DEVELOPMENT OF THRUST VECTORING SYSTEM ON A TURBOJET

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Abstract. This paper describes the development procedure of a Thrust Vectoring Control (TVC) system model on a Turbojet engine. The work has been conducted during the collaboration between Politecnico di Torino and Alenia Aermacchi; the cooperation has been carried out thanks to a Ph.D internship program. During the first phase of the analysis there was the need to design and develop a more detailed turbojet engine deck. The software was developed to model steady state and transient turbojet engine performances, and to handle variable RPM up to boundary conditions. It uses Matlab programming language as a modeling platform, and was validated by using various data collected through the ground test-bed and few flight tests. The modular nature of the software and the boundary condition initialization procedure allow this tool to be very flexible and customizable. Using the data provided by the 1-D model, Computational Fluid Dynamics (CFD) calculations were carried out. Initially a 2-D axisymmetric nozzle was modeled, in order to verify the nozzle internal flow. Subsequently a 3-D model with three deflecting vanes was developed. The application of such technology on an UAV may considerably reduce the vertical tail surface, leading to a reduced radar footprint (increased stealth).

Keywords. Simulation; UAV – Unmanned Aerial Vehicles; Turbojet; Transient; Steady State; Model; Gas Turbine

1 Introduction

This paper describes the roadmap of a research work carried out in Alenia Aermacchi, through the collaboration of a Ph.D student of Politecnico di Torino on the Thrust Vectoring (TV) performance applied to an Unmanned Aerial Vehicle (UAV).

The growing market of UAV led to a re-definition of roles, and aircraft technologies. It allowed, for the first time since decades, a complete redesign of the aircraft shape. In particular by eliminating (or moving out of the airplane) any human being, several axioms of aircraft design are no longer valid. The position of engines, aerodynamic surfaces, and avionics can be customized in a completely new way. While in conventional aircraft the canopy is usually looking to the sky, an UAV eye, where such device is needed, is generally looking down (i.e. EO pods, or frontal HUD), this simple consideration implies that the frontal part of an UAV fuselage is not necessarily similar to the one of a conventional airplane. Depending on the role the UAV shall cover, different performances are requested. Concepts such as endurances flights of more than 48 hours, or automatic takeoff and landing are not uncommon in the UAV field.

Thrust Vectoring has been studied and applied (in particular in the Eastern countries [6]), since 1980s. The main target of such application was an improvement in aircraft performances. Western countries studied thrust vectoring too, and NASA in particular developed several research programs such as: F/A-18 HARV (High Angle of Attack Research Vehicle), F-15 EFM (Enhanced Fighter Maneuverability), and X-31, which were mainly centered in investigating the post-stall performances of an airplane, and improve them ([1], [2], [3] and [4]). In particular, X-31 in the nineties flew with a mechanical Thrust Vectoring System, similar to the one adopted in this study.

Thrust Vectoring can be used in fast and maneuverable airplanes, but can improve performances of other classes of airplanes too, for example, by reducing the dimension of the vertical tail required for the lateral plane stability. The most noticeable benefit of such quasi-tailless or completely tailless configuration relates to the smaller radar footprint of such shaped airplane. This characteristic may lead, de facto, to better stealth performances. With the two latter arguments in mind, Alenia Aermacchi started a research on TV application for UAV.

1.1 Sky-X UAV

One of Alenia Aermacchi's technological demonstrators UAV, the Sky-X, was chosen to investigate TV performances. Sky-X is a swept wing, high wing airplane, with retractable landing gear and turbojet engine. The particular configuration of the V tail, and the position of the turbojet engine (in the aft, top of the fuselage), was chosen in order to reduce the IR signature of the airplane, although the flight control system was a little more complex to develop. The choice of such position for the turbojet engine introduces an adverse component in pitching moment, which cannot be neglected. Figure 1 shows a three view of the Sky-X airplane, and an isometric view; the picture highlights its aerodynamic configuration. The most relevant technical specifications of such UAV are summarized in Table 1. Sky-X made its maiden flight in May 2005, and performed in several strategic missions such as: collision avoidance, autonomous in-flight refueling join-up, Automatic Take- Off and Landing (ATOL).

Table 1: Sky-X UAV relevant dimensions.

Dimension	Value	Unit
Length	7.8	m
Wingspan	5.94	m
Height	1.86	m
Empty Weight	1000	kg
Loaded Weight	1200	kg
MTOW	1450	kg
Powerplant	4.43	kN
Max Speed	648	km/h
Cruise Speed	482	km/h
Service Ceiling	7250	m

Figure 1 : Sky-X UAV Three view.

