A qualitative evaluation method for engine and its operating-envelope using GSP (Gas turbine Simulation Program)

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Abstract

Regarding to the project SUAV (Smart Unmanned Aerial Vehicle)[1] in KARI (Korea Aerospace Research Institute)[2], several engine configurations has been evaluated. However it's not an easy task to collect all the necessary data of each engine for the analysis. Usually, some kind of modeling technique is required in order to determine the unknown data.

In the present paper a qualitative method for reverse engineering is proposed, in order to identify some design patterns and relationships between parameters. The method can be used to estimate several parameters that usually are not provided by the manufacturer.

The method consists of modeling an existing engine and through a simulation, compare its transient behavior with its operating envelope.

In the simulation several parameters such as thermodynamics, performance, safety and mechanics concerning to the definition of operation-envelope, have been discussed qualitatively.

With the model, all engine parameters can be estimated with acceptable accuracy, making possible the study of dependencies among different parameters such as power-turbine total inertia, TIT, take-off time and part load, in order to check if the engine transient performance is within the design criteria.

For more realistic approach and more detailed design requirements, it will be necessary to enhance the compressor map first, and more realistic estimated values must be taken into account for intake-loss, bleed-air and auxiliary power extraction. The relative importance of these "unknown" parameters must be evaluated using sensitivity analysis in the future evaluation.

Moreover, fluid dynamics, thermal analysis and stress analysis necessary for the resulting life assessment of en engine, will not be addressed here but in a future paper.

With the methodology presented in the paper was possible to infer the relationships between operation-envelope and engine parameters.

Introduction

One of the important aspects of an aircraft design and development is to define its operation envelope. Such limits depend on many parameters as turbine overtemperature, shaft speeds, surge margin and maximum gearbox torque.

Momentary peak of temperature during startup, power transients or emergency operation, may reduce considerably the lifetime of an engine. The objective of a designer is to find an equilibrium point between performance, safety and lifetime. To achieve with the goal, the following tasks must be integrated:

- Engine performance analysis.
- Thermal and stress analysis.
- Life consumption assessment.

For the conceptual design of SUAV, many commercially available engines were selected previously. Although the performance deck for each engine was available, there are many "hidden" parameters crucial for an accurate evaluation.

A commercially available simulation program GSP (Gas turbine Simulation Program by NLR)[3] was used. The GSP code was applied principally for the calculation of off-design and transient conditions. For on-design calculations, an independently developed code by the authors was used for determining the input parameters required by GSP.

The results of the simulations for steady-state conditions have been compared with available data in order to verify the accuracy of the model in off-design conditions. For the first approach, standard scaled maps were used for the compressors and turbines, obtaining accuracy better than 90% for all range (from idle to take-off power). Using more representative performance maps for each component, it was possible to improve the accuracy up to 95%.

The method implemented in the present paper, using GSP code in combination with the on-design calculation code, has demonstrated how fast the designers can evaluate any engine configuration, simulate its off-design and transient responses and finally deduce the design criteria.

The present paper describes the methodology used for the modeling an existing engine. Once the GSP model is "tuned" with the existing off-design data, it's possible to evaluate all thermodynamic parameters in each point of engine and its dependencies on time in transient mode.

This information can be integrated and compared with the operation-envelop (the maneuverability and the performance rating table) provided by the manufacture. As we will see later, this information can be also used to guess and estimate manufacturer's design criteria.

Because the accuracy of the estimation, the results of the simulation cannot be quantified unless a more complex model is developed or experimentally measured.

As a preliminary design approach, a qualitative design guide was developed in the present paper.

Analysis tools

On-design Code

The on-design code was developed as a tool for determining missing information required by GSP. The code has developed by the authors and it's based upon simple thermodynamic one-dimensional relationships and experimental correlations. It takes into account real gas effects, slip factor, dependencies among fluid velocity, specific speed and efficiency estimation.

