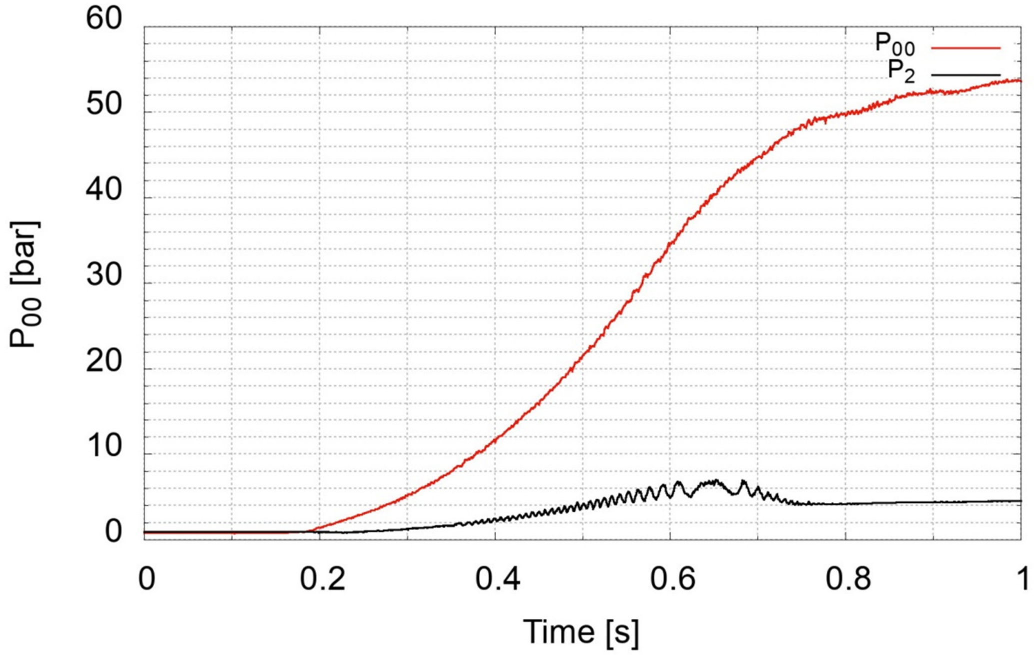

Figure 1: Total inlet pressure and static outlet pressure

At such rate, the stator outlet pressure can be seen to oscillate at low rate between 0,35s and 0,7s, where the rotating speed is high enough to allow non-shocked flow pass through the rotor. In such steep pressure gradient, the total-to-static pressure ratio (Figure 2) shows the stator quickly achieves sonic flow immediately the inlet pressure is applied. In such scenario the rotor blade load is quite high at the beginning and the possibility of flutter or supersonic buzzing is considerable, despite not be part of this analysis.

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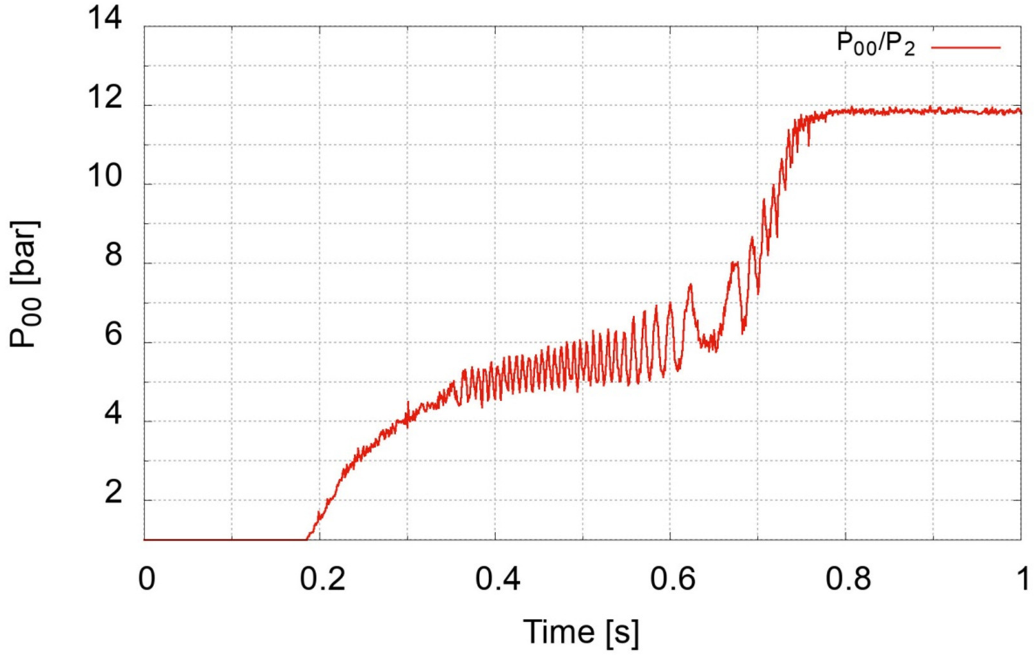

