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TURBOJET TRANSIENT PERFORMANCE SIMULATION

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Abstract. *This work aims to give the reader an overview of the gas turbines modeling, particularly for the turbojet engine, considering the study at design and off design point at steady state operation and the transient behavior of the engine. Initially the jet engine was modeled to calculate the design point operation. The assumptions and calculations for determining the working fluid properties in each component and the parameters for assessment of its performance are presented. At off design operation, it was presented a methodology for determining the operating line based on components maps operation: compressor and turbine. It was made use of the control system; the controller presented was the Proportional - Integral - Derivative (PID) and the parameters for evaluating the transient response. The study was conducted for a turbojet engine operating at transient regime and the results obtained were compared using two software's, one developed in house and the other a commercial software.*

Keywords: *gas turbines, simulation, performance, transient, turbojet*

1. INTRODUCTION

Gas turbines modeling plays an important issue on gas turbine design. Many mathematical models have been developed to simulate the engine behavior and are commercially available, to name just a few: GasTurb, GSP and NPSS. The mainly difference between them is the level of details regarded.

For preliminary studies on engine performance, basic models are set to evaluate basic performance indicators such as thrust and fuel consumption. In these basic models, a set of engine features are not taken into account or simply set as a standard values, neglecting their change with time. Examples of these considerations are the amount of bleed air on compressor and the heat exchange rate between the work fluid and engine casing. They are both ignored on the first approach at design point in several text books like Gas Turbine Theory (Saravanamuttoo *et al*., 2001) and Gas Turbine Performance (Fletcher and Walsh, 2004).

Saravanamuttoo *et al.* (2001) covers the whole calculations on engine design point for the turbojet and turbofan. At off-design calculations it gives the details procedures for single-shaft turboshaft and turbojet. Transient performance is treated in a more qualitative way. Saravanamuttoo *et al.* (2001) briefly discusses the acceleration and deceleration as a result of the net torque produce by changing the fuel flow. The principles on control systems are presented in a simple way with a general description of this theory.

Walsh and Fletcher (2004) cover the whole engine operation. The transient control approach is made by the presentation of a qualitative description of a generic control system. This approach is kept when treating the transient mechanism. The book covers the compressor behavior and shows its running line profile on accelerations and decelerations. Time response requirements are presented for a series of gas turbines applications. The book presents important phenomena that were not considered during steady-state operation like: heat soakage, volume packing, tip clearance change, combustion delay and control system lag. The surge margin definition and requirements are presented. The book finishes the transient discussing control systems strategies and transient performance. As an example quoted by the authors, Fig. 3 shows compressor exit pressure and fuel flow versus time during a surge event occurring shortly after a throttle re-slam, for a two spool gas generator. For this example the combustor has remained alight and three surge cycles occur until the engine fully recovers. If the combustor should flame out during a surge then the engine will run down.

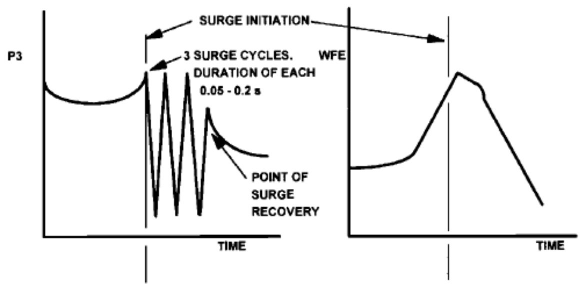

Figure 1: Pressure and fuel flow versus time during a surge event following a hot reslam (Walsh and Fletcher, 2004)

2. GAS TURBINE PERFORMANCE

2.1 Design point

In gas turbine the first step on designing a new engine is to establish the thrust/power output for a given operating condition based in thermodynamic cycle analysis. At this condition all engine parameters are defined and the performance calculated, this condition is known as design point. At this point the engine configuration, component design and cycle parameters are well defined (Walsh and Fletcher, 2004).

The basic cycle used by all gas turbines engines is the Brayton cycle in which, it is considered an open cycle (Walsh and Fletcher, 2004). The gas turbine engine chosen to study in this work is a small turbojet operating in simple cycle in the thrust class of 5 kN. To define the design point we may split the necessary parameters into two groups: operational parameters and project parameters. The operational parameters may be ambient conditions such as temperature, pressure and relative humidity; flight speed; or it may also be regulation constraints such as noise level. Project parameters are features imposed by the engine designer such as (but not limited to) compressor pressure ratio, compressor and turbine isentropic or polytropic efficiencies, intake efficiency (or pressure recovery) and burner exit temperature. As the model becomes more complex, more parameters may be necessary set as input.

In order to start the study some definitions are important to have in mind as cycle operation and station numbers, because all calculated performance parameters are referenced to them.

Figure 2 shows the chosen turbojet configuration and station numbers used for each component. A generic sketch of a temperature versus entropy diagram is shown in Fig. 3. The station numbers of interest are 2, 31, 4, 5 and 8. All the nomenclature of each station through this work was kept the same used in GasTurb® and shown in Table 1, this will keep results comparison simple.

