Flight Mission Study With PROOSIS

Francisco Carmona Guerrero
Email: franciscocguerrero@gmail.com
University instructor: Stefano Discetti
Universidad Carlos III de Madrid
Company instructor: David Castaño de la Mota
Empresarios Agrupados, Simulation Department

The purpose of this study is the creation of a tool capable of performing flight mission analysis. This simulation tool must be capable of combining some specified flight profile and particular aircraft, to define the actual conditions under which the engine is operating. It will be implemented on the software PROOSIS.

The developed tool has to fulfil a number of requirements: incorporate an intuitive and simple interface so that it may be used without prior PROOSIS experience, while at the same time it must encompass the inherent complexity coming from modelling a turbofan engine. It must also incorporate a database from where several engines, aircraft, and flight missions may be chosen by the user for the simulation. And finally, the accuracy of its results needs to be validated and contrasted, in order to ensure fidelity to real-world engine operation. To this end, PIANO software will be the program to execute the comparisons and evaluate the precision of the developed tool.

This work has been done in and for Empresarios Agrupados.

Keywords: PROOSIS, mission study, modelling, simulation, tool.

This document represents the essence of the Final Bachelor Degree Project done by Francisco Carmona Guerrero.

List of Acronyms and Abbreviations

ADS-B	Automatic Dependent Surveillance - Broadcast
BADA	Base of Aircraft DAta
FAA	Federal Aviation Administration
MTOW	Maximum Takeoff Weight
NEST	Network Strategic Tool
PIANO	Project Interactive Analysis and Optimization by Lissys Limited
PROOSIS	PRopulsion Object Oriented SImulation Software

List of Symbols

BPR	Bypass ratio
C_D	Drag coefficient
C_{D0}	Zero-lift drag coefficient
C_L	Lift coefficient
D	Aircraft drag force, $[N]$
FPR	Fan pressure ratio
g	Gravitational acceleration, $[m/s^2]$
h	Design cruise altitude, $[m]$
k	Coefficient of C_L^2 in the drag polar equation
L	Aircraft lift force, $[N]$
m	Aircraft mass, $[kg]$
M	Design cruise Mach
$\dot{m}_{inlet}$	Air inlet mass flow rate, $[kg/s]$
$\dot{m}_f$	Mass fuel flow rate, $[kg/s]$
N_H	High pressure shaft speed, [rpm]
N_L	Low pressure shaft speed, [rpm]
q_w	Pitch rate, $[s^{-1}]$
Q	Aircraft side-slip force, $[N]$
r_w	Yaw rate, $[s^{-1}]$
SFC	Specific fuel consumption, $[g/kN/s]$
T	Aircraft thrust force, $[N]$
V	Aircraft velocity, $[m/s]$
ε	Thrust angle of attack, $[rad]$
ν	Thrust side-slip angle, $[rad]$
γ	Climb angle, $[rad]$
μ	Bank angle, $[rad]$

1 Introduction

This work pursues the generation of a program which will allow for the simulation of a flight mission, paying special attention to the behaviour of the engine. The program's user will have the possibility to analyze certain aspects of the simulation, so that its focus will be, for instance, on outputs of the aircraft's powerplant (for example, thrust provided along the flight), and the required inputs (such as fuel flow) needed so that the mission may be successfully accomplished.

Such simulation tool will consist of three main components: aircraft, flight profile, and engine, to be explained in the following section.

This tool has being developed in PROOSIS, for the advantages it offers regarding engine modelling, mainly due to the TURBO Library.

Regarding the validation, the results obtained from the developed tool have been contrasted with those from PIANO, a software used by the Federal Aviation Administration (FAA). For additional information about this program, the reader is referred to Ref. [1].

The objectives, whose accomplishment has been required in order to develop the tool, are the following:

- Generation of an engine database. Such information will be used for the designing of the engines.
- Generation of an aircraft database. Required so as to include the effects of selecting one or other aircraft in the simulation.
- Generation of a flight profile database. Each of the flight profiles included will contain altitude and velocity information about the given mission.
- Engine design. The engines to be offered for selection in the simulation must be designed.
- Development of the program. This program (i.e., the simulation tool) will allow the interaction among the aircraft, engine, and flight profile components. But it will also let the user select among a number of different configurations for the mission simulation.
- Validation. In order to assess the validity of the developed tool, how well do results adhere to reality, the developed tool's outcomes will be compared to those obtained from the software PIANO.