Figure 2: Stator pressure ratio (Total-to-static)

As shown in the Figure 3, the rotor starts to move around 110ms after the pressure is applied at the previously mentioned rate. This results in an acceleration rate of approximately 40kRM/s,

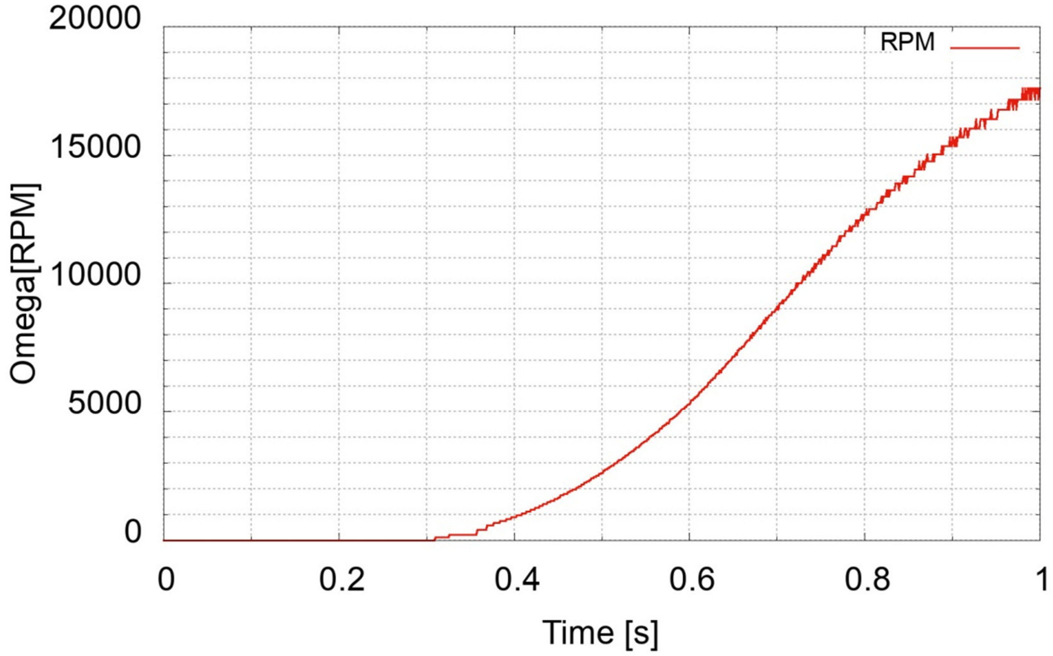

Figure 3: Turbine rotating speed

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The stator outlet temperature is calculated as shown the Figure 4, as well as the Total temperature in the rotating frame.