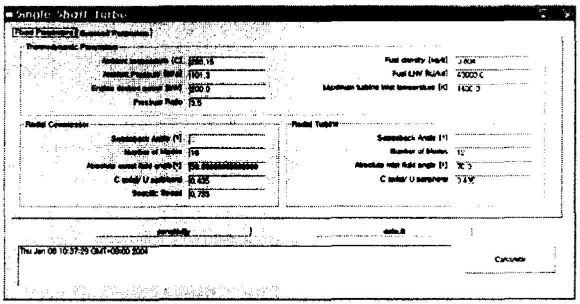

Figure 1: On-design code screenshot

The program requires only few initial parameters such as ambient temperature and pressure, desired engine power, pressure ratio and maximum achievable turbine inlet temperature. Also other parameters such as velocity relationships between wheel velocity and fluid velocity are optional for the calculation of geometrical configurations of the turbine and the compressor wheels (see fig 1).

The program outputs all the results in a text format containing thermodynamic states in all fluid paths through compressor, combustion chamber and turbine. It also gives estimation of geometrical data as well as compressor wheel diameter, blade angle, etc.

The code is based on object-oriented architecture and it's easy to model other engine configurations.

GSP (Gas turbine Simulation Program)

The GSP code is also based on one-dimensional thermodynamic relationships and it is suitable for off-design performance calculation, both for steady-state and transient simulation.

Its component-based modeling environment facilitates the user to configure any kind of gas turbine. It also includes real gas effects as well as thermal and mechanical inertia and volume effects required for more realistic estimation of the engine transient mode.

Modeling approach

In the present paper a two-spool turboshaft is analyzed.

Using information available from the manufacture and literature data, it was possible to generate an on-design model to be used as input data for GSP.

Design Point	Value
Total temperature at engine inlet [K]	288.15
Total pressure at engine inlet [kPa]	101.33
Power [kW]	410
Fuel mass flow [kg/s]	0.039
N1 (gas generator rpm)	54610
Air mass flow [kg/s]	1.998
Compressor Bleed total pressure [kPa]	796.1
Compressor discharge total temperature [K]	570
Turbine exhaust total temperature [K]	862
Compressor Efficiency [%]	81.00
Relative exhaust total pressure loss	0.0162
Gas generator turbine efficiency [%]	80.57
Gas generator turbine efficiency [%]	80.57

Table 1: Design point from manufacture data

In table 1 shows the main characteristics of the engine analyzed in the present paper. In this stage of calculus, several unknown parameters such as compressor efficiency are calculated and tuned by trial and error using the on-design code.

Other parameters such as spool inertia and N2 (power turbine speed) are not calculable by the on-design code, since these parameters are only meaningful for transient behavior and it's beyond of the capability of the code.

PT (power turbine) spool inertia as well as its speed and GG (gas generator) spool inertia will not affect off-design and steady-state behaviors, so in this stage of calculation it will be just estimated using other similar engine data. Later in this paper these parameters will be subject to analysis (see table 2).

Guessed Parameters	Value
Gas generator spool inertia [Kg m^2]	0.01
Power turbine spool inertia [Kg m^2]	0.05
N2 (power turbine rpm)	35667

Table 2: Guessed parameters for design point

Once it's completed all the parameters required by GSP, it's now possible to calculate off-design performances and to be compared with available data. Figure 2 shows the final GSP model.

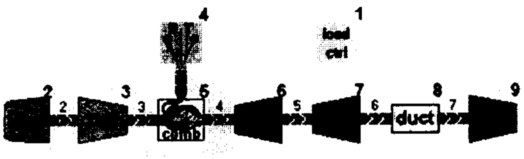

Figure 2: GSP model screenshot

Off design

The off-design behavior depends strongly on each component map, especially on compressor and turbine maps.

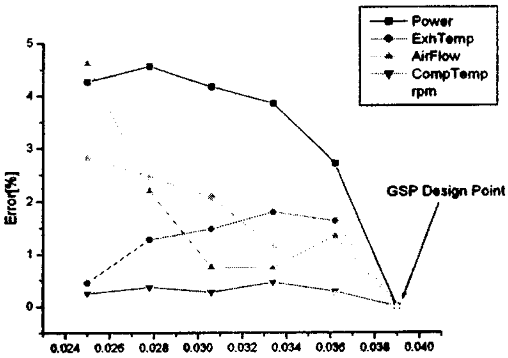

Figure 3: Relative off-design error, maximum deviation of 5%

GSP provides several "standard maps" for different components such as fan, compressor, inlet duct and turbine. These maps are scaled according to each case with the design point.