2 Methodology

This section focuses on the procedure followed when developing the tool. It includes three main blocks: data acquisition for the databases, engine design, and a general outlook based on the developed mission tool.

2.1 Data Acquisition

Information on the three principal components of the tool (namely, the aircraft, engines, and flight profiles) was required in order to enable the later mission simulations. What were the specific data needed, and where were they obtained from is now addressed. In some cases, information was not readily available. In such cases, it was necessary to estimate it from correlations or through certain assumptions.

2.1.1 Mission

Mission profile data was required so as to set the ambient conditions at which the aircraft is flying (hence at which the engine is operating), and in order to determine the rates of change of the aircraft position (vertical and horizontal velocities).

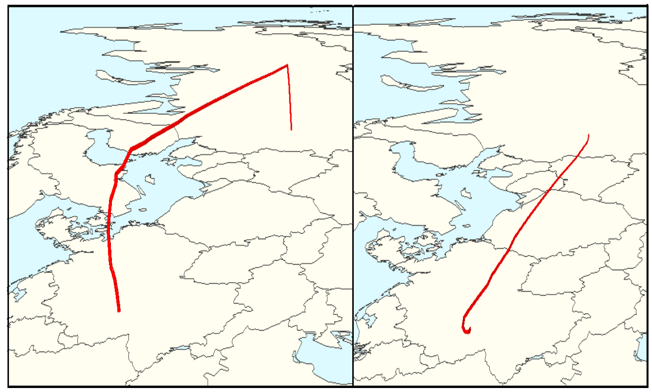

Fig. 1: A320 aircraft trajectory (3D left, 2D right) obtained from EUROCONTROL NEST modelling tool
Source: NEST software tool

Data required was derived from the equations of motion of the aircraft, seen in Eq. 1, which represents such equations in the wind-fixed reference frame.

$$
\begin{aligned}
m\dot{V} &= T\cos\varepsilon\cos\nu - D - mg\sin\gamma \\
mr_w V &= T\cos\varepsilon\sin\nu - Q + mg\cos\gamma\sin\mu \\
-mq_w V &= -T\sin\varepsilon - L + mg\cos\gamma\cos\mu
\end{aligned}
\tag{1}
$$

Regarding the input used as flight profile for the simulation, several options will be offered to the user (default mission from database, customized profile, etc.). This, together with the impossibility of obtaining real data for all flight variables (angles, speeds, forces) along the complete flight time, has made it necessary to impose certain assumptions, or rather, simplifications on the profile.

Most relevant ones are the vertical profile approximation, and the disregard of the takeoff and landing phases from the flight mission. The latter simplification is supported by statistical data, as these flight periods represent usually both very low times and fuel burnt, compared to the complete flight [2].

Vertical profile approximation means that all forces and velocities are contained on the vertical plane. This has effects mainly on the angles, such as thrust side slip ($\nu = 0$) and aircraft bank angle ($\mu = 0$) (so that lift force is inside this plane).

Fig. 1 shows a typical commercial mission flown by the A320. On the right we can see the flight profile projected in a 2D representation. It may be seen how most of the flight takes place inside this vertical plane. This is usually the common case, excluding takeoff, landing, loitering, and bad-weather avoidance.

According to the simplifications, variables required to complete the profile definition were found to be the altitude and velocity along the flight time. Several alternatives were considered as to where this information could be obtained from. Among them, the most significant were internet-based services such as flightradar24.com or flightaware.com, and

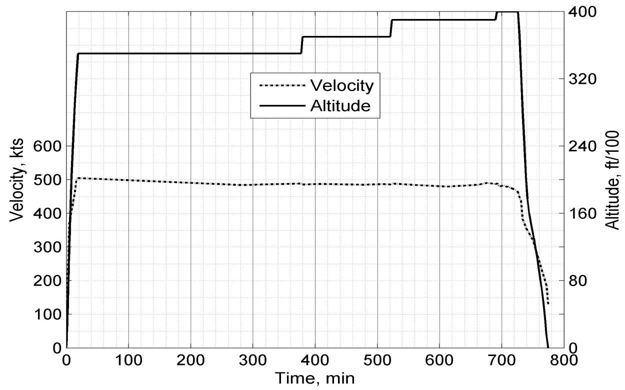

Fig. 2: Velocity and Altitude profile example for a long range flight mission

the tool used by EUROCONTROL to assess air traffic capacity management, NEST.