1.2 Research work plan

The research went through different disciplines, since several fields had to be investigated. The analysis started by collecting information on the turbojet engine, this phase led to the definition of two 1-D models: a steady state model, and a transient model. Section 2 describes the development and validation of such models. By using the data calculated and validated in Section 2, turbojet engine nozzle and plume analysis could be exploited, Section 3 describes those analyses. Once confident data on plume thermodynamic properties was available, a more detailed CFD 3D model was developed. Through CFD the envelope of thrust vectoring vanes was investigated; Section 4 summarizes this part of the research, finally findings and conclusions are reported.

2 Turbojet 1-D Steady State and Transient Models

The first phase of the development was centered in the definition of the most important thermodynamic properties of the turbojet engine stage by stage. The powerplant of the Sky-X UAV, is a single spool turbojet. This engine was designed originally to thrust drones or cruise missiles. Due to this operational scenario the engine is rather simple, it performs a considerable thrust at 100% RPM, but provide a modest modularity in thrust. For this reason an extended envelope version, which could operate at lower RPM (for the taxi phase), and provide a higher reliability, was designed.

The engine (shown in Figure 2), is a single spool, three stage axial compressor, and single stage turbine, fixed convergent nozzle turbojet. It has an annular combustion chamber, which feeds the turbine blades.

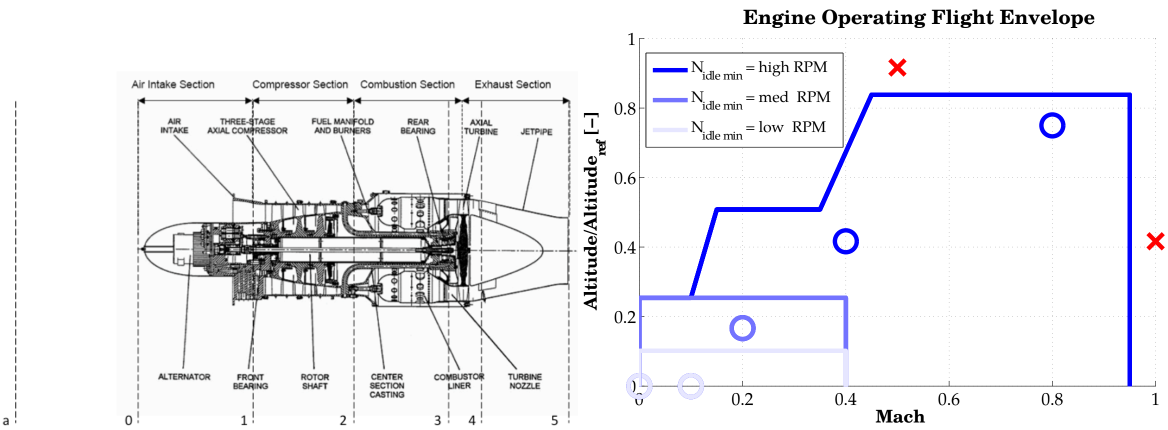

Figure 2 : Turbojet engine stage numbering, engine operating envelope.

2.1 Steady State Model

Since the early stage of development of the TV research it was clear that the information on the engine performances lacked of detail. For this reason an analytical 1-D model of the engine was developed, using Matlab Simulink. The model calculates engine performances stage by stage, by using the well-known analytical approach reported in [11], and [5], while compressor map was obtained initially through [9]. The model is based on Matlab. It is 1-D (mono-dimensional), and calculates the engine properties from idle to max dry (in the max min allowed RPM envelope) by giving only few inputs:

1. Altitude (this input is used in order to calculate the ISA pressure at that height).
2. Mach (the Mach speed changes the airflow properties at the compressor inlet).
3. ΔT ISA (affects engine performances).

The simple GUI (Graphical User Interface) allows to access many tools to save data, load data, and plot graphics. But the user can access and change dozen of parameters in order to tune the engine model as desired:

1. Engine envelope shape (that is plotted once the user start the simulation, and checks if a feasible point was requested) can be modified. For example, Figure 2 shows a generic engine envelope presenting three different zones were the minimum RPM allowed changes based on the values of Mach and altitude.
2. Every component's efficiency (and efficiency shape) can be adjusted.
3. Fuel properties can be changed.
4. Bleed % can be adjusted according to the load requested.
5. Extracted power can be changed.