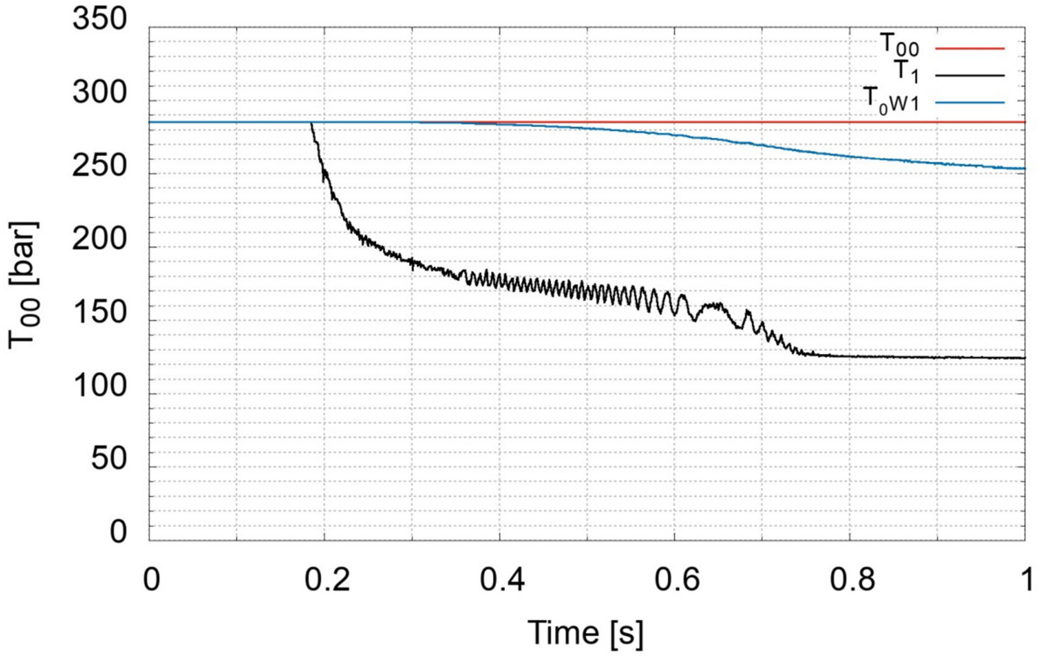

Figure 4: Total inlet and static outlet Temperature at stator and total inlet temperature at stator in relative rotating frame

The gas-dynamical conditions identified at this transient is then used to evaluate the Mach number at stator exhaust as well as the Mach number at the relative frame of rotation as seen by the rotor blade, which is shown in the Figure 5.

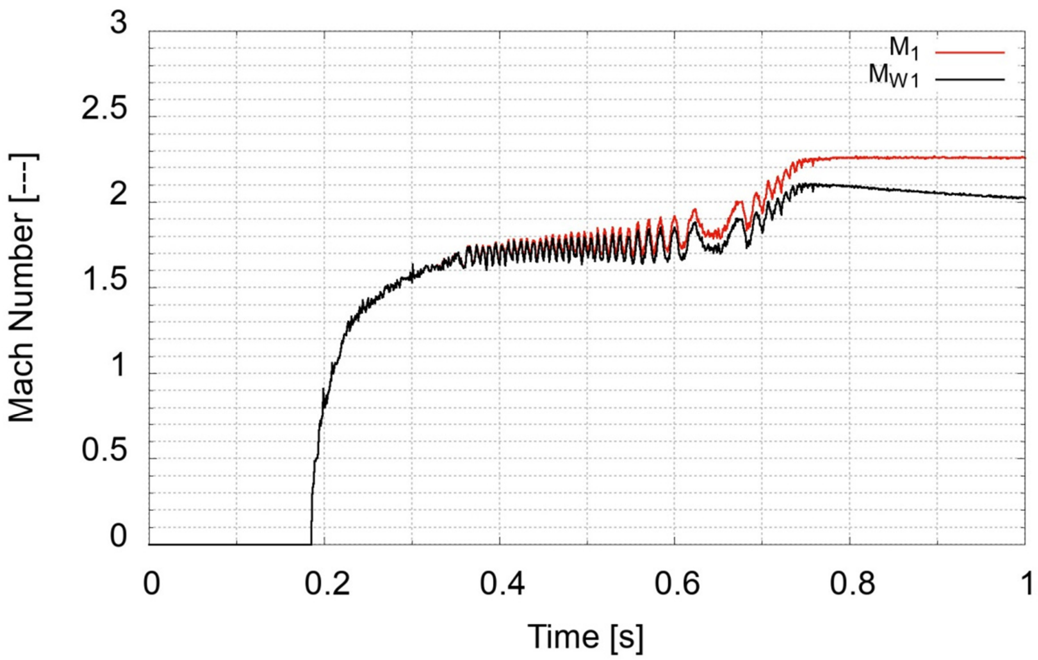

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Figure 5: Stator Mach number at outlet and Rotor relative inlet Mach number

The fast start can show the discrepancy between the Mach number at stator outlet and the relative frame of rotation. At such levels the losses in the rotor ar maximum and, as presented in the table (Figure 5), those values are outside the optimum conditions for this turbine.
The next evaluation of starting transient shows the slower condition, where a total pressure in excess of 7bar was used with a pressurization rate of around 20bar/s at constant total inlet temperature in the order of 275K.