The former relays on FAA data, and on ADS-B (Automatic Dependant Surveillance - Broadcast), which are devices that receive flight information transmitted by the aircraft. The problem of such systems is coverage, specially for long range flights, where it may happen that certain flight periods are not monitored by these devices.

This is the reason because of which NEST software was employed. An example of the outcomes that may be obtained with this tool are shown in Fig. 2, showing a long range fight flown by the A388.

2.1.2 Aircraft

Aircraft data is necessary for two reasons. The first is the interest on certain aircraft coefficients and dimensions, in order to be able to compute the lift and drag aerodynamic forces. The second is required so that certain simulation *limits* or *constraints* can be assessed, checked. This is the case of the maximum number of passengers an aircraft can carry, or the MTOW (maximum takeoff weight), which must not be exceeded by the initial aircraft mass. Therefore, in the hypothetical case in which the user selected to board more passengers than feasible (according to the aircraft), a warning would be released. Same happens with the other constraints.

Aircraft information has been obtained mainly from the well-known book *Jane's All the World's Aircraft*, manufacturer's web pages (mainly Airbus and Boeing), and the BADA OPF files. These files are provided and maintained by EUROCONTROL, thus its reliability as a data source.

Following is a list containing the aircraft that may be selected in the simulation, with their respective manufacturers. This list encompasses aircraft with different characteristics (short, medium, and long range aircraft).

- A320-214 (Airbus)
- A380-861 (Airbus)
- BAC 111-400 (BAC)
- Fokker70 (Fokker)
- 747-200 (Boeing)
- 767-300ER (Boeing)
- 777-200ER (Boeing)
- 777-300 (Boeing)

As mentioned before, some data were not readily available. The most relevant case is that of the maximum fuel capacity of the BAC 111 aircraft. It was estimated using information on the ferry range[1].

Under certain assumptions (such as constant cruise velocity and altitude), and using the cruise range equation (2), it was possible to derive an equation depending on the initial and final cruise lift coefficients (Eq. 3). These coefficients, for fixed altitude and velocity, depend on the aircraft mass (under level flight approximation).

$$R' = \int_{t_1}^{t_2} V\,dt \tag{2}$$

$$R' = \frac{V}{SFC}\frac{1}{\sqrt{kC_{D0}}}\left[\arctan\left(\frac{C_{L1}}{\sqrt{C_{D0}/k}}\right) - \arctan\left(\frac{C_{L2}}{\sqrt{C_{D0}/k}}\right)\right] \tag{3}$$

Therefore, using Ref. [2] to find non-cruise weight fractions, it was possible to estimate initial aircraft mass, which, subtracted the final one (assumed to coincide with the operating empty weight), yielded the fuel burned, hence the tanks' capacity.

Now that both the flight profile and the aircraft have been explained, the focus will be set on the engine component.

2.1.3 Engine

The type of engine to be modelled for later simulation is a turbofan. It consists of a two-stages plus booster engine, in which the booster is an additional stage that allows to have an extra pressure ratio across the core flow. This booster is attached to the low pressure shaft, which connects the low pressure turbine and the fan.

This configuration is the typical one nowadays, specially for commercial aircraft gas turbines. An exception is the Rolls-Royce preference for the three-spool engines, layout in which the fan is driven by the low pressure turbine, an intermediate compressor is powered by an intermediate turbine, and finally the high pressure turbine driving the inner most compressor.

Regarding the type of exhaust, it is an unmixed flow one, so that there are two jet streams exiting the engine through the nozzle. Mixed flow exhaust are more commonly seen in military engines.

[1] Ferry range is the maximum range an aircraft can cover, with null payload and fuel tanks filled to maximum capacity

CFM56-5B4	Sea Level, Static	Cruise
Weight, $[kg]$	2381.38	2381.38
Flat rated temp. $[°C]$	43.9	0
Thrust, $[kN]$	120.10	22.24
BPR	5.7	—
SFC $[g/(kN \cdot s)]$	9.63	16.98
$\dot{m}_{inlet}$, $[kg/s]$	408.2	—
OPR	29.1	—
FPR	1.65	—
N_H, $[rpm]$	15183	—
N_L, $[rpm]$	5200	—
M	0	0.8
h, $[ft]$	0	35000

Table 1: Turbofan CFM56-5B4 data

Data was obtained for two engine operating conditions: sea level, static conditions and maximum throttle setting, and cruise. This information was obtained from manufacturer's web pages, and Élodie Roux book *Turbofan and Turbojet Engines: Database Handbook*, among others. It includes OPR (overall pressure ratio), FPR (fan pressure ratio), thrust force, BPR (bypass ratio), SFC (Specific Fuel Consumption), inlet air flow rate $\dot{m}_{inlet}$, high and low pressure shaft speeds (N_L and N_H), etc.