The model provides 56 parameters (while the original outputs only the 12 main ones), and saves them in a Matlab Structure, easy to access and use for plotting or comparison purposes. Plotting tools allow easy comparison between different simulations (different conditions) and are integrated with the original deck in order to compare the results of the two models (for the properties calculated from the original deck). The principle of the algorithm is based on the assumption that when the engine is in a steady condition it means that the spool is turning at a constant RPM. Since the spool is directly connected on one side to the compressor and on the other to the turbine, this means that the Work produced by the turbine is exactly the one required to the compressor. In other words, the spool does not accelerate or decelerate, but keeps the same RPM due of the equilibrium condition on its sides. For this reason the algorithm starts from calculating the flow condition on one side, the inlet (air intake) and on the other too (the outlet, nozzle), and finds out at a given RPM of the spool the single point that provides a balance in the work produced/used by the turbine/compressor. That's the mainstream of the algorithm. By the way it is not completely linear since few properties depend on each other, thus require iteration: the isentropic coefficient, constant pressure heat capacity, and combustion chamber Temperature rise values depend upon Temperature and fuel/air ratio.

Several points of the UAV operating envelope were tested, starting from SLS (Sea Level Static) condition, and investigating throughout the various cruise conditions. Using both test flight data and test bench data the model was validated. The plots that will be presented in this paper show x – y axes labels divided by a reference value, in order to obtain values closer to the range [0 – 1].

Figure 3 shows the comparison between the results of the analytical model and the ones provided by the original engine deck. The results were obtained while investigating the SLS condition (Table 2), and two different versions of the simple original deck (depicted with blue nablas, and black crosses) were used as term of comparison for the steady state model (indicated with red plus). The thrust is the most important property to measure, and the model calculates it properly, showing a perfect matching with the original engine deck. Another key parameter to look at is the SFC (specific fuel consumption), and the models shows a good matching for this property too.

The choice to develop a completely new deck arises from the need to know with a good degree of detail not only the main properties of the turbojet engine, but also the internal properties such as turbine disk temperatures, pressure, and so on.

Table 2: SLS conditions.

Property	Value	Unit
Height	0	km
Mach	0	–
ΔT_{ISA}	0	K

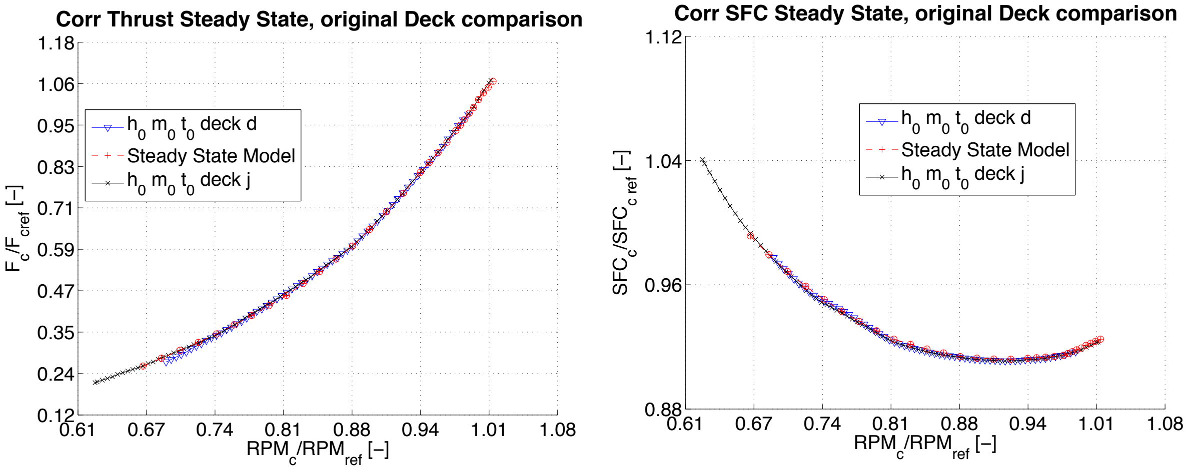

Figure 3 : SLS thrust and SFC results.

In order to have a more detailed outlook on the model, as comparison, a different condition is described in this paper: a low cruise condition (summarized in Table 3). Once again thrust and SFC are depicted, and both properties show a good accuracy when compared to the reference values of the original deck. In particular, Figure 4 shows a good matching from the lowest RPM to the highest, meaning that both thrust and (indirectly) fuel mass flow have been modeled correctly.

Table 3: Low cruise conditions.

