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Model-based dynamic performance simulation of a microturbine

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Abstract. Microturbines can be used not only in models and education but also to propel UAVs. However, their wider adoption is limited by their relatively low efficiency and durability. Validated simulation models are required to monitor their performance, improve their lifetime, and design engine control systems. The aim of this study is to develop a numerical model of a micro gas turbine for engine performance predictions and prognostics. To build a reliable zero-dimensional model, the available compressor and turbine maps were scaled to available test bench data with the least-squares method, to meet the performance of the engine achieved during bench and flight tests. A steady-state aeroengine model was then developed and compared with experimental operating points. Selected flight data were then used as input for the transient engine model. The EGT temperature and the fuel flow were chosen as the two key parameters to validate the model, comparing the numerical predicted values with the correspondent experimental ones. The observed difference between the model and flight data was lower than 3% for both EGT and fuel flow.

1. Introduction

Microturbines are 25 to 500 kW gas turbine engines evolved from piston engine turbochargers, aircraft Auxiliary Power Units (APU) or small jet engines. The main components are the same as the gas path components from a full-size gas turbine. They often have a single or double stage radial compressor, and a radial or axial turbine. Rotational speed is usually greater than 40000 revolutions per minute, and for some applications goes as high as 150000 rpm.

Microturbines present many applications. One major use is likely to be for energy production, as standby or backup power, where power availability is critical. Alternative fuels are another area when microturbines can be used: in fact, they represent a useful tool for research [1] [2]. Their use for propulsive purposes in Unmanned Aerial Vehicle is increasing in the last years, as more producers make more microturbines available, and with a wide range of thrust classes [3]. However, engine downsizing is accompanied by a significant increase in Reynolds Number, resulting in a decrease in both turbomachinery and overall engine performance. Because of this, research in understanding the behaviour and performance of microturbine is critical, specifically implementing simulation models to study them in an effective way.

Modelling the dynamics behaviour of a complex non-linear system such as that of a gas turbine is very useful, because it can monitor its performance parameters for fault diagnosis, performance, and deterioration control. The literature shows many examples of the use of engine performance simulations to decrease design and development costs for full-scale gas turbine engines. In [4] a transient engine model of the Viper 632-43 was created, and different machine learning techniques were used to estimate and predict an engine parameter. Also [5] and [6] describe the proposition and development of an integrated health monitoring platform for performance analysis and degradation diagnostics of gas turbine engines. In [7] a new method for the simulation of gas turbine fuel systems based on an inter-component volume method has been developed. On the other hand, very little literature is available regarding engine performance simulations of microturbines. In [8] a steady-state mathematical modelling of the microturbojet Jetpol GTM120 was developed, and a comparison with laboratory test stand experimental data was carried out. In [9] a three-dimensional numerical simulation of combustion in Jetpol GTM140 miniature turbine engine was developed. Few works have been performed regarding the creation of a transient microturbine engine model and its validation with flight data.

This research is based on extensive data gathered from test bench experiments and flight missions of a twin-engine target drone. The goal of this work is to implement and validate a numerical model of a gas turbine to be used for engine prognostics and health management. For this purpose, an engine simulation model of a microturbine was created for design point, off-design steady state, and off-design transient operations, validating it with experimental data from bench tests and flight tests.

The first step was to create suitable compressor and turbine maps to be used in the engine model. This was a challenging task, because of the very low availability of component maps for such engines, and for the inherent behaviour of microturbines that is very different from full-scale turbojet engines. Both maps were based on CFD analysis of components of similar size. The creation of a tabular map in the right format for the engine simulation software and the map scaling to correctly describe the behaviour of turbomachinery components in off-design operating condition were the two critical tasks to accomplish.

The second step was to implement the engine simulation model. The Gas Turbine Simulation Program (GSP) was used. The experimental data belong to two different microturbines of the same thrust class, the Polish Jetpol GTM140, and the German JetCat P140 Rxi-B. Specifically, steady-state data were available for the former engine, while flight data for the latter one. The design point was simulated and used to simulate the other the steady-state off-design engine operating points.

Finally, transient simulations were performed. For correctly setting up the simulations, data cleaning and data reduction were conducted on flight telemetry record datasets.

2. Reference data for model setup

2.1 Test rig data

The reference microturbine on which the numerical model is based were two: the Polish Jetpol GTM140 and the German JetCat P140 Rxi-B.