Additional variables to specify cruise conditions were needed (cruise altitude h and Mach M).

An example for the particular case of the CFM56-5B4 engines is seen in Table 1. This engine powers the A320.

As in the aircraft case, some data has to be somehow estimated. It included, mainly, the cruise thrust force and cruise SFC of some engines. The former was calculated equating thrust to drag (level, unaccelerated cruise flight) for a reference cruise mass, and the latter was obtained with use made of some coefficients provided in the BADA OPF files, which permit its calculation based on the aircraft flying speed.

The engines included in the simulation tool to be user-selected, as well as their manufacturers and main applications are illustarted in Table 2.

2.2 Engine Design

Now that data about the three components has been gathered, the engine design may begin. Specially important for this section have been Ref. [3] and [4].

This design should actually be referred to as "matching", rather than "design". This is so due to the fact that the engines are not been designed, as some information is already known. However there are other data whose values must be found.

Engine	Manufacturer	Application
CFM56-5B4	CFM	A320-214
GE90-85B	GE Aviation	777-200/-200ER
GP7270	Engine Alliance (GE, P&W)	A380-861
JT9D-7R4G2	Pratt & Whitney	747-200/300
PW4060	Pratt & Whitney	767-300/300ER
PW4098	Pratt & Whitney	777-300
RR Spey 511-14	Rolls-Royce	BAC 111-300/-400
RR Tay 620-15	Rolls-Royce	Fokker 70

Table 2: Turbofan engines

This is the case of the nozzle areas (both the core and bypass streams), and the performance maps. PROOSIS offers very interesting capabilities regarding the computation of these turbines, compressors, and fan maps. This computation consist actually in a scaling process, based on some default performance maps.

Therefore, when defining a partition, the nozzle areas and the *scalars*[2] are selected as "data to be designed", so that they are now unknowns instead of data, as they were previously considered. This increase in the number of unknowns will require the specification of additional boundaries, so as to balance the number of unknowns to that of data and equations.

These boundaries include that information collected for the engine case (BPR, FPR, ...).

The drawback of defining these "data to be designed" in the partition and then using a steady calculation in the Wizard Experiment[3] is that only one design point may be considered.

This is solved by generating a default partition, and then selecting the data that must actually be calculated (nozzle areas and scalars) making use of the calculation known as Extended Steady. It offers the possibility to select "data to be desinged" *after* the partition has been created. And then, the number of points can be specified (in the present case, static sea level maximum throttle, and cruise), and the boundaries can be imposed for each of these design points. The problem of this multipoint design is the fact that it requires the initialization of a large number of algebraic[4] variables, so that there are some convergence issues.

Such problem is worked out by using first the single point design, for both design points, independently. The

[2]Scalars are the variables used to scale the performance maps

[3]The Experiment Wizard is an interface which allows the user to define calculations without coding skills required

[4]Algebraics are variables whose values are found upon iteration until convergence, based on an initial guess value provided by the user

values obtained for these algebraics is then used to initialize these variables in the multipoint design.

2.3 Simulation Tool Overview

Once that the databases have been generated, including that containing the design of the engines, the details on the actual mission tool are explained.

This explanation will focus on the different components and functions in which the mission analysis tool consists of, showing which is the main objectives and required inputs of each of these elements of the tool. The main view of the simulation tool is illustrated in Fig. 3.