It's possible to modify the standard map data to fit it with the available steady-state operating line form performance deck.

However, in view of the accuracy of the assumptions made in this model, it's acceptable the use of standard maps for each component without a readaptation.

In figure 3 shows relative off-design deviation of the GSP model compared with the manufacture's performance deck. The range of evaluation was from 0.025 to 0.039 kg/s of fuel mass flow, which corresponds to a power variation from 50% to 100% approximately.

The relative deviation of the model from real data is less than 5% inside the evaluation interval. It's possible to reduce the deviation modifying the maps in order to represent better each component. This task requires more sophisticated reverse engineering method and it's not justifiable for the overall accuracy of the current model and will be left for the future work.

Transient Responses

During starts or power-up, it's difficult to avoid an overtemperature at turbine inlet for a certain period. The value of the excess temperature depends primarily on how fast the power is increased and how "heavy" the total spool inertia is.

The overtemperature and its duration affect severely the lifetime of an engine, its safety, replacement period and maintenance cost.

A close look to this dependency will enable to find the relationships between its design criteria and the operation-envelope of the aircraft. Consequently the design-criteria of some manufacturers can be reverse engineered from its operating limits.

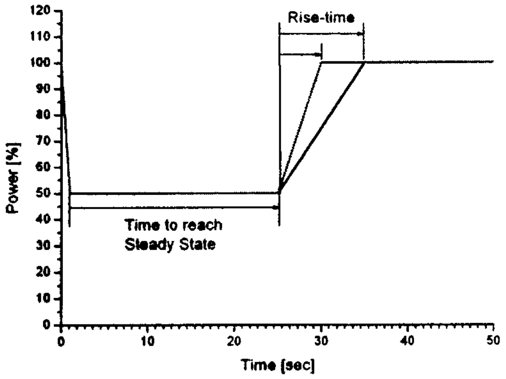

Figure 4: Power output profile, the red line represents 5 sec rise time and the black line represents 10 sec of rise time.

In the present paper a simple case of power transient is considered. Initially the power is set to 50% and maintained constant during 25 sec until all the parameters reach their steady state conditions. Then the power is increased up to 100% at a constant time rate. The duration of this maneuver is called *rise-time* (see fig 4).

Several transient responses were analyzed for different PT spool-inertia and rise-time.

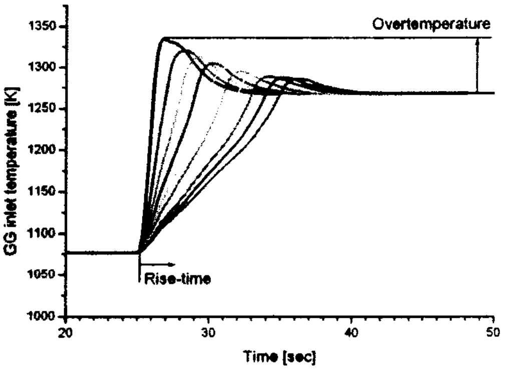

Figure 5: Overtemperature dependence with rise-time, "faster is better".

In figure 5 shows the overtemperature reached for different rise-time with GG spool inertia of 0.01 $kg.m^2$ and PT spool inertia of 0.05 $kg.m^2$. The overtemperature is caused by the relatively high amount of fuel injection with respect to the air mass flow (due to low GG speed), in order to accomplish with the power demanded within the given time interval.

The rise-time was varied from 1 sec to 10 sec, with the power increasing from 50% to 100% for all cases.

As explained above, in the figure 5 can be observed that as long as rise-time increases, the overtemperature diminishes. An optimum rise-time is a compromise between overtemperature and the maneuverability of the engine.

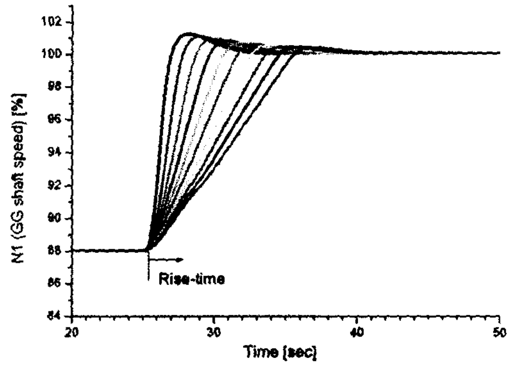

Figure 6: GG shaft speed, for this configuration and control logic, approximately 10 sec are required to reach 100% rpm. Approximately 88% rpm corresponds to 50% of full power.