Table 1. Station numbers.

0	Ambient (not shown in Fig. 2)
1	aircraft engine interface (not shown in Fig. 2)
2	compressor inlet
3	compressor exit
31	burner inlet
4	burner exit
41	turbine stator exit = rotor inlet
5	turbine rotor exit
6	jet pipe inlet
8	nozzle throat

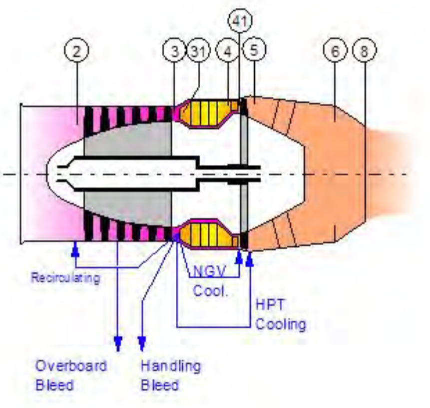

Figure 2. Turbojet engine (GasTurb®)

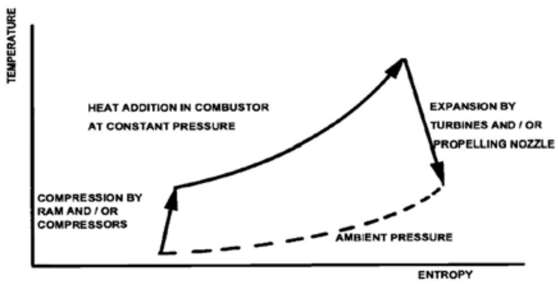

Figure 3: Generic temperature versus entropy diagram (Walsh and Fletcher, 2004)

2.2 Off-design point

The engine design point, as mentioned above, defines a single operating point in which the gas turbine cycle and its components are well matched, so operating at higher efficiency. How a gas turbine, independent of their utilization, for power generation or propulsion, needs to operate away from design point to supply the required demand of the whole operational envelope the operations out of this point must be also studied. Common situations are when the aircraft is taxing, during idle, climb or landing.

Once the design point of the engine is stated the components dimension are known and needed to be tested all possible operating points. The performance of the main component as, compressor and turbine, are represented by maps, or chart. These main components are tested in all possible range of operations, testing all limits, and the

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performance maps generated. Since, to generate the performance maps on test bench is high cost these maps are firstly generated using specially computer programs, specific for each component (Tomita, 2003; Barbosa, 1987). These maps are incorporated as a library into a gas turbine performance code and used to simulate the engine performance (Bringhenti, 1999 and 2003). The results of the engine performance may be used to establish engine operating limits, define the engine control strategy and predict possible malfunctions. The performance maps may be plotted as corrected mass flow versus efficiency and pressure ratio for the compressor and enthalpy drop versus corrected flow and efficiency for turbine. Specific component maps, as an example, for compressor and turbine are shown in Fig. 3 and Fig, 4. These maps were developed for the gas turbine under study, but not used in the results shown below, using specific computer programs (Tomita *et al.*, 2012). An example of the corrected parameters used to describe the components maps are shown in Table 2 (Walsh and Fletcher, 2004).

Figure 3: Compressor map

Figure 4: Turbine map

Table 1: Quasidimensionless parameters groups

Performance Parameter	Compressor	Turbine
Mass flow	$\dot{m}\frac{\sqrt{T_{02}}}{P_{02}}$	$\dot{m}\frac{\sqrt{T_{04}}}{P_{04}}$
Rotational Speed	$\frac{N}{\sqrt{T_{02}}}$	$\frac{N}{\sqrt{T_{04}}}$
Pressure Ratio	$\frac{P_{03}}{P_{02}}$	$\frac{P_{06}}{P_{04}}$
Isentropic Efficiency	η_c	η_t

2.3 Transient behaviour

Up to now it has been discussed the engine operation at steady-state. The last behavior of the engine to be studied is in this work is the transient operation, where there is an unbalanced power between compressor and turbine, and the time is involved. This is a very important issue on helping engineers to develop engines control systems and verify if the power required can be delivered within the engine limits safe operation. The transient response plays important rule on dog fighter aircrafts that changing throttle and intake positioning all the time due to maneuvering to attend the mission. For power generation transient performance is verified in order to verify if it is possible to achieve the expected power within a certain time interval.

Gas turbine, specially turbojets, may be required to operate most of time at off design condition, or at partial load. When moving from one operating point to other the transient behavior can be observed, during accelerations or decelerations. This transition does not follow the engine operating line as shown by steady state operation but it will respond with a specific behavior based on the input command that is dependent on the engine configuration and may cause damage to engine if no attention is paid to maximum temperature or surge margin (Saravanamuttoo *et al.*, 2001).

The main purposes for studying transient behavior are:

- Evaluate engine stability on acceleration and deceleration;
- Forecast a failure on the engine performance;
- Support control system development.