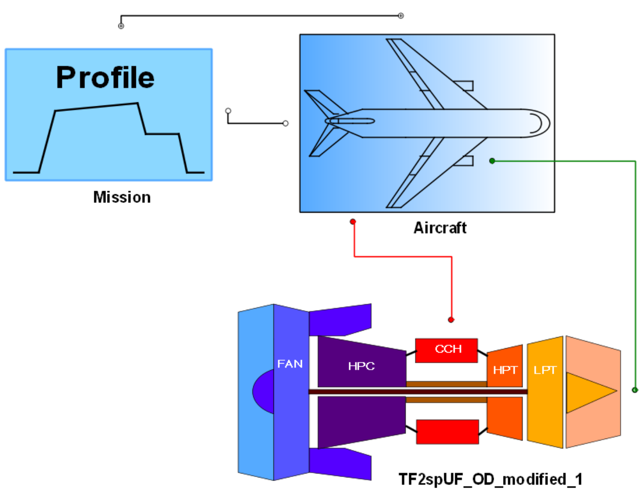

Fig. 3: Schematic showing main view of the simulation tool

The global behaviour is as follows. The Mission component (top left) provides the ambient conditions and aircraft velocity, information which is sent through the black-port lines to the Aircraft component (top right). This component is in charge of the computation of the required thrust for the given conditions. This thrust force is then sent to the Engine component (bottom) through the green port, where it is used as input data in order to obtain the fuel flow rate. This burnt fuel rate is eventually used by the Aircraft component as a means to update the aircraft weight, taking into account the number of engines that power the selected aircraft. With the new mass and flight conditions (provided, again, by the Mission component), the current thrust is once more obtained. This loop evolves until completion of the flight time, depending on the chosen simulation configuration.

Mission component

Its purpose is to provide information about the flight conditions. This information is derived from the altitude and velocity evolutions along the selected profile, and it includes the ambient conditions, true airspeed, vertical and horizontal velocities, climb/descent angles, and given flight altitude. There are four options in which the user may define the profile.

- Default flight. Mission profile loaded from a database.
- Custom flight. Mission profile completely user-defined.
- Discrete flight. Mission profile is divided into several segments (according to altitude blocks). Each of these flight sections is defined by the user by specifying certain flight parameters (vertical velocity, cruise range, Mach number, etc.).
- Cruise flight. This option allows only the representation of the cruise phase. It requires the specification of the cruise range, Mach number, and altitude.

Aircraft component

Two are the main functions of this element: loading data depending on the aircraft selected by the user, and obtaining the thrust required according to the equations of motion.

However, it also fulfils many other tasks, such as allowing the user to specify the payload to be loaded (with two options, either as passenger number and average passenger mass, or as a percentage of the maximum aircraft payload mass), and the fuel required (fuel load and contingency fuel).

Another relevant mission of this component is to provide warnings or even stop the simulation in the case that certain data inputs do not agree with the aircraft limits. This is the case of the MTOW. If, according to the payload and fuel load, the initial aircraft mass exceeds the MTOW, the simulation is stopped with a warning informing the user about the load conditions. Same happens if the maximum passenger capacity is surpassed.

Other limits are not related to capacity or overstress of the structure (such as MTOW), but with flight feasibility. This is true when checking that there is still fuel in the aircraft tanks. Two warning are shown here. The first when there is only contingency fuel left (simulation continues), and the second when all fuel loaded has been burnt (simulation stops).

Engine component

The objective of this component is allowing the selection of the engine to be used throughout the simulation. Then, at the Experiment Wizard level, this information will be used to load one or other engine designs. The engines that may be chosen are those seen in Table 2.

This engine is modelled through the schematic shown in Fig. 4. As explained in the engine section, it is a turbofan with two stages plus booster. Nozzle exit streams are separated.

Some calculations can be defined regarding the engine, to be explained next, as well as the specific functions generated for the simulation tool.

Functions and Calculations

Two functions have been defined. One is for calling data coming from XML files which encompass aircraft information. Such information includes aircraft weights (maximum payload, maximum fuel, operating empty weight, maximum landing weight, etc.), wing span and reference surface area, number of engines, maximum passenger capacity, stall speed, weight of the standard engine carried for the actual version of the aircraft, and C_{D0} and k values for different aircraft configurations.

The second function is in charged of converting the indicated airspeed (that speed seen by the pilot in the airspeed indicators) to true airspeed (actual aircraft speed). This is required for the case in which "discrete fight" is selected as the option to input flight profile. In this case, depending on the segment, flight velocity might be entered as indicated airspeed.

Regarding the calculation defined at the Experiment Wizard level, most important ones are summarized next. First, there is a calculation which, according to the chosen engine, will load the corresponding engine design, and the engine weight (so that the engine weight is taken into account by updating the aircraft weight using the weight difference between the standard and selected engines). There are also some calculations which allow the modification of certain engine variables. Most relevant cases are those in which pipe losses, bleed values (or their variations according to relative shaft speed), and turbine power extraction may be specified.