For the first engine, test rig measurements [10] of temperatures and pressures at various stations of the engine, Exhaust Gas Temperature, air and fuel mass flow rate, and thrust were provided at several shaft speeds. For the second engine, bench test measurement [11] of thrust and fuel flow were provided at different shaft speeds. Comparing these two last parameters (Figure 1), it is possible to notice that the performances of the two engines are in good agreement.

2.2 Flight data

Many flight missions were recorded for an air target UAV in twin-engine configuration mounting two JetCat P140 Rxi-B. For this paper, the Air Force Institute of Technology (ITWL) in Poland provided 4 data records of flight telemetry, with measurements at 50 Hz of the following parameters: speed, ambient temperature and altitude by the Pitot tube, shaft speed, EGT, fuel flow rate. The flight data telemetry available refer to 4 different missions with various profiles, resulting very useful for transient engine validation because they represent a wide range of engine operation. To give an idea of the mission profiles, a summary of their main characteristics is reported in Table 1. From now on, the flights will be designated with a number from 1 to 4.

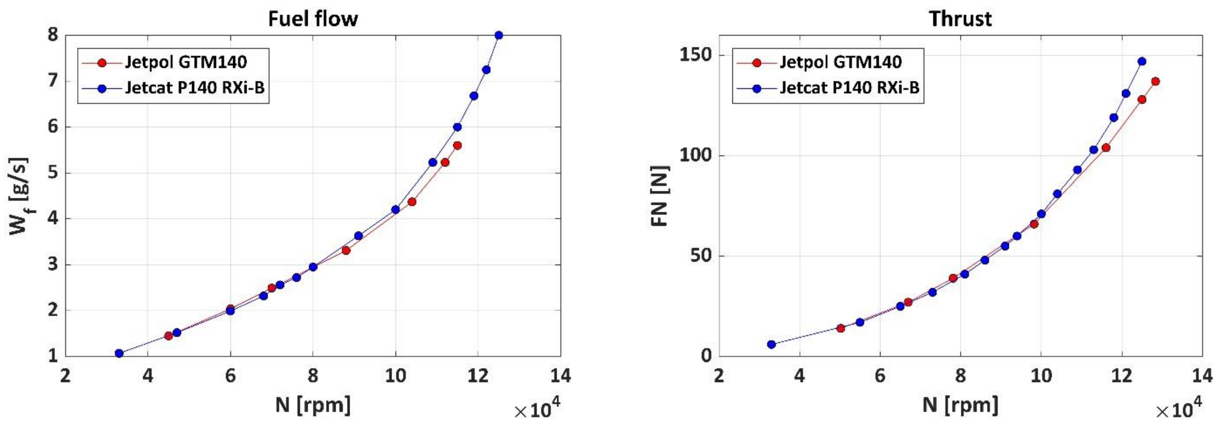

Figure 1 Fuel flow (on the left) and thrust (on the right) comparisons between the two engines.

MISSION N°	MISSION PROFILE
1	Climb to 3000 m and cruise for 1 min; Flight duration = 33 min V_{av}@cruise=329 km/h; V_{max}@cruise=353 km/h
2	Climb to 600 m and cruise for 47 min; Flight duration= 70 min V_{av}@cruise=259 km/h; V_{max}@cruise= 280 km/h
3	Climb to 3000 m and cruise for 8 min; Flight duration= 40 min V_{av}@cruise=343 km/h; V_{max}@cruise= 372 km/h
4	Incremental climbs @ 1000, 2000, 3000 m; Flight duration= 45 min V_{av}@cruise=343 km/h; V_{max}@cruise= 386 km/h

Table 1 Description of mission profile for available flight data.

2.3 Engine specifications from manufacturers

Table 2 shows engine manufacturers' specifications. Looking at the values in the table, it is evident that the engine parameters are almost identical, except for the Engine Compression Ratio and the Design Maximum speed, which are mainly influenced by design choices. The performances at Design Point are very similar as well.

MANUFACTURER DATA	Jetpol GTM 140	Jetcat P140 Rxi-B
Engine Compression Ratio	2.8	3.4
Air flow rate [kg/s]	0.35	0.34
Maximum EGT [°C]	700	720
Mass Flow [kg/s]	0.35	0.34
Design Maximum Thrust [N]	140	142
Design Maximum RPM	120000	125000
Fuel consumption [kg/s]	0.007	0.007

Table 2 Engine specifications from manufacturers.