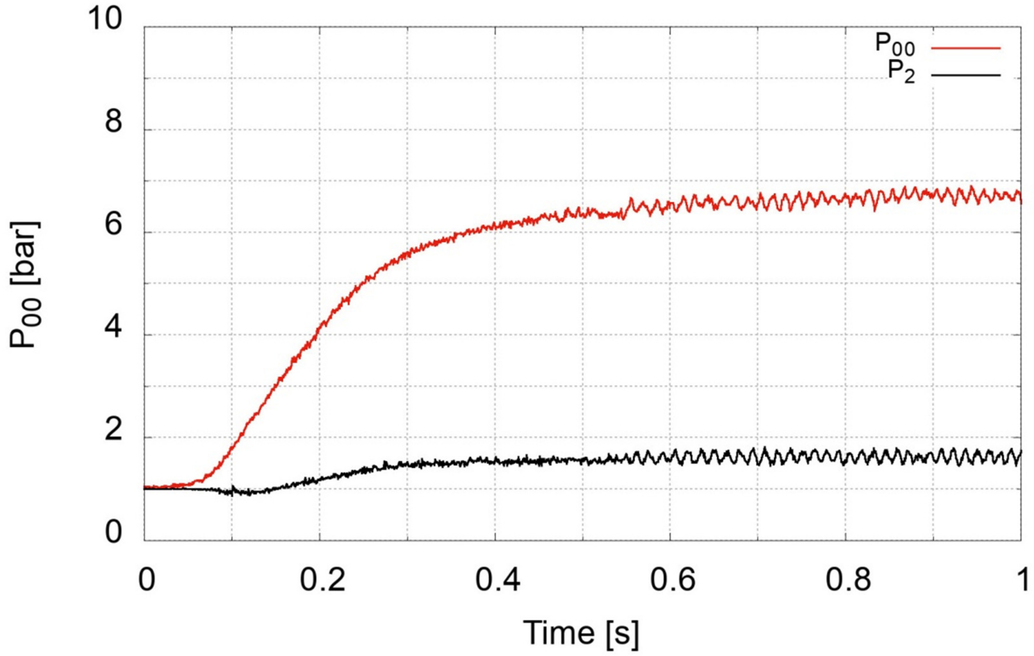

Figure 6: Total inlet pressure and static outlet pressure

At such pressure profile, is possible to identify the continuous oscillation of the total inlet pressure due to valve system of the tested hardware, where reflects in the static pressure at stator outlet, as shown in the figure Figure 6.

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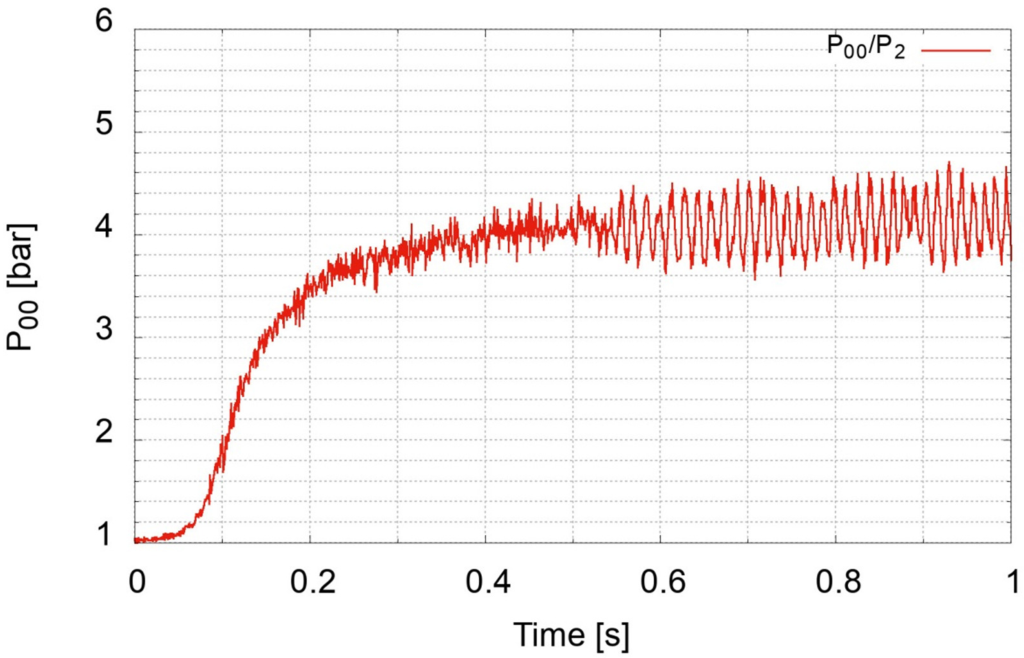