Property	Value	Unit
Height	3	km
Mach	0.4	–
ΔT_{ISA}	10	K

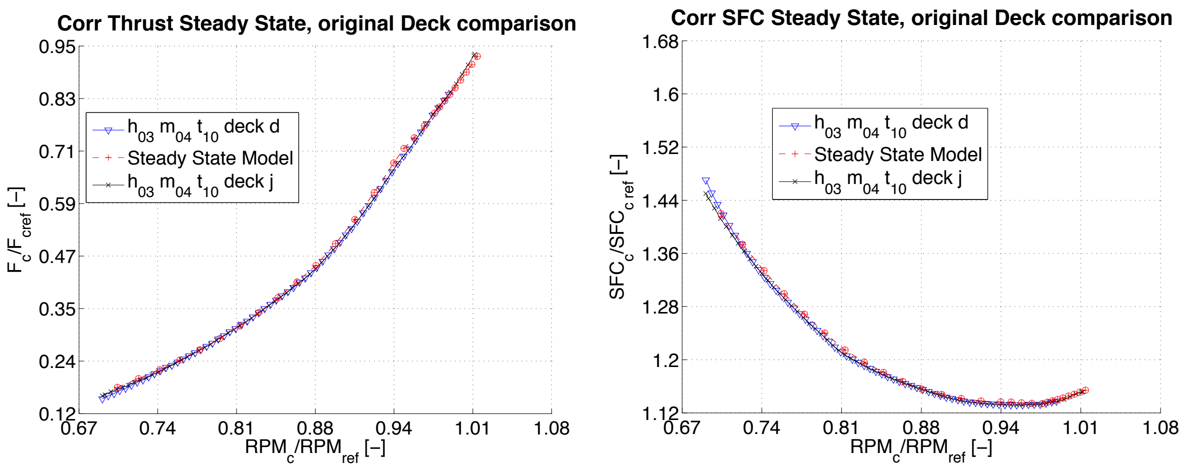

Figure 4 : low cruise thrust and SFC results.

Thanks to the steady state model, it was possible to estimate several components efficiencies, as well as to identify correctly the most relevant properties on the turbine disk.

The knowledge of turbine disk properties, in different engine operating conditions, enabled successively to develop an extent investigation on the plume properties (CFD 2D), and on the forces and moments acting on the Thrust Vectoring (TV) vanes.

2.2 Transient Model

As stated in the introduction, the focus of the research is to obtain as much information as possible on the turbine and nozzle section of the engine. Since the target of the Ph.D. is the definition of a thrust-vectoring engine, applied to the UAV airplane, a transient analysis was mandatory. In particular the engine dynamics must be taken into account, when designing the requirements for the flight control system control laws. There was the need to define how perform the engine while going from min to max power (max dry) and, in general its dynamics. By using the same core and notation of the steady state model, a transient model was investigated. The general concern was to develop a model as easy to use as the previous one, without loosing any of the properties calculated.

For this reason there is a great commonality between the codes of the two models (and they use the same components maps and parameters load routines). Once again Matlab was used as a core function, but the engine dynamics are now modeled by using Simulink. That's the reason why the Graphical User Interface uses both Matlab and Simulink. Two different models were developed, one receives the input from the user (by using a throttle joystick), and the other one uses a text file as input.

The inputs, which are requested from the model in order to work, are time-dependent and are:

1. Throttle setting command: basically the physical position of the throttle lever.
2. Altitude: height of the flight, as sensed from the Air Data Computer.
3. Mach: speed of the UAV, as sensed from the Air Data Computer.
4. Outside Static Temperature: temperature of the environment surrounding the UAV, as sensed by the Air Data Computer.

During the simulation the compressor map shows up with the current working point of the turbo-jet, and moves depending on the input the user provide, leaving a trail behind, so that the past time history is always available. When the simulation stops a tool to plot and to manage the data becomes available.

The transient model does not vary that much from the steady state one. The main difference is that while previously the model ran by equalizing the compressor and turbine work, so there was an equilibrium in the work balance equation, when considering the transient model, the spool can actually accelerate and decelerate due to the difference between the work required from the compressor or produced by the turbine. So in this case the balance equation falls, but there is a new one that can be used. During each time-step every property must be calculated by using the RPM speed and acceleration of the previous step. The routine estimates the RPM and the acceleration of the spool at the step *i* by looking at the one at the step *i-1*. So by initializing the model in a steady condition, and calculating the inertial moments of the spool is possible to define a transient model.

An issue to this approach is that in modern engines a digital Engine Control Unit (or ECU) is always tuning the fuel flow in order to comply the thermal and physical engine envelope. For this reason by analyzing engine flight data a simple ECU was modeled in Simulink.

In the Figure 5, a flight time history data is compared to the results of the calculated data of the transient model. The plot shows the RPM of the spool with the superimposed throttle command request value (dashed black line). The real flight data time history is depicted in blue (dash dot line), while the model calculated results are reported in solid red line. Since the time history is quite long, the plot on the bottom of Figure 5, shows the error between the real data and the calculated one. With a max error ranging around 3%, and an average error of less than 0.5% the model gives satisfactory results. Several other time histories were tested and gave similar results.