2.4 Combination of engine parameters for numerical simulation

It is easy to notice that the two microturbine just described are very similar to each other, and the data available complement each other giving all the necessary information to create a microturbine transient engine model that can be reliably validated. From the above observations, the following assumptions for implementing the engine model are deduced:

- maximum shaft speed (at Design Point) set to 125 000 rpm, like the JetCat P140 Rxi-B;
- bench test measurements and factor for map scaling derived from the Jetpol GTM140;
- transient performance equal as JetCat's ones, measured during flight missions.

2.5 Compressor and turbine performance maps

Component maps are of paramount importance for the creation of a reliable engine model. They allow to easily determine how the machinery will perform at nearly any on- or off- design conditions. Performance maps also reveal the operating limits of the machinery to ensure safe operation of the device. For this paper, it was necessary to generate maps with a suitable tabular format that could be loaded into GSP software.

This process started from performance maps of a compressor and a turbine used on microturbines of similar size of the ones analysed in this study. These plots were provided by Rzeszow University of Technology, and were calculated using CFD analysis [12][13][14]. For each component, there are two maps, one of Pressure ratio versus Mass Flow and one of Efficiency vs Mass Flow. Then, Smooth-C and Smooth-T tools from GasTurb software were used, to digitize the plots, generate new interpolated speed lines, and create β-lines. In this way, for each operating point of the turbomachinery component, values of four component parameters were found, defining them univocally. The next phase consisted in scaling the maps. Specifically, only for the compressor map a scaling was performed, because the initial plots of the turbine were already dimensionless. To best represent the behaviour of the compressor, a least squares scaling method was performed. For each of the map variables, factors and deltas were evaluated using values of multiple operating points; these are the solutions of an overdetermined system of equations in a least square sense. The factors and delta were then used to find the values of the scaled map. Although the scaled map does not match with the unscaled map at design point, this method has the advantage of minimising the error between the different operating point data in a least square sense. Finally, the values of each map were written in GSP tabular format, ready to be entered in the software.

3. Model implementation and results

3.1 Design point simulation

With the assumptions given above, it was possible to implement the aeroengine model using the GSP software. The structure of the engine model (Figure 2) is that of a simple turbojet with two added Duct components after the turbomachinery elements, necessary for transient simulation. With Design Point simulation, the gas turbine design point performance is fixed to represent a particular gas turbine configuration. The components are "sized" to the design point using data from the Design tab sheet of Component settings, and the component maps are not used. This kind of simulation is always necessary before Off-Design, Steady-State or Transient calculations since the design point is used as the reference point for off-design operating points. The results of the Design Point simulation are in Table 3.

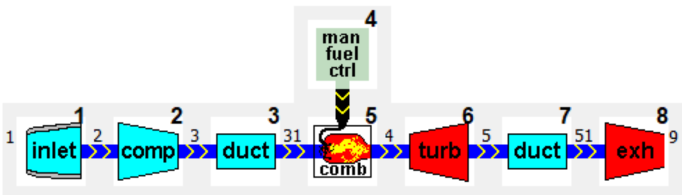

Figure 2 Graphical representation of engine model on GSP Model Window.

Rotor speed [rpm]	TT1 [°C]	PT1 [bar]	PT3 [bar]	EGT [°C]	FN [N]	$\dot{m}_f$ [kg/s]	$\dot{m}_a$ [kg/s]
125 000	15	1.0133	2.8371	628	142	0.0087	0.35

Table 3 Results of design point simulation.

3.2 Steady-state off-design simulations

The model was then tuned to simulate various steady-state off-design points. The simulation points were chosen considering the operating points tested on the rig [10]: 70 000 rpm, 88 000 rpm, 104 000 rpm, 112 000 rpm. It is possible to notice that operating points below 70 000 rpm were not picked: this is because, even if idle speed for both engine is about 35 000 rpm, simulating those operating points has no practical use, because the flight data show that the engine does not work under 80 000 rpm during operation (this last point will be discussed later).

Figure 3 shows the accuracy of the steady-state simulations: in the two plots, representing the fuel flow and the thrust respectively, the green line, corresponding to the numerical model, is in good agreement with the test bench measurements, especially in the regimes with shaft speed higher than 80 000 rpm, not exceeding 5% difference in values. This means that the behaviour of the steady-state model is very similar to the real engines.