Figure 7: Stator pressure ratio (Total-to-static)

The total-to-static pressure ratio (Figure 7) shows the fast shock formation at stator nozzle throat. The oscillation is inherent of the pressure losses at the valve system operating way below its expected pressure limits

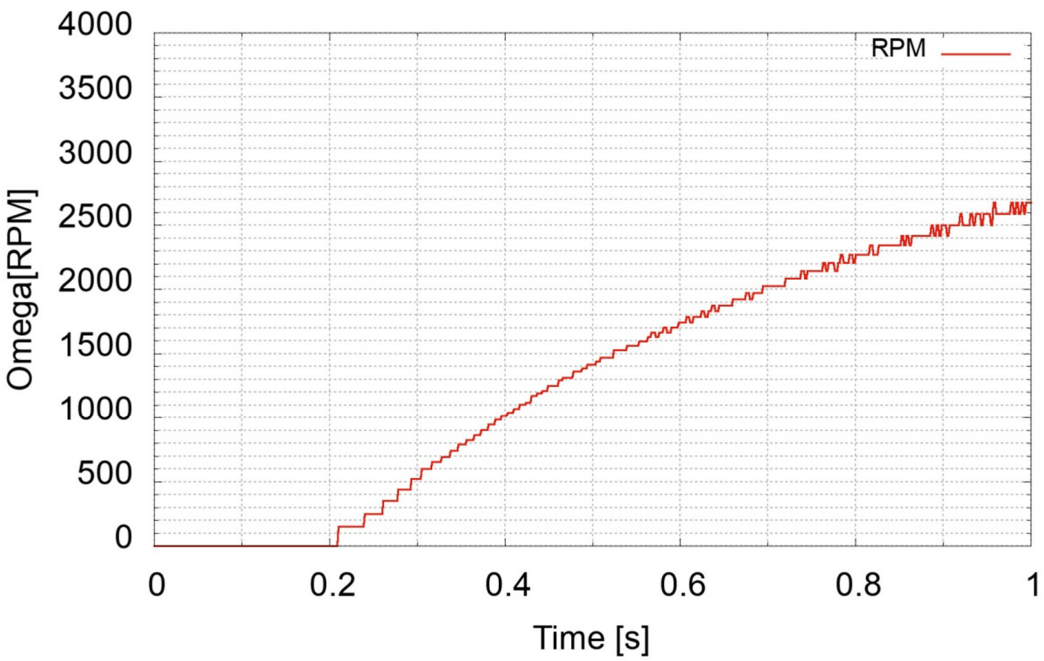

Figure 8: Turbine rotating speed

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At such starting transient profile, the rotating speed rate is quite low, as show in the Figure 8), which allows the pressurization and gas-dynamic conditions match the slow inertia of the mechanical system.