The compressor running line differs from the steady state during acceleration or deceleration when transient behavior is considered. In Figure 5 it is possible to see the running line during acceleration, solid line. The transient running line shows that the pressure ratio on the compressor map, when the acceleration starts, is greater than the pressure ratio on steady state working line. At low rotational speed acceleration is critical because the strong reduction on surge margin. The red circle in Fig. 5 shows that when an acceleration start a reduction on corrected mass flow and an increase in pressure ratio is observed, this is because the variation on pressure and temperature are faster than spool speed, due to inertia. Once inertia is overcome the shaft begins to accelerate, increasing the corrected mass flow rate, and the transient running line becomes almost parallel to the steady state running line, for this case. As fast as the acceleration becomes, transient running line moves close to the surge line.

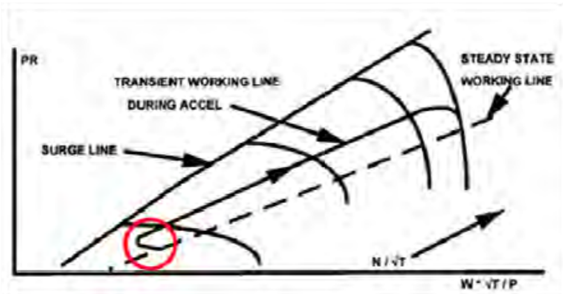

Figure 51. Compressor behavior during acceleration (Walsh and Fletcher, 2004)

A deceleration, unlike acceleration, usually does not represent a problem for the engine stability for a single shaft turbojet, because there will be an improvement on the surge margin as shown in Fig. 6. The problem that may come to appear is flame out, therefore deceleration need to be controlled.

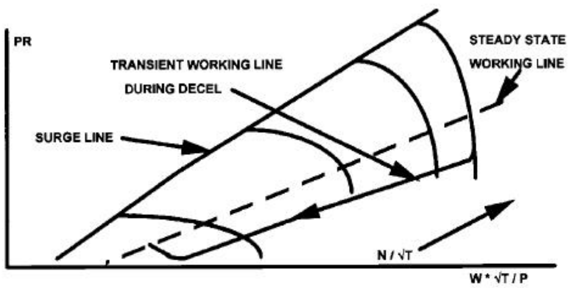

Figure 6. Compressor behavior during deceleration (Walsh and Fletcher, 2004)

An important parameter on transient requirements is the time of engine response. Depending on the application the engine response will vary in several ways. For military aircrafts the total time from idle to 98% of speed is less than 4 seconds (Walsh and Fletcher, 2004). On marine applications time requirements are less though there is a long period to go from idle to the desired speed compared to aircraft engines. Under normal operations the marine gas generator take up to 30 seconds from idle to 95% of rotational speed. For decelerations the time is about the same. It is reasonable that big engines present a slow response due to the inertia of rotating parts. This behavior is observed when writing the dynamic equation for the rotating components. In Eq. (1): I is the polar moment of inertia; $\dot{W}$ is the net power; N is the engine rotational speed and dN/dt is the acceleration/deceleration of the rotating group.

$$\frac{dN}{dt} = \frac{\dot{W}}{I \times N} \quad (1)$$

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The performance of the gas turbine to step response can be measured in terms of the following parameters (MPS-22 Class Notes):

- Raise time tr: it is the elapsed time until the response reaches 90% of its steady-state values;
- Delay time td: it is the time necessary to the response to reach 50% of its final value;
- Peak time tp: the instant when the response reaches the first peak when overshoot occurs;
- Stabilization time ts: time necessary to the signal to be in the range of 2% to 5% of its steady-state value;
- Overshoot: percentage of the signal at maximum peak that overcomes the steady-state response.

$$M_p = \frac{c(t_p) - c(\infty)}{c(\infty) - c(0)} \times 100\% \tag{2}$$

The parameters discussed can be seen in Fig. 7 for a generic step response. It may notice that some of these parameters lose their purpose if the response is not oscillatory, such as peak time and overshoot.

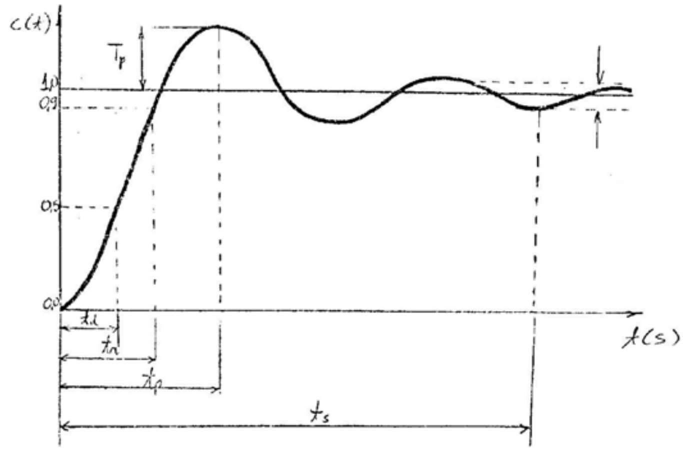

Figure 7. Step response performance parameters. Source: MPS-22 Class Notes

Control systems are used in very different fields of engineering. These systems aim is to help to control a process, for example, where it receives a variable as input and set an output variable accordingly to its functionality. In this work the interest is in the behavior of a gas turbine. With the gas turbine model in hands, it is possible to define, depending on the expected response, a controller that will aid the engine to develop the desired response in safety.