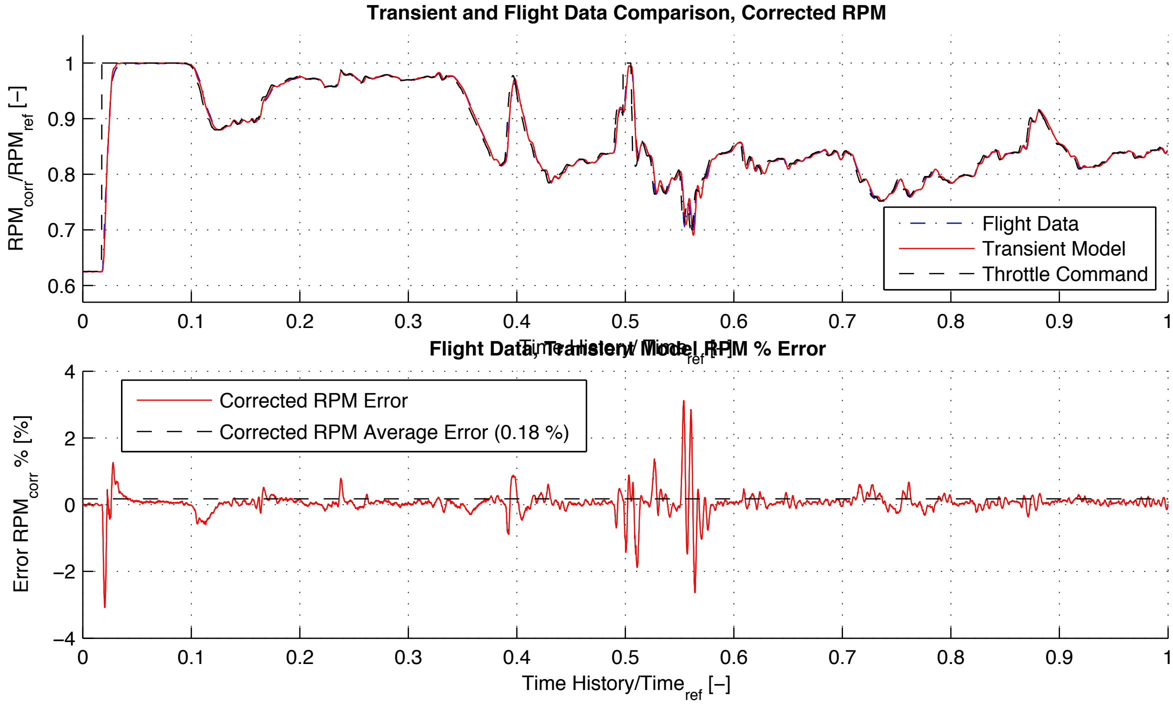

Figure 5 : transient model results.

3 Plume and Nozzle CFD 2D analysis

Once the boundary conditions on the turbine disk were calculated, defining a CFD axisymmetric model of the nozzle was possible. Since the thrust vectoring system in study is based on three vanes, which moves inside the turbojet plume through an actuation system, it was mandatory to investigate the plume properties before analyzing the effective TV performances.

The plume investigation was performed in two steps:

1. Definition of a CFD 2D axisymmetric analysis, and validation of the turbine disk assumptions.
2. Comparison of the plume results with a plume calculator software.

3.1 CFD 2D model

The CFD model enables to calculate the development of the plume jet, and to verify that the boundary conditions on the turbine disk, which were calculated earlier with a simple thermodynamic equation, hold in the N-S model. A simple grid (shown in Figure 6) was designed in order to adjust the boundary condition parameters, and verify that the plume development was correct.

CFD 2D results were compared to the 1D steady model. The investigation analyzed several working points of the turbojet, both in SLS and cruise condition. After each simulation was ended the most relevant parameters of the Navier-Stokes analysis were collected and compared to the steady state model 1-D. Figure 7 shows the results of such comparison: the blue (and black) solid line refers to the steady state model, while the red and blue stars refers to the CFD results. In particular the thrust property (depicted in Figure 7, left) matches throughout the entire engine RPM envelope, showing a good estimation of the boundary conditions.