3 Validation

This section will show how have the results coming from the developed tool been validated. This validation has consisted in comparing the results of the outcomes obtained in the PROOSIS mission tool, to those obtained using PIANO-X software, a free version of the PIANO program. The reader is again referred to Ref. [1] for more information on this software, as well as on its main users and range of application.

The validation has been divided on three main blocks:

- Global performance. It refers to the complete flight, so that the evolutions of certain variables has been compared, along the full flight time.
- Point performance. This type of performance is that in which a given flight instant is addressed, meaning that flight variables (velocity and altitude) are fixed, as well as aircraft mass.
- Block performance. Here, different range and payload combination are compared (regarding the cruise flight segment).

Some of the main results of the validation have been included in the Appendices.

4 Conclusions

Now that the simulation tool has being developed, employed, and validated, several conclusions may be extracted. These ideas provide a general view on the scope of this work.

The created program represents a way to perform simulations on how turbofan engines operate. Not any generic gas turbine engine, but actual engines that power real-world aircraft, and whose designs have been carried out so that they may be readily used for these simulations. The conditions under which these air-breathing engines work are set according to the aircraft and flight to be flown. Data about these two additional components has being gathered, in an attempt to incorporate two new libraries, from where flight profile and aircraft may be user-selected.

This innovation means a wide range of options and alternatives. Indeed, several different-purpose studies may be done using this tool. Nevertheless, besides the selection of engine, aircraft, and flight mission, new capabilities have been added. The definitions of such new features have been drove in agreement with two main objectives: the pursue of a simplified interface which does not overwhelm the user, and the need to include enough options to ensure that diversified simulation targets may be accomplished.

Of course, these two aims oppose each other, thereof having been necessary to achieve some compromise. The output of such trade-off includes features that allow the user to specify the aircraft configuration (payload and fuel loading), and some parameters whose definition has a great impact on the engine simulation: bleeds, turbine power extraction, duct losses, etc.

However, the validation, although good regarding qualitative aspects, has not shown the expected accuracy on the quantitative results. According to the validation performed, this quantitative lack of accuracy is intimately related to data used in the modelling. In particular, simulations have shown a very sensitive dependence on some aircraft parameters. Specially on the zero-lift drag coefficient, C_{D0}. The problem with this variable (which has effects throughout the complete simulation) is the fact that different sources provided dissimilar values, modifying the tool results. Were it feasible to obtain exact data about this variables, accuracy would be greatly increased.

However, this quantitative error is *scaled*, with a similar average error for most of the flight profiles. Qualitative behaviour is, on the other hand, accurately represented.

This is all seen in the results obtained in the validation analysis, some of which are provided in the Appendices.

References

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[3] Alexios Alexiou. *Introduction To Gas Turbine Modelling With PROOSIS*. Laboratory of Thermal Turbomachines (LTT) - National Technical University of Athens (NTUA), 2 edition, April 2014.

[4] Alexios Alexiou. *TURBO 4.0 Library: Reference Manual*. Laboratory of Thermal Turbomachines (LTT) - National Technical University of Athens (NTUA), 2014.