In control theory there are two main ways to execute the control of a plant: with open and closed loop.

Open loop systems are ones that output has no effect on the control action (Ogata, 1997). This means that output is not measured and there is no feedback. This type of control is usually done in plants that are not affected by any disturbance because the plant will follow exactly the input signal. Open loop systems also do not face big stability problems because it does not intend to correct errors.

Closed loop systems are extremely dependent on the plant response as they are fed with the output. They actuate on the error signal and try to set it to zero or eliminate the offset. The error signal is the difference between the output and the reference input, or set point, and it is used as an input to the controller (Ogata, 1997).

On gas turbine the commonest controller is the PID controller. It is a composition of three independents controller: Proportional, Integral and Derivative (Razak, 2007). Araki (2013) defines these terms as follows:

- Proportional: the control signal is proportional to the error at instant *t*;
- Integral: the control signal is proportional to the integral of the error signal from a time reference until present;
- Derivative: the control signal is proportional to the derivative of the error.

The control variable on gas turbines is the fuel flow. Others variables of interest such as rotating speed, thrust or power output, SFC, and surge margin may be controlled indirectly from fuel control.

The fuel control is implemented by using sensors to measure the variable of interest, for example, temperature and pressures. These variables are the output in the closed loop control and may be measured by sensors installed in the engine, since thrust is not a directly measured parameter. The error signal reaches the controller, then; the controller outputs command signal to the engine ordering it how to perform.

It is not scope of this work discuss the procedure to determine the gains of a PID controller. There are several procedures to design a PID controller depending on requested response. These procedures also depend on whether there is a mathematical model for the engine.

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The behavior of an engine in response to a step input on fuel control will be analyzed. The parameters for the study were stated by Silva (2011) when a turbojet in the thrust class of 5kN was simulated and results were obtained by running his analytical model.

3. PERFORMANCE CALCULATION

In this work the software GasTurb® was used to simulate all the required conditions. Just a few information's about the software are given, for more details the reader should refer to the manual.

GasTurb® is a userfriendly and complete platform developed to simulate all most all gas turbine engines in operations today. It is used worldwide by research centers like Massachusetts Institute of Technology (MIT) and University of Oxford, by engine manufactures such as Rolls Royce, Pratt & Whitney and Volvo Aero Corporation, as well as aircraft manufacturers such as Boeing and Airbus (GasTurb, 2013).

The software provides the user three degrees of simulation depending on how detailed the simulation must be. A wide range of engine types is available as a library and the user can simulate the engine at design, off-design and transient operation. It provides other simulation possibilities such as Monte Carlo analysis, sensitivity and engine optimization but these analyses are out of the scope of this work.

The engine chosen to study in this work was a turbojet in the range of 5 kN. The engine purpose is to use in power generation, cogeneration plant, using a free power turbine configuration and the same gas generator used in the turbojet version. The first step was concluded and the gas generator was manufactured and are in test.

The engine analysis was made in three steps: design point; off-design point and transient. Firstly, the results at design point were compared using two softwares: a commercial one, GasTurb®, and a model developed by Bringhenti (1999 and 2003) and complemented by Silva (2006 and 2011). Secondly, the off design analysis was made to determine the engine operating line. These operating points are used in transient analysis because the beginning and ending of a transient are steady state points. The third step is the transient simulation.

The engine simulation was done setting a design operational point at sea level at stationary conditions. The data are presented in Tab.3.

Table 2. Turbojet design point parameters.

Thrust (N)	5,235
η_i - intake isentropic efficiency	0.98
rc - pressure ratio	5.00
η_c - compressor isentropic efficiency	0.85
SM (surge margin) (%)	15
Rotational speed (rpm)	28,150
η_b - combustor chamber efficiency	0.99
Δp_b (%) - combustor chamber pressure loss	5
T (k) - maximum cycle temperature	1,173
PCI (MJ/kg) - lower calorific value	43.0
η_t - turbine isentropic efficiency	0.87
η_m - mechanical efficiency	0.99
Inertia (kg.m²)	0.0125

The operational data for the simulation were set as: sea level; static flight Mach number; no bleed was taken into account; no correction for tip clearance was made.

The performance parameters obtained at design point were shown in Tab. 4. The results obtained for both software's are in good agreement. The bigger difference in results is less than 3%. The major proportional discrepancy occurs on thrust parameter. For the data used GasTurb® gave 185 N of extra thrust, when the expected thrust was 5,235 N.

Table 4. Performance Simulation results at design point

	In house model	GasTurb®	Δ%
Thrust (N)	5,235	5,420	-3.41328
Fuel flow (kg/s)	0.14912	0.15236	-2.12654
f	0.0182	0.0188	-3.19149
SFC (g/(kN.s))	28.4840	28.1255	1.274644
Ts (N/(kg/s))	646	669	-3.43797
Cj (m/s)	564.11	575.87	-2.04213

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In Tab. 5 it can be seen that the results from the in house model are in good agreement with the commercial software, no parameter differing more than 1%.