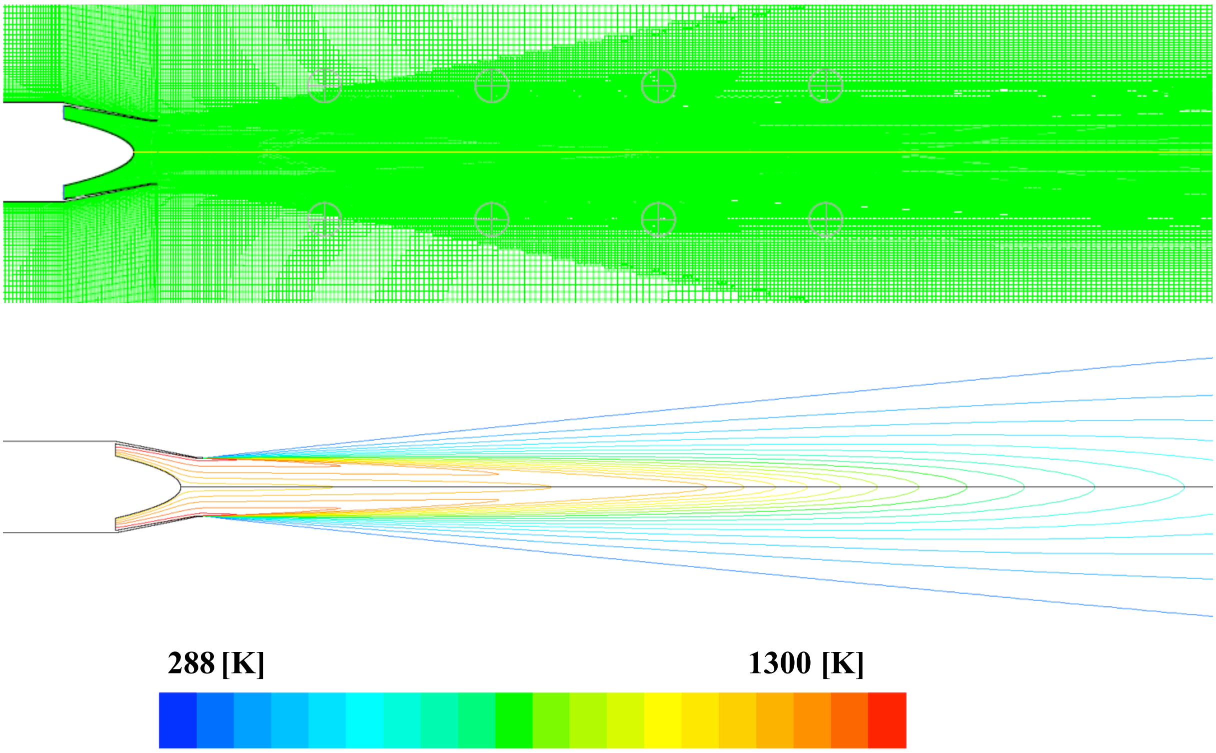

Figure 6 : CFD 2D grid and results.

The Exhaust Gas Temperature (EGT), showed in Figure 7, right, contains a more detailed plot. The engine EGT sensor indeed is placed on the nozzle skin, quite close to the turbine disk section, the solid blue line shows the results of such sensor, while the blue stars show the results of a CFD probe placed in the very same position in the CFD model. By looking to the EGT calculated by the steady state model, and the values reported by the sensor there was a considerable difference; in the turbine disk the temperature gradient was quite dramatic. Through a test performed with some thermo-sensitive paints, a considerable temperature gradient was found on the turbine disk blades. Since the EGT probe is placed near to the turbine blades, it actually measures a temperature that is higher than the average one (reported with red stars in the CFD, and black solid line in the steady state model). The most relevant engine parameters are well described by the CFD, this implies that the assumption made on the turbine disk properties are correct. The plume properties (needed for the thrust vectoring forces acting on the vanes) can be calculated using CFD.

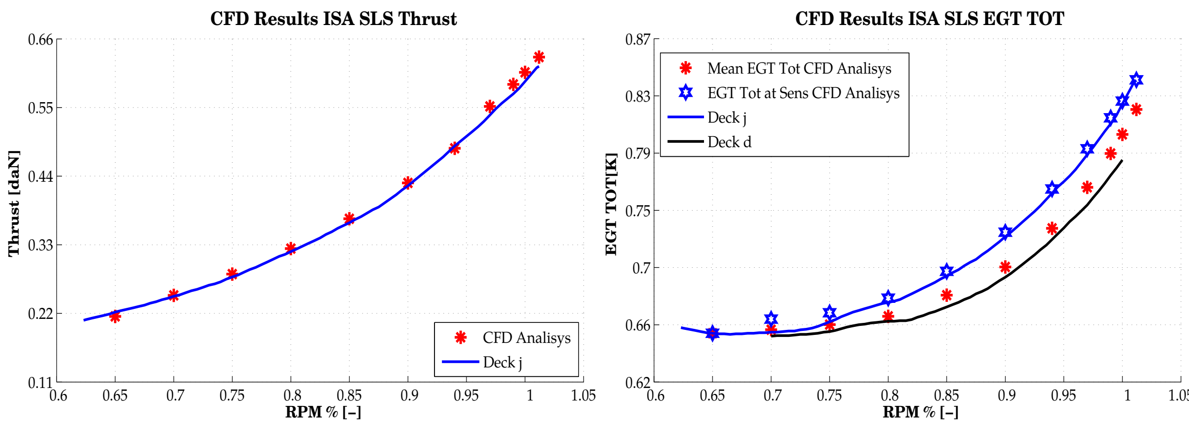

Figure 7 : CFD 2D grid and results.