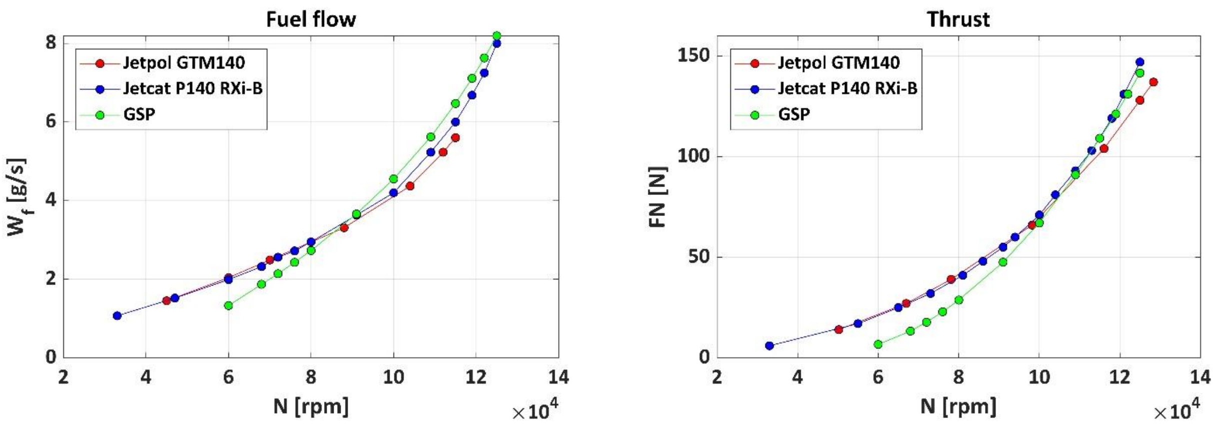

Figure 3 Fuel flow and thrust comparison with GSP numerical model.

3.3 Transient simulations

Modelling the transient behaviour of a gas turbine is the most challenging part of the process of developing an engine model. The various dynamic effects have a significant impact in defining the behaviour of the engine.

To assess whether a transient model is accurate or not, it is necessary to see the time evolution of the parameters when a series of inputs are given to the system. This means that the main requirement is to have extensive telemetry records for a wide range of operations, for two reasons:

- to provide the model with the right input values;
- to validate the model comparing its output with the recorded performance values from flight data.

For this study, extensive telemetry records for 4 different flight missions were available. The sample rate was 50 Hz, implying that, for a flight of about 30 minutes, flight records would be a table of about 90 000 rows, each of them representing a time step for which solving the system of equations numerically, implying a very high computational cost. Furthermore, the recorded data also included long time intervals before the start and after the end of each flight. Those portions of the dataset, if included in the input, could completely invalidate a simulation process. Two approaches were used to reduce this amount of data:

- bringing the sample rate down to 1 Hz;

- considering only the data that register an engine speed greater than 80 000 rpm. It was observed that the engine, during flight operations, never goes below this speed value. This is a simple trick to cut the irrelevant records from the dataset, that corresponds to:
  - the minutes before take-off, when the engine is idling but the target drone has not yet been launched;
  - the minutes after the end of the mission: this time intervals begins when the parachute opens, the engine idles and then it is turned off, and end either when the telemetry is turned off or when the target drone is recovered.

The data reduction was considerable: in Table 4 the length of original dataset and reduced dataset for each mission is reported. After the reduction, the time necessary for the software to simulate a mission was in the order of the hour, like the real-time flight duration.

MISSION N°	ORIGINAL DATA (ROWS)	REDUCED DATA (ROWS)
1	100742	1325
2	221372	3827
3	121958	1811
4	135389	2215

Table 4 Length of original and reduced datasets.

The second important step was to create an input dataset suitable for the use in GSP, selecting which variables to use to simulate properly the missions, and a validation dataset.
In this work, it was decided to choose 4 input parameters, that describe ambient and engine conditions:

- altitude;
- Mach number;
- dTs (temperature correction factor for ISA model);
- engine shaft speed.

Two validation parameters were selected:

- Exhaust Gas Temperature (EGT);
- fuel flow.

The first is probably the most important variable for monitoring the engine health state, and usually it is used alone as validation parameter. The comparison of fuel flow values, in addition, helps evaluating how the fuel control system reacts to sudden variations of input parameters during real-flight scenarios.
The plots in Figure 4 and Figure 5 show the trend of the parameters chosen for validation as a function of mission time: the comparison demonstrates that the numerical model accurately predicts the behavior of the engine even in situations in which there is a sudden variation in ambient and engine parameters, such as non-stationary portions of a flight mission. Specifically, the graphs shown here are from mission 1 and its simulation.
The average error for EGT and fuel flow is not over 3%.
Considering that:

- the accuracy of the measurement from experimental testing of microturbines is not as high as for a full-scale turbojet engine;
- the performance can vary significantly from a single engine to another of the same manufacturer, due to their low cost that implies higher tolerances on the components in the production process;
- the model is 0-dimensional and does not take into account any geometry of the engine components;
- the component maps were taken from CFD analysis and not from experimental testing of compressor and turbine of Jetpol GTM 140;

The GSP engine model created shows very satisfying results when compared to real flight data, with average error of each output parameter under 5%. It is therefore possible to conclude that the model is validated.