Table 5. Working fluids properties at each station.

Station	In house Temperature (k)	GasTurb® Temperature (k)	Δ%	In house Pressure (Pa)	GasTurb® Pressure (Pa)	Δ%
Amb	288.15	288.15	0	101,325	101,325	0
2	288.15	288.15	0	101,325	101,325	0
3	484.35	484.21	0.029	506,625	506,625	0
4	1,173.00	1,173.00	0	481,294	481,294	0
6	1,003.06	1,007.87	-0.48	230,616	231,132	-0.22
8	856.32	864.84	-0.99	123,847	124,619	-0.62

It follows from Tab. 5 or Fig. 7 that the propelling nozzle is choked. The pressure of exiting gas is greater than the ambient pressure since the critical pressure ratio is approximately 1.87 and the actual pressure ratio is 2.28.

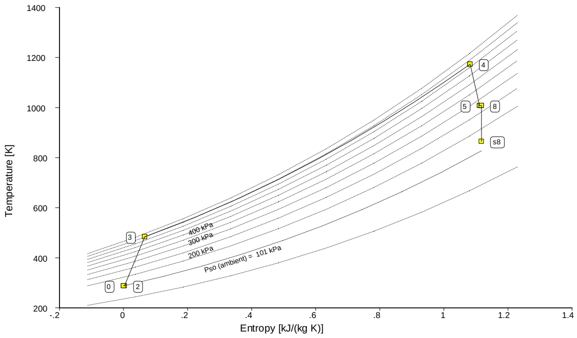

Figure 7. Turbojet Cycle

The off-design matching procedure requires the components maps for compressor, combustion chamber, turbine and propelling nozzle. These maps contain information about the behavior of the component when operating at off design point. In order to run a simulation and get the most accurate results all maps early mentioned must be used in order to match the constrains on each station.

GasTurb® allows user to run off design operation using standard maps or a specific map. If a specific map is desired in the simulation it must be given in a specific format, ".MAP", that is the software Smooth C output for compressor map, or Smooth T for turbine map. The user may take data from real engines and upload to GasTurb® using these programs. Smooth also generates β-lines for compressor and turbines maps. At the beginning of this work it was planned to use real compressor an turbine maps, but unfortunately it was not possible at this time, therefore the off design simulations were made using standards maps.

Running GasTurb® at off design mode the compressor and turbine operating lines can be obtained, Fig. 8 shows the operating line on compressor map. These lines were made using 20 operating points. The first point which is marked with a red circle is the engine design point. The others are found reducing corrected speed of a constant step of 0.025 down to the value of 50% corrected speed. This procedure was made just as an example case.

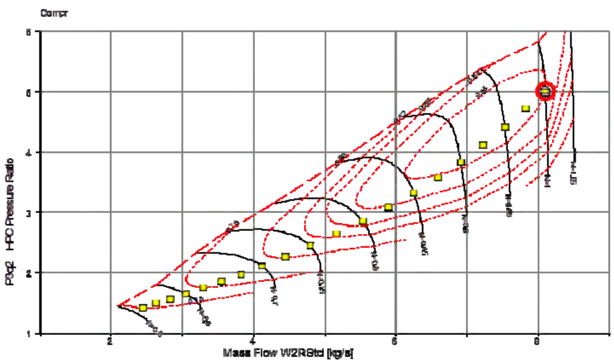

Figure 8. Operating line on compressor map

The results in Fig. 8 show that the running line moves closer to surge line as rotating speed is reduced. Hence there is a reduction on surge margin. In turbines there are no major problems when reducing the rotating speed as they do not face surge problems at all. For very low speeds the operating points do not represent a real operating point since the engine cannot work properly under these circumstances, unless an action is taken.

The last step on the engine analysis is to evaluate its behavior on transient operation. In order to perform this analysis, the turbine and compressor maps are required. As stated above the engine running line was drawn considering standard components maps. On transient analysis, these maps will be used again.

To run the transient analysis using GasTurb® it is necessary extra input data information: polar moment of inertia and PID gains. In several cases the proportional gain is sufficient to perform a good control (GasTurb®, 2013), but a combination of all gains may be used to reach quicker responses. GasTurb® uses default values for each gain on PID controllers, which are 0.2 for proportional and 0.1 for derivative while integral gain is set as null. This control is used when the controlled variable is the rotational speed N. The error is the difference between (N_{demand}-N). The PID controller generates a signal that actuates on fuel flow and is proportional to the error. The control on fuel flow aims to correct the rotational speed to the desired value.

The transient evaluation in this work will be made based on fuel step response. In the first step, will be simulate an engine acceleration from low rotational speed to design point by raising the fuel flow. In the second step, a deceleration is performed by reducing the level of fuel flow. Since the controlled variable is the fuel flow, there is no need to implement a PID controller because the user will be able to directly control it. This would be impossible if the variable was N because there is no possible way to directly control it.