Appendix A: Turbofan modelled in PROOSIS

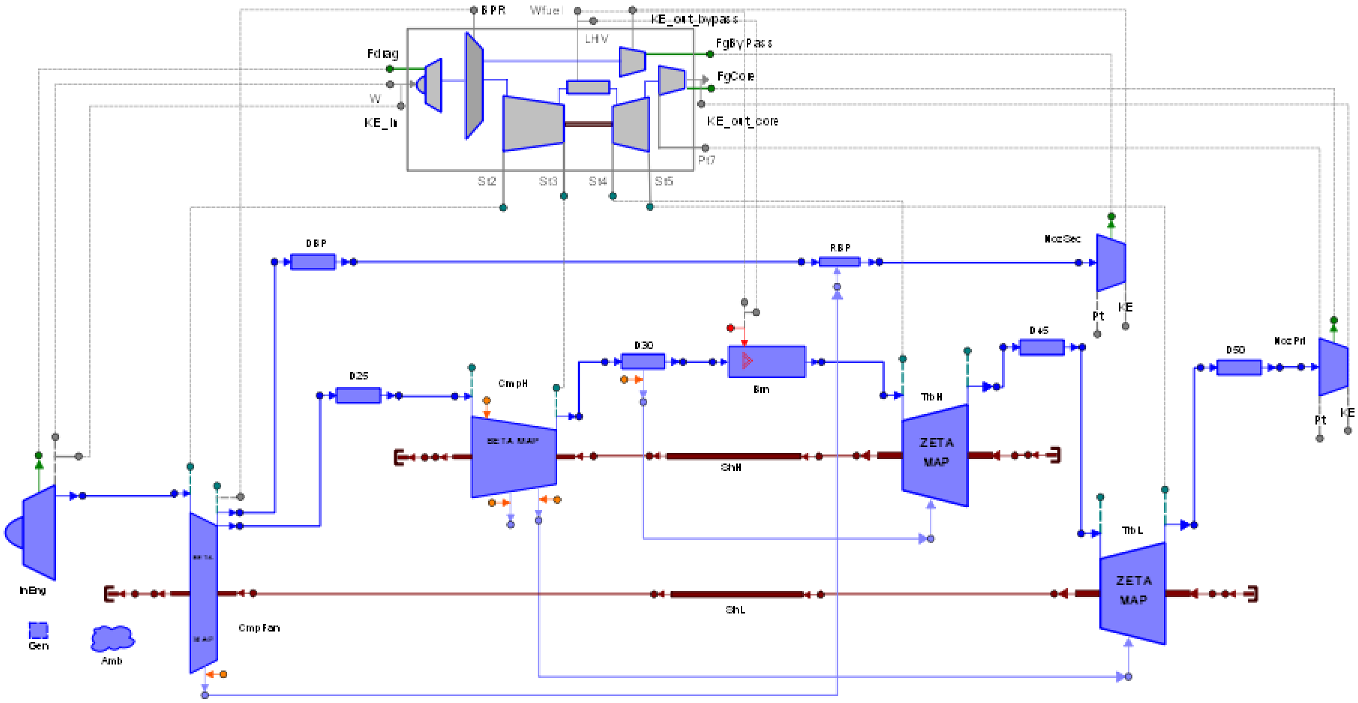

Fig. 4: Turbofan engine modelled in PROOSIS

Appendix B: Validation results

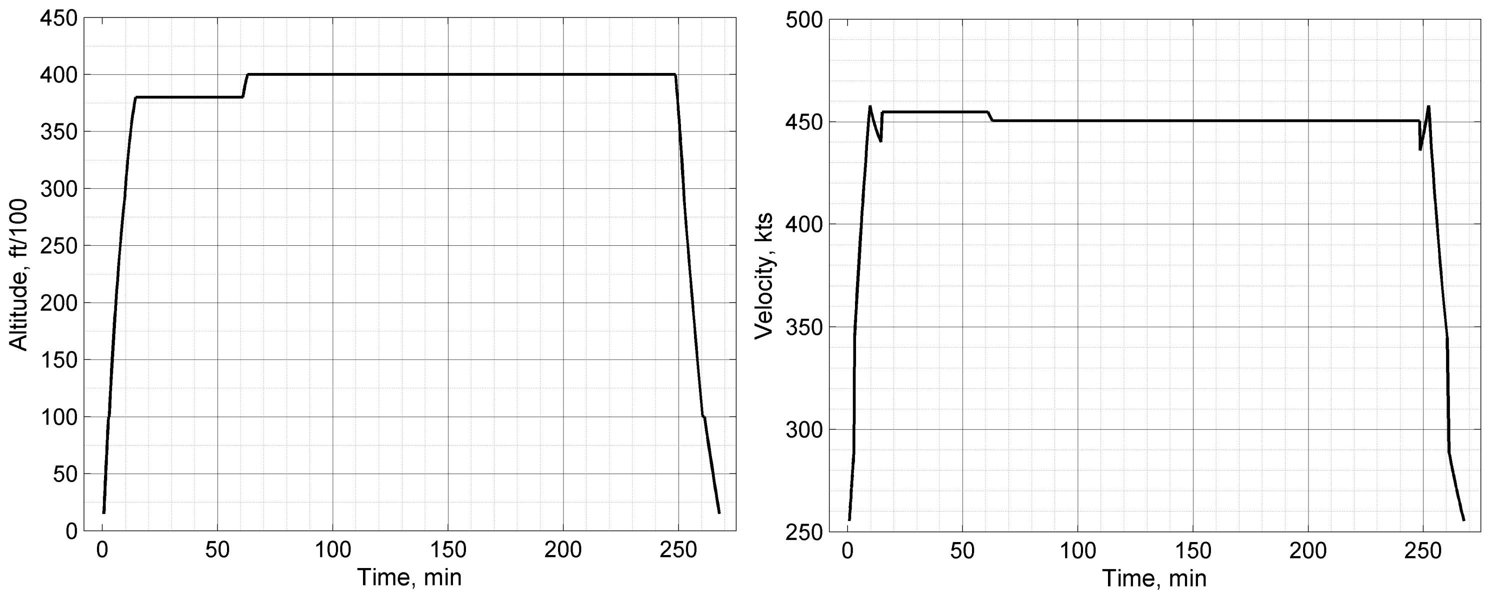

Fig. 5: Flight profile for validation: altitude and velocity

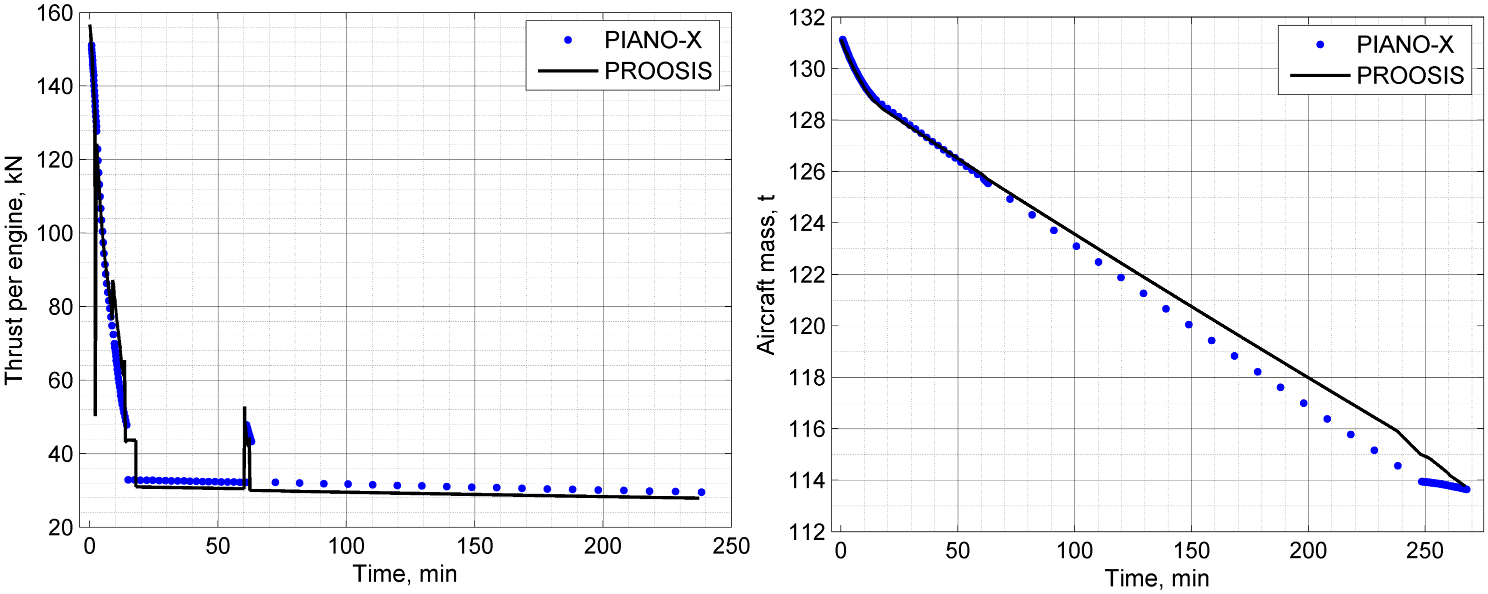

Fig. 6: Aircraft mass (right) and engine thrust (left) evolutions

	PROOSIS	PIANO-X	Δ% Error
C_D	0.03690	0.03541	4.21
C_L	0.612	0.617	-0.81
L/D	16.59	17.43	-4.82
$\dot{m}_f, [kg/s]$	0.75	0.790	-5.06
SFC, $[g/(kN \cdot s)]$	15.31	17.03	-10.10
Drag, $[kN]$	96.79	92.81	4.29
Lift, $[kN]$	1606.11	1618.11	-0.74
Thrust, $[kN]$	48.76	46.41	5.06

Table 3: Point Performance Results