The overtemperature also depends on each control system implemented. The GSP model analyzed in the present paper uses a simple PID control system. The gain coefficients (proportional, integral and differential) can be "optimized" for a certain application. However it must be taken into account that a "fast" control system will reduce engine lifetime, and even compromise the engine security.

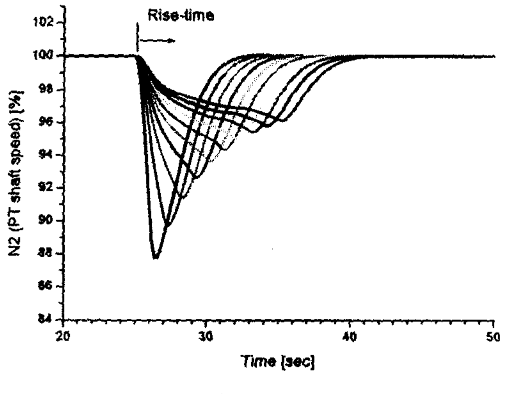

Figure 7: PT shaft speed, the 13% rpm is the maximum perturbation and corresponds to 1sec rise-time.

In the figure 6 and 7 show the time dependency of the gas generator and the power turbine shaft speeds. The N1 (GG shaft Speed) is set to 88% for 50% of the engine full power. And the N2 (PT shaft Speed) is controlled within 13% of maximum deviation.

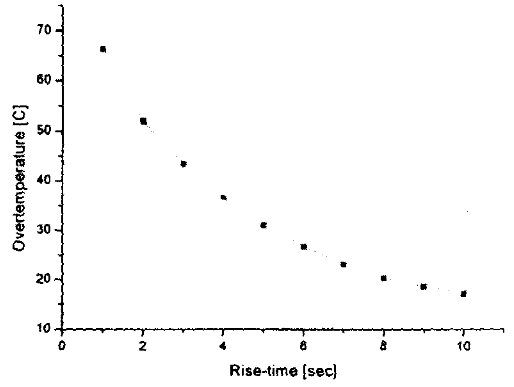

Figure 8: Overtemperature vs. rise-time. I_{PT}=0.05kgm^2, I_{GC}=0.01kgm^2.

Figure 8 shows the overtemperature dependency with rise-time.

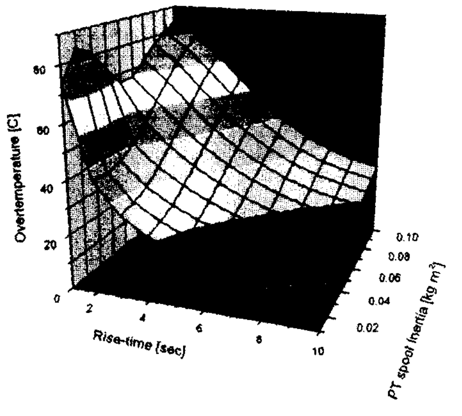

Figure 9: Overtemperature vs. rise-time and PT spool inertia.

The same load profile (see figure 4) was applied to the model with different PT spool inertia, varying from 0.01Kg.m^2 to 0.1Kg.m^2. The results of the simulation shows that the maximum overtemperature is increased with greater PT spool inertia (see fig 9).

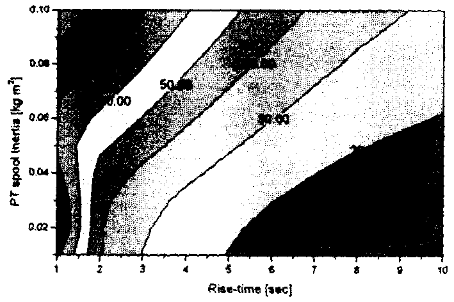

Figure 10: Overtemperature Map

Figure 10 is the contour representation of the figure 9 and contains the same information. In the contour map can be easily visualized "eligible" zones.

A quick glance shows that "heavy" PT spool and "fast" demand of power will produce high overtemperature reducing the lifetime of the engine.