The performance parameters to be evaluated are: outlet combustion chamber total temperature T4, thrust, surge margin and rotation speed.

During acceleration the engine will be accelerated from 60% to 100% of its rotational speed. In other words, the engine will move from a partial load to its design point. As early mentioned, N can not be controlled itself. Thus the fuel flow for each steady state was computed and the control signal was given in term of a fuel step. The correlation between N and $\dot{m}_f$ is given in Tab. 6.

Table 6. Fuel flow on each rotating speed

N (%)	$\dot{m}_f$ (kg/s)
100	0.15235
90	0.09017
80	0.05868
70	0.04602
60	0.03992

Performing the acceleration test it was possible to draw the compressor running line, as can be seen in yellow in Figure . Initially, there is a decrease in surge margin as can be observed and the operational point approaches to the surge line at low compressor speeds. In Figure 12 the surge margin profile is presented. It gives a better description on how surge margin changes with time. In the first 0.1 s there is a peak of surge margin followed by a quick drop, then it oscillates and stabilizes at 24% in 0.44 s, regarding criterion of 98 % for stabilization time.

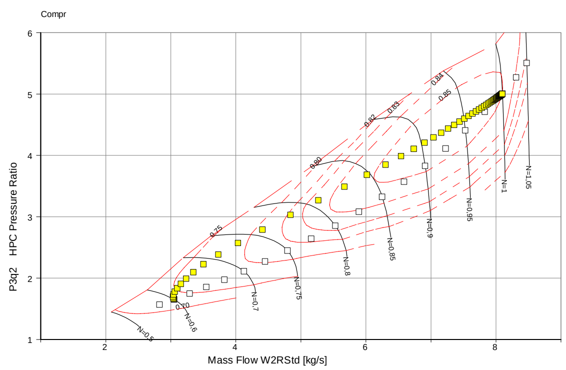

Figure 9. Transient running line during acceleration

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Figure shows the temperature response during transient operation, as can be seen the temperature stabilization occurs after 0.2 s. There is an overshoot of 31% with a peak at 0.07 s. The turbine entry temperature stays above 1,200K for 0.07 s, between the instants 0.04 s and 0.11s. The response delay is 0.02 s and the raise time 0.03 s.

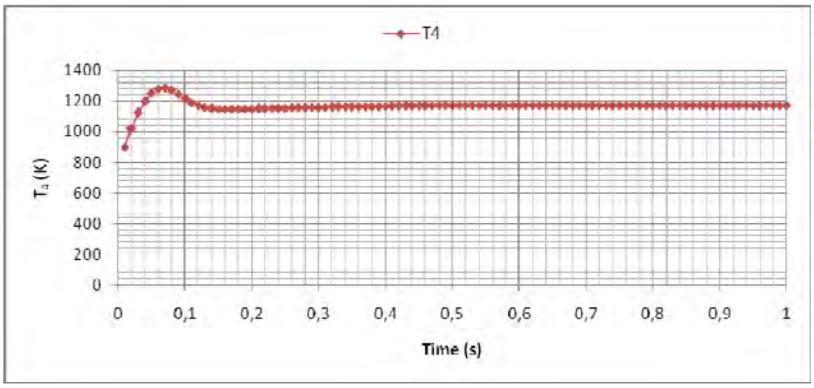

Figure 10. T_4 response during acceleration

Thrust has a smooth change with time, as it is shown in Fig. 11Figure . Its profile does not present any oscillation with time. The response to step stabilizes after 0.39 s and has a delay of 0.12 s. The engine takes 0.25 s to raise thrust to 90% of its final value.

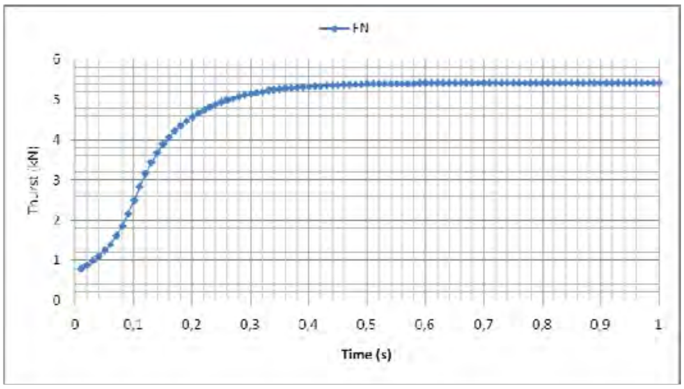

Figure 11. Thrust response during acceleration

The surge margin shows good stability response since it does not become negative at any moment during acceleration, Fig. 12. As stated earlier, it takes 0.44 s before stabilizing. The delay time is just 0.02 s and raise time is 0.04 s.