3.2 Comparison of the plume shape

The development of the plume is important, in particular the angle of expansion of the plume in the first meters. In order to calculate correctly the forces acting on the vanes, a comparison between the CFD results and results obtained through specific software (REP3), which calculates plume of missiles and nozzles was made. The comparison shows a good compatibility both in terms of contours of temperatures but also in terms of plume expansion angle. Figure 8, which plots the total temperature contours, in [K], shows the classic Navier-Stokes (N-S) CFD solution in the lower part of the image, compared to the upper part, which depicts the REP3 result. The results show similar plume angle as well as a comparable temperature gradient. Since the two plots return coherent results, the assumptions made on the boundary conditions and on the model set-up were considered to be valid.

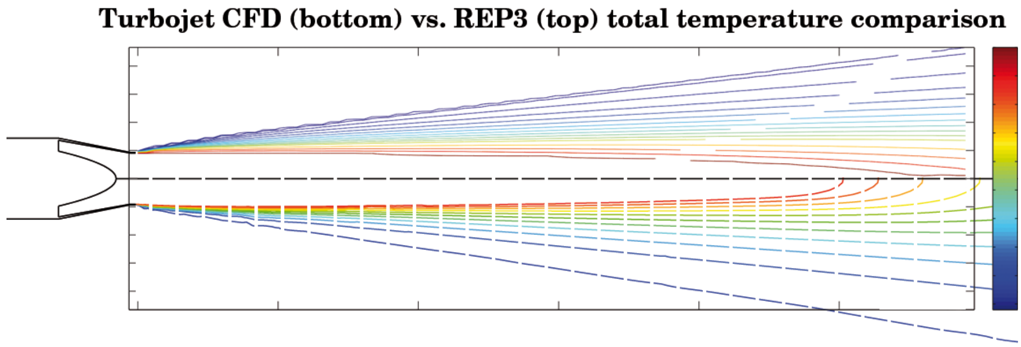

Figure 8 : CFD 2D / REP3 comparison.

4 Vanes deflection CFD 3D analysis

Once the boundary conditions on the turbine have been validated, a complete CFD 3D analysis of the thrust vectoring assembly could be started. A detailed CAD assembly model was available. Starting from that complex model, a simplified one was obtained. The latter (shown in Figure 9) was used as a starting point for the CFD 3D analysis. In the simplified model, the actuators kinematics was removed as well as the complex piping, which feeds the engine. Even the thrust vectoring vanes were simplified, in order to keep only the part in contact with the turbojet exhaust.

The plot shown in Figure 9 presents a cutout view of the result of a CFD analysis.

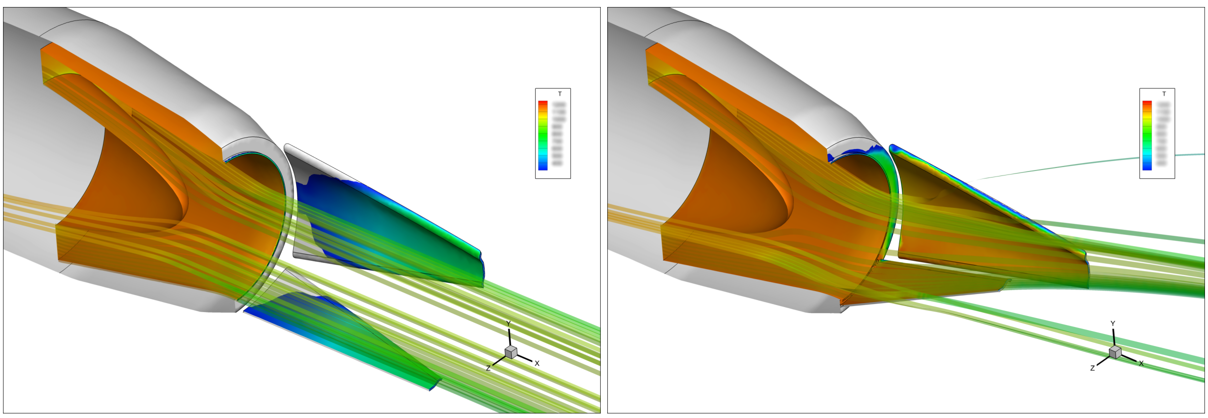

Figure 9 : CFD longitudinal deflection contours and streamlines of static temperature.