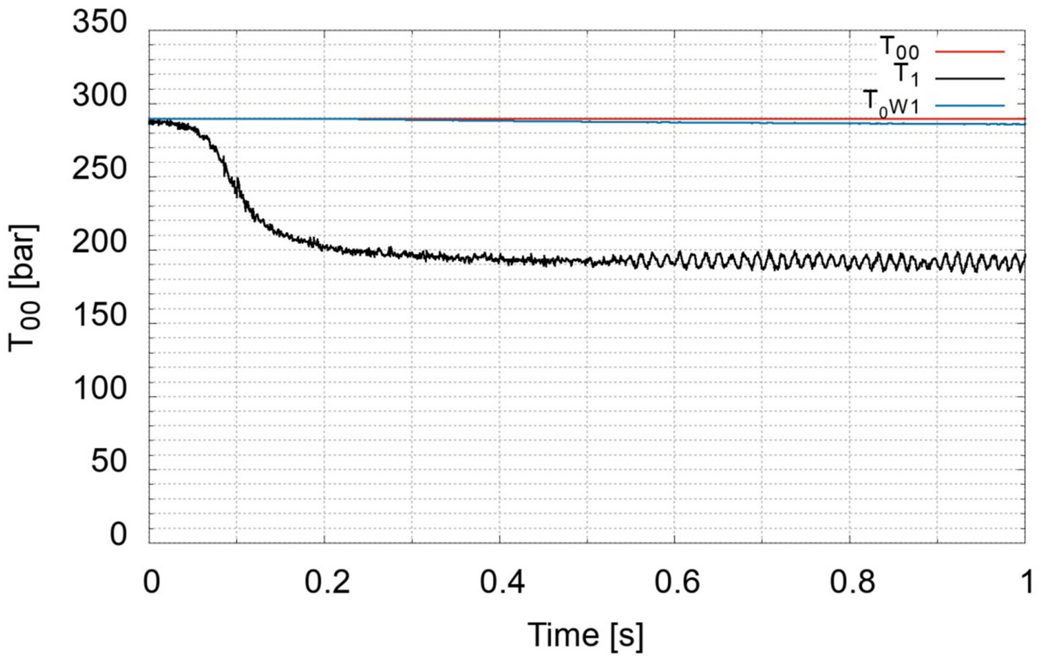

Figure 9: Total inlet and static outlet Temperature at stator and total inlet temperature at stator in relative rotating frame

Once more, the total temperature at rotating frame can be calculated, as well as the static temperature of the nozzle exhaust, as shown Figure 9.

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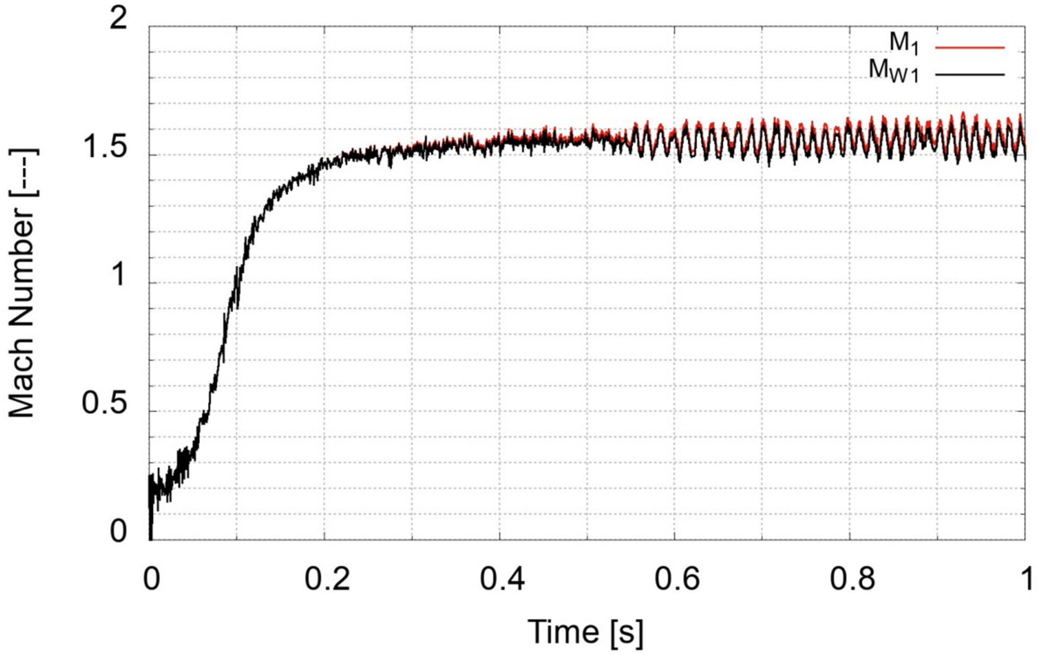

Figure 10: Stator Mach number at outlet and Rotor relative inlet Mach Number

The slow condition of this starting dynamic result in a relative inlet Mach number stay within the desired limits of performance, as shown in the graph of Figure 10.