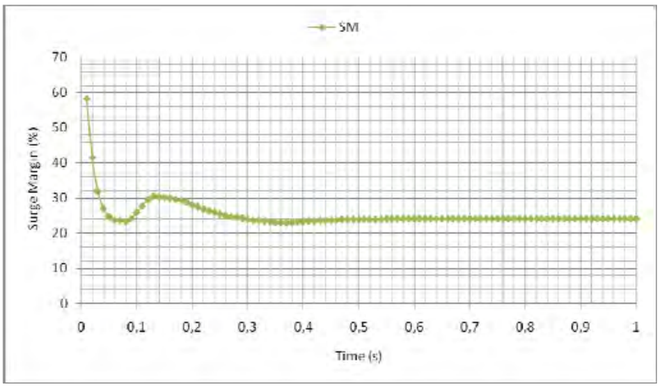

Figure 12. Surge margin response during acceleration

On deceleration test the engine is brought from its design point to 60% of its nominal speed. The running line, in yellow, on compressor map is shown in Fig. 13. It moves to the final point under the steady state operating line. Surge margin improves during deceleration for a single shaft turbojet.

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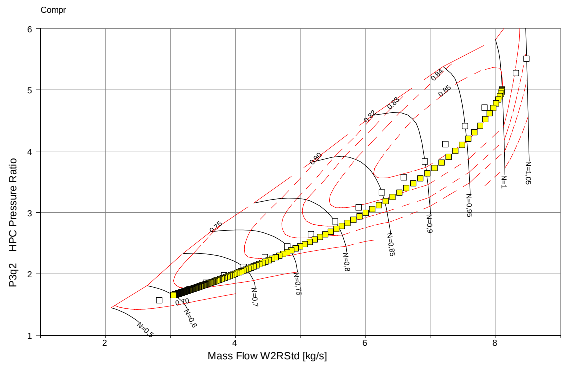

Figure 13. Running line during deceleration

Temperature profile during deceleration are shown in Fig. 14. The temperature presents short oscillation and stabilizes after 1.59 s. The engine faces no problem as there is no raise on temperature above the limit. There is an overshoot of -25% at 0.36 s. The raise time is 0.12 s with a delay on response of 0.05 s.

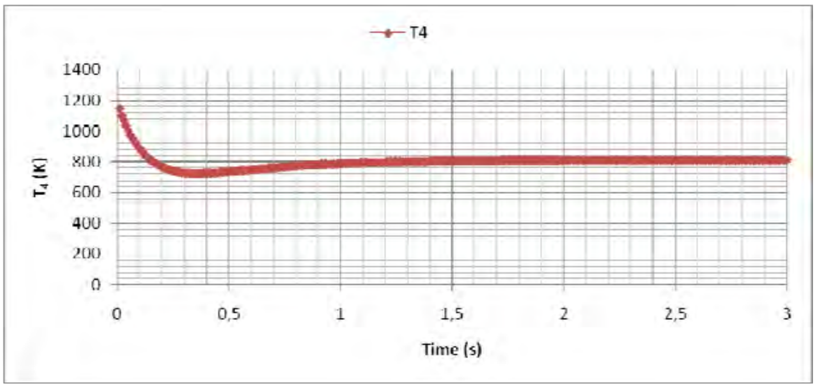

Figure 14. T4 response during deceleration

As well as acceleration the thrust response has a smooth path between two steady state points. It has a slow response compared to the temperature and surge margin with a delay time of 0.14s and raise time of 0.47s. There is no overshoot since the response is not oscillatory.

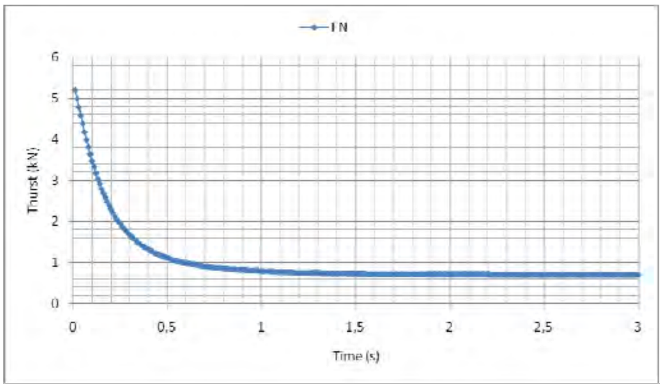

Figure 15. Thrust response during deceleration

Surge margin during deceleration does not represent a threat on compressor stability. Figure 16 shows the surge margin variation with time. Overshoot happens at 0.73 s with a magnitude of 22%. The engine takes 0.11 s to response on surge margin, with a raise time of 0.25 s. It takes 1.99 s before stabilize the surge margin.

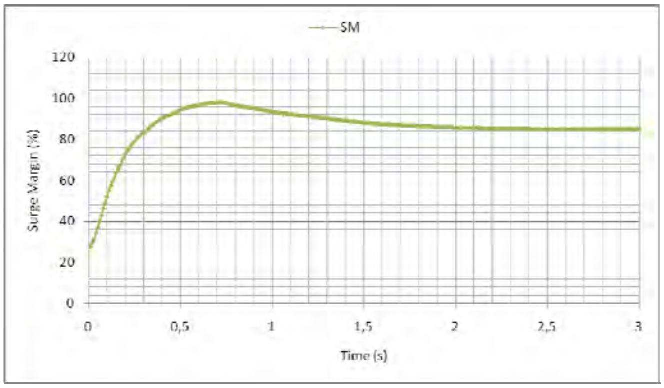

Figure 16. Surge margin response during deceleration

The results from transient analysis just acquired are summarized in Tab. 7.