The analysis is performed at max dry throttle setting, with no deflection of the TV vanes (on the left), and with maximum longitudinal deflection (on the right). Static temperature is shown on the volumes skins, as well as on the streamlines ribbons. As the TV vanes enter in the exhaust jet of the engine, the temperature on the vanes skin rises, and the obstacle considerably deflects the exhaust jet.

Once several points of the envelope were solved, a summarizing map of the TV system performances could be made (shown in Figure 10).

The map shows with different colors, the forces envelope at various throttle settings and environment settings. In particular at Mach 0.3 and altitude of 5 km the effect of sideslip was investigated. The results show that while in the advantageous condition (TV deflection in order to compensate a sideslip) the benefit is considerable, in the adverse condition (TV deflection in order to give rise to a sideslip angle) the losses between nominal (no sideslip) flight and the sideslip condition can be neglected.

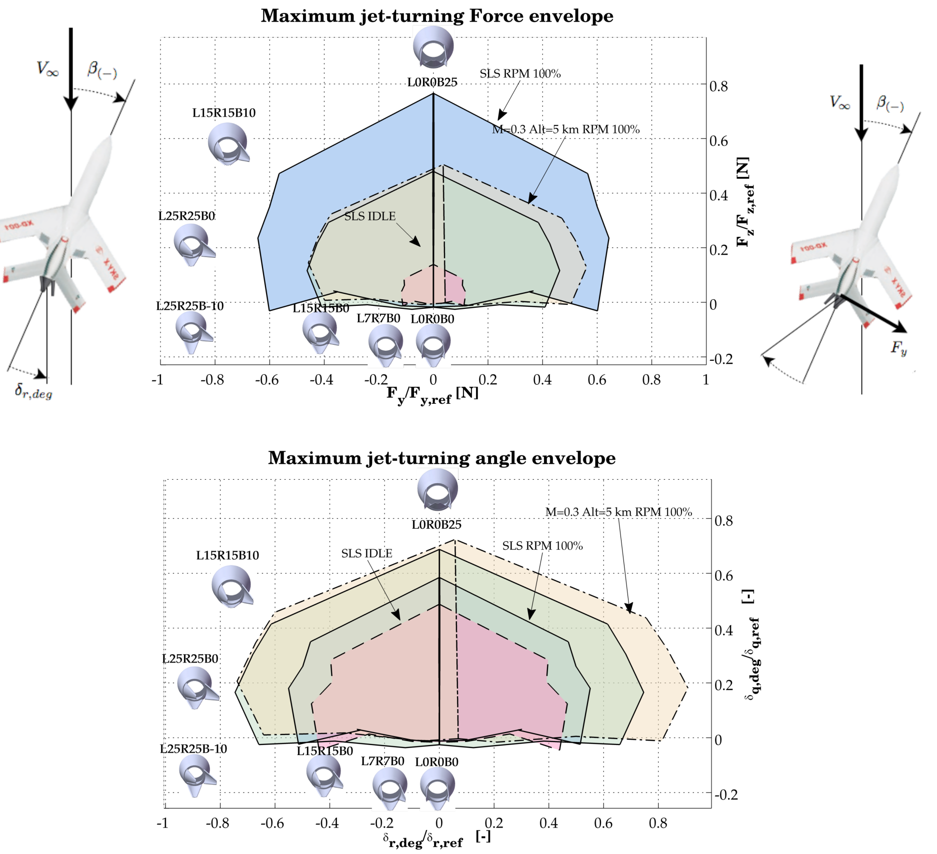

Figure 10 : Thrust Vectoring performances results.

Those findings were compared to the one found in the NASA technical reports ([1], [2], [3] and [4]), and the results in lateral directional plane, show great accordance. In particular the plot of Figure 10 (bottom), contains the results in terms of deflection of the exhaust jet, which were obtained using the same deflection angle definition used by NASA, thus allows to compare directly the TV system effectiveness with other studies.

5 Conclusion

Through the development of three models: steady state, transient and CFD, much information on the engine dynamics was found. Efficiencies of many engine components' could be estimated. A detailed analytical engine deck was developed, both steady state and transient. While the original, simple model output only the 12 most relevant parameters, and was limited to steady state, the two turbojet engine decks developed calculate 56 parameters, and can calculate transient engine dynamics too. Engine transient performances can be calculated as well as critical engine operation envelope. The transient model error lies inside the engine performances scattering band. The detailed knowledge of the engine average values stage by stage led to the definition of several CFD models. Thanks to the CFD models plume analysis and thrust vectoring vanes design was possible. The final three vanes design produces satisfactory trim pitch, and lateral-directional thrust vector deflection. The results are in agreement with the NASA reports. In the lateral-directional plane the thrust vectoring effectiveness allows to investigate a reduced tail or even tail-less configuration, which could reduce the radar footprint of the UAV, enhance its stealth capabilities and improve its flight envelope.

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