5. Performance validation

Using the presented set of equation, the relative inlet Mach number in the rotor can provide the initial loss magnitude for the turbine. At the stator, the Figure 11shows the dependency between the losses measured in a cascade condition, which was validated for LUMEN OTP during P6.2 and P8.3 test campaign.

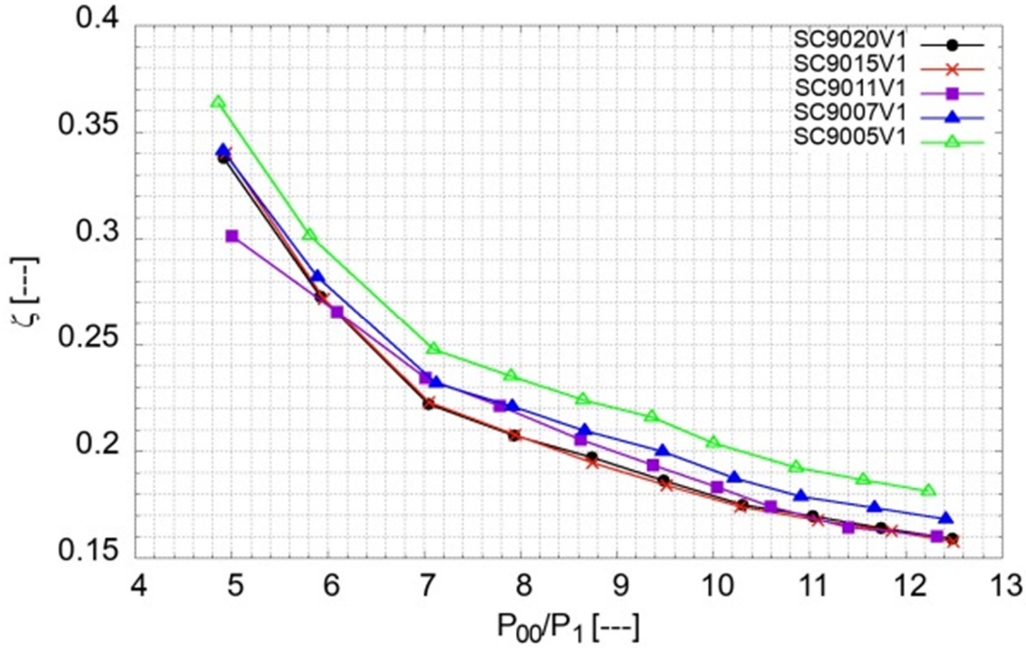

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Figure 11: Stator losses in function of outlet Mach number for various profiles [9

In all cases, during the first 150ms the stator is already at expect conditions. The losses are usually not elevated and can be reduced until possible flow separation. For this work, a complete performance map in function of the inlet pressure and temperature was created and implemented in the calculating code of Blade Runner.