Table 7. Transient performance results

	Acceleration			Deceleration		
	T4	FN	SM	T4	FN	SM
tr (s)	0.03	0.25	0.04	0.12	0.47	0.25
td (s)	0.02	0.12	0.02	0.05	0.14	0.11
tp (s)	0.07	-	0.10	0.36	-	1.99
ts (s)	0.20	0.39	0.44	1.59	1.00	1.99
M (%)	31	-	-0.5	-25	-	22

4. CONCLUSIONS AND COMMENTS

This work presented an overview of the turbojet engine operating at design, off design and transient operation.

After the overview on transient operation it may say that the engine performs very quick responses. For civil aircrafts, Fletcher and Walsh (2004) quoted that the gas turbine must accelerate from idle to 95% of maximum thrust at about 8s. Military applications require quicker responses. From idle to 98% of maximum speed it is required a time of less than 4 s. On decelerations from maximum thrust on takeoff to 75% it is required about 4 s. It is seen that the TJ 5kN overcomes all this values on the acceleration and deceleration performed between 60% and 100% of rotational speed. The surge margin did not represent a problem as it became positive on both tests.

At design point the thermodynamic cycle calculation was made using an in house developed software and GasTurb® and the results were compared. At off design and transient calculations was done using GasTurb®. In this study to perform the off design and transient analyzes would be used the compressor and turbine maps specially developed to the studied engine. Unfortunately, it was not possible because the programs SmoothC® and SmoothT® could not be used, and it was not possible to upload the real component maps to GasTurb®. Then, the program was run using standard maps for compressor and turbine and the operating lines were shown.

Transient performance studies were made to evaluate the engine on step response. Profiles of maximum temperature, thrust and surge margin from an acceleration and deceleration were collected and analyzed. It was showed that the engine responds quickly to fuel flow changes and no surge margin problem was detected during acceleration or deceleration. Transient operating running lines for compressor were showed for a general profile of accelerations and decelerations maneuvers. The influences of PID constants are also discussed in the text.

As ideas for future works, it could be done a study for a specific engine requirement, as rotational speed or power/thrust demand, to develop a controller to actuate on that variable applying PID control strategies.

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6. REFERENCES

NPSS, Numerical Propulsion System Simulation, 2013, <http://www.grc.nasa.gov/WWW/RT/RT2001/9000/9400naiman.html>.

GSP, Gas Turbine Simulation Program, 2013, <http://www.gspteam.com/>.

GasTurb, Gas Turbine Performance, 2013, <http://www.gasturb.de/>.

Saravanamuttoo, H.; Rogers, G. F. C; Cohen, H., 2001, "Gas Turbine Theory", 5ª ed, Prentice Hall.

Fletcher, P.; Walsh, P.; et al., 2004, "Gas Turbine Performance", 2ª ed, Blackwell.

Tomita, J. T.; Bringhenti, C.; Barbosa, J. R.; Martins, V. A. C." Performance Evaluation of a 5 kN Gas Turbine Based on Specially Designed Components". Proceedings of ASME Turbo Expo 2012 Turbine Technical Conference & Exposition 2012 June 11-15, Bella Center, Copenhagen, Denmark, 2012.

Bringhenti, C., "Variable Geometry Gas Turbine Performance Analysis", Ph. D. Thesis, ITA, Brazil, 2003.

Bringhenti, C., "Steady State Gas Turbine Performance Analysis", MSc Thesis, ITA, Brazil, 1999.

Barbosa, J.R., "A Streamline Curvature Computer Programme for Performance Prediction of Axial Compressors". Ph.D. Thesis, Cranfield Institute of Technology, England – 1987.

Tomita, J.T., "Numerical Simulation of Axial Flow Compressors". MSc Thesis, ITA, Brazil, April 2003.

MPS-22; Notas de Aula, Adade, A.; ITA.

Ogata, K., 1997, "Modern Control Engineering", 3ª ed, Prentice Hall.

Araki, M., 2013, Available at <http://www.eolss.net/Sample-Chapters/C18/E6-43-03-03.pdf>

Razak, A. M. Y., "Industrial Gas Turbines Performance and Operability". CRS Press, 2007.

Silva, F.J.S. "Simulação de Desempenho de Turbinas a Gás em Regime Transitório." Tese de Mestrado, Instituto Tecnológico de Aeronáutica, São José dos Campos, Brasil, Agosto 2006.

Silva, F.J.S. "Estudo de Desempenho de Turbinas a Gás sob a Influência de Transitórios da Geometria Variável". Tese de Doutorado, ITA, Brazil, 2011.

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