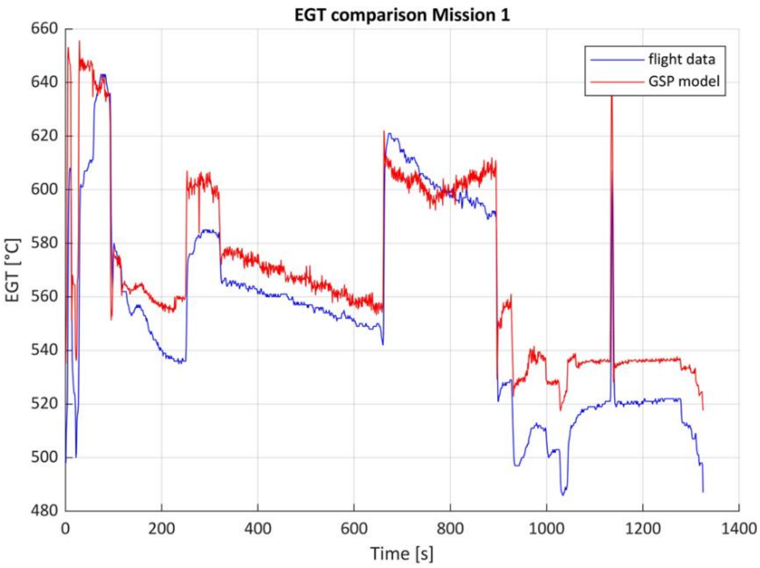

Figure 4 EGT comparison for Mission 1.

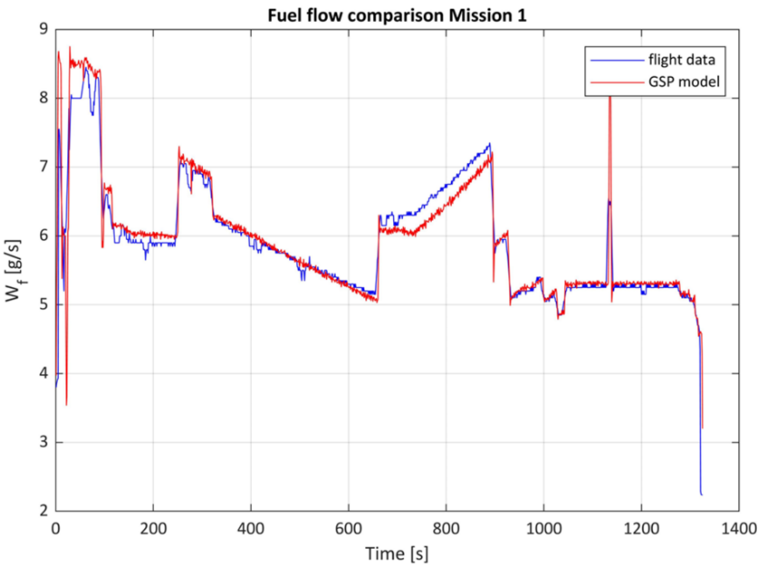

Figure 5 Fuel flow comparison for Mission 1.

4. Conclusions

This paper presents the implementation of the numerical model of a microturbine in steady-state and transient conditions, and its validation using experimental data from real flight mission. These are the main achievements of the work that allowed for the successful implementation of a reliable and precise simulation model:

- Generation of suitable compressor and turbine maps, that match the engine performance values from experimental testing;
- Implementation and fine tuning of the numerical model in GSP software, for the Design Point and Off-Design Steady State simulations, and the reproduction of the experimental flight mission to simulate transient engine operation;
- Validation of the model using rig and flight test data.

The results show the suitability of the model to predict the microturbine performance with a maximum error lower than 5% for steady-state simulations, thus making the model accurate enough to perform

transient simulation. Moreover, the comparison between the experimentally recorded in-flight data and the estimated values on the GSP model underlines an average error between the model and the real values around 3%.
To sum up, the approach demonstrated in this study based on using rig and flight data has proven to be effective in creating a transient 0-dimensional numerical model of a microturbine, even without having exact compressor and turbine maps available. The model is suitable for predicting emissions and generating training datasets for ANN, for the purpose of the developed engine health management system.

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