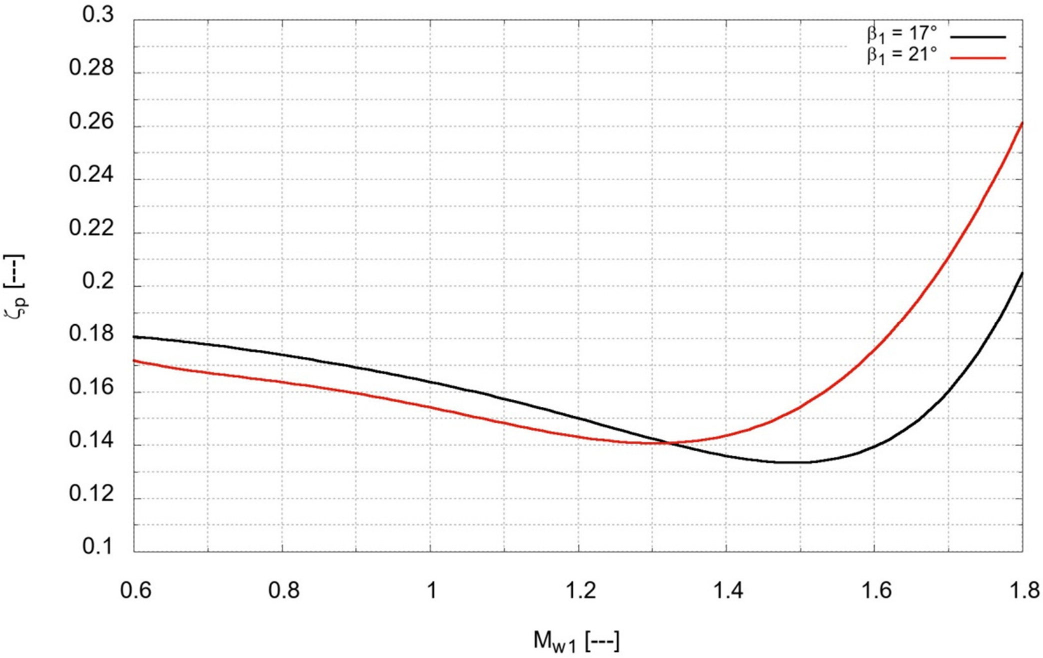

Figure 12: Rotor losses in function of Inlet Mach number

Finally, to assert the final performance, the losses inherent of shock structure and friction for the rotor, as show Figure 12, were evaluated in each point of the transient.

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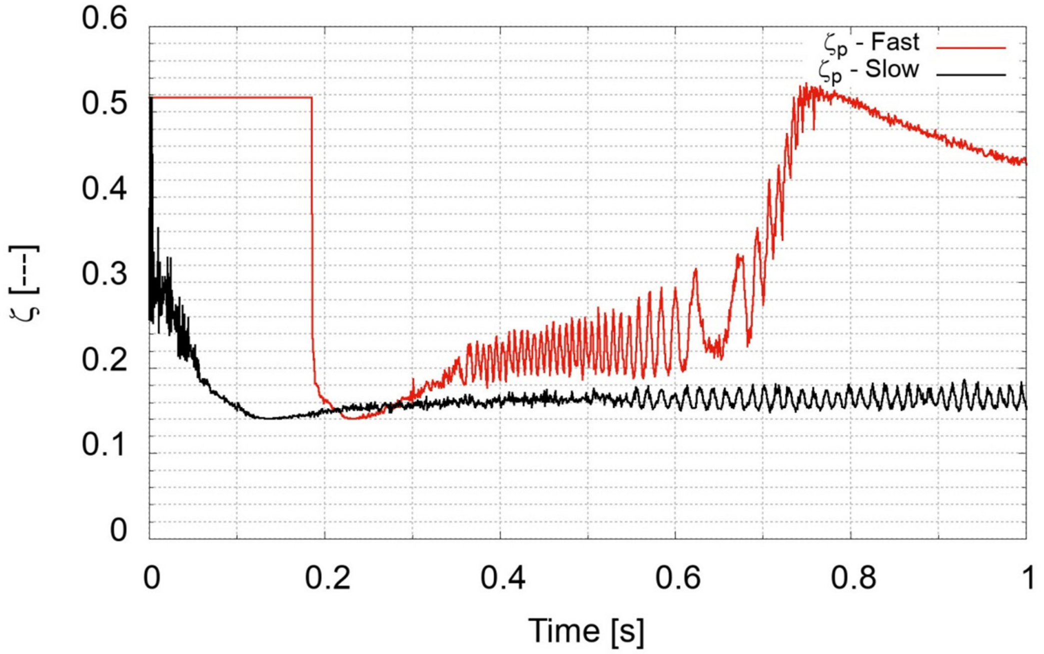

Figure 13: Rotor losses calculated during transient

The performance during transient, as shown Figure 13, indicates that the slow transient adopted produces lower losses, while the fast transient would take a bit longer to achieve the desired rotor efficiency.

5. Conclusion

Knowing the performance during transient is essencial for the cycle understanding and evaluate ther minimum operating condition required for the constrained gas-dynamic parameter available. During this work, was possible to identify the two extremes of the staring transient for a supersonic impulse turbine operating at partial admission.

The analysis of performance allows achieving an optimum condition in minimizing the overall losses, while identifying the dynamic that can result in major losses. The current work implemented in the Blade-runner tool will allow to better design the transient for a turbopump while understanding its major characteristics at conditions not usually evaluated.
The work has shown also the major phenomena happening during the transient and its importance of analysis. Especially for the low size of turbomachinery, as the case for LUMEN demonstrator. The validation of such models will also improve the design methodology while considering the presented effects in the design phase.

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