Another important parameter that must be considered is the period or duration of the overtemperature. In the figure 11 shows two extreme cases corresponding to minimum and maximum PT spool inertia with 1sec of rise time.

For the case of I_{PT}=0.01kg.m^2, the overtemperature persists for brief time, however for the case of IPT=0.1kg.m^2, the overtemperature lasts for longer period.

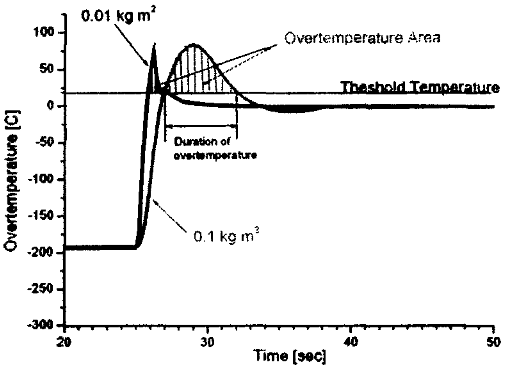

Figure 11: Overtemperature area considers time effect in the engine lifetime.

Turbine blades are one of the hottest sections of an engine and they are normally under stress due to high rotational speed, therefore several blade failure modes are related with creep, which depends on time, stress and temperature$^{4)}$.

Several engine manufacturers have certain operating limits for each operating conditions such as take-off, 30 min OEI (one engine inoperative) power and engine starting.

For example, *Allison 250 installation manual* states that during starts, an overtemperature in excess of 810C (37C hotter than takeoff temperature) with a momentary peak of one-second maximum at 927 C (154C hotter than takeoff temperature) shall be permitted for a period not to exceed 10 seconds.

This idea is represented as the area under the overtemperature peak (see fig 11). Threshold temperature is defined as the base temperature from which the overtemperature area is defined, and for the case analyzed here was 20 C higher than the steady state temperature.

It's important to realize that the overtemperature-area is just a qualitative guide. It's a poor representation of the real process and it should be interpreted with much care.

For a more accurate estimation, will be necessary an *integrated life assessment of the turbine blades* based on analysis of fatigue and failure theory combined with:

- Fluid Dynamic and Thermal Analysis, to determine the thermal and mechanical loads on a turbine blade.
- Stress Analysis, to calculate the thermal and mechanical stresses in the blade material.

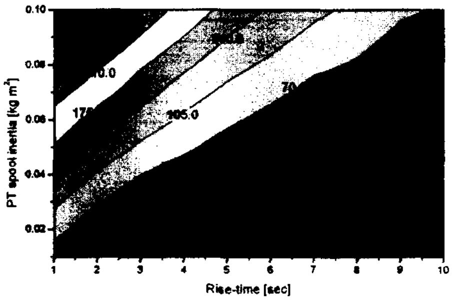

Figure 12: Overtemperature-Area Map

The remarkable result of the overtemperature-area map is that the momentary peak of overtemperature is permissible as long as it lasts for a short period (see fig 12).

A detailed analysis will enable the designer quantify and find out relationships among several operation limit data with its engine component design. A direct numerical comparison would be possible between different OEI (one engine inoperative) power rate and simulation data.

Conclusion

A method for gas turbine design was analyzed. The use of GSP code combined with an on-design thermodynamic model, enables the designer quickly evaluate many engine configurations.

Although the model is rough (5% deviation with neglecting intake loss, bleed air and mechanical loss), it's still valuable for behavior analysis and qualitative effect studies.

With the engine performance analysis was possible to determine the operational conditions of the turbine and find out unknown parameters such as TIT that usually is not available.

The method discussed with a simple analysis tool is suitable for a qualitative design guide. If the total spool inertia and an acceptable overtemperature and its duration are determined, then a minimum rise-time (maneuverability) can be defined. This means that if the operation-envelope of an aircraft is known, then engine parameters can be deduced. Inversely, if a given aircraft design is known, then the operation-envelope can be defined.

With a more detailed life assessment based on fluid dynamic and thermal analysis combined with failure theory, will enable a more realistic estimation and enhance significantly the accuracy of the results.

The method is general and may be applied to other designs.

Acknowledgement

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