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Research article
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Validation of a Cessna Engine Model

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SUMMARY

Environment is one of the most important concerns in the aerospace industry. Engine efficiency is directly linked to the amount of harmful emissions produced. Modelling of gas turbine engines needs to be improved in order to reduce these emissions. The purpose of this study is to model the engine using two outputs: the thrust, which is the force moving the aircraft forward, and the fuel flow used to produce the thrust. These outputs are modelled as function of three inputs: the Mach number, the altitude and the throttle lever angle. The data needed was acquired using the Research Aircraft Flight Simulator (RAFS) from the Laboratory of Applied Research in Active Controls, Avionics and Aeroservoelasticity (LARCASE). Key words: engine, turbofan, modelling, flight tests, identification, validation

Introduction

The environment is one of the most important concerns in the aerospace industry. During the combustion reaction, the engine produces carbon dioxide (CO) which is responsible for the greenhouse effect, and thus global warming. It also produces harmful substances like NO. In order to reduce these particle emissions, the easiest way is to directly reduce fuel consumption. Reducing fuel consumption can be performed by optimizing different processes. For example, the engine efficiency can be increased by improving the functioning of its different components, or by the way in which they work together. However, to perform such improvements, engineers need a better understanding of the engines, mainly of the different parameters influencing their functioning. Either the task is improving the engine efficiency or gaining a better understanding of the system, the modelling process is necessary. Modelling is describing a system by linking its outputs to its inputs. The inputs are usually the air conditions at which engines are functioning while the outputs are the main engine parameters such as fuel flow and thrust.

System Presentation and Model Objective

The engine’s basic operation principle is to compress incoming air, spray fuel engine, and ignite it to create a high-temperature flow. This acceleration is the source of a force called “thrust” which allows the aircraft to move forward. Therefore, aircraft speed and air properties widely impact engine performances. In this study, the Mach number quantifies the aircraft speed, and air properties vary with the altitude according to the ISA model. Mach number and altitude are used as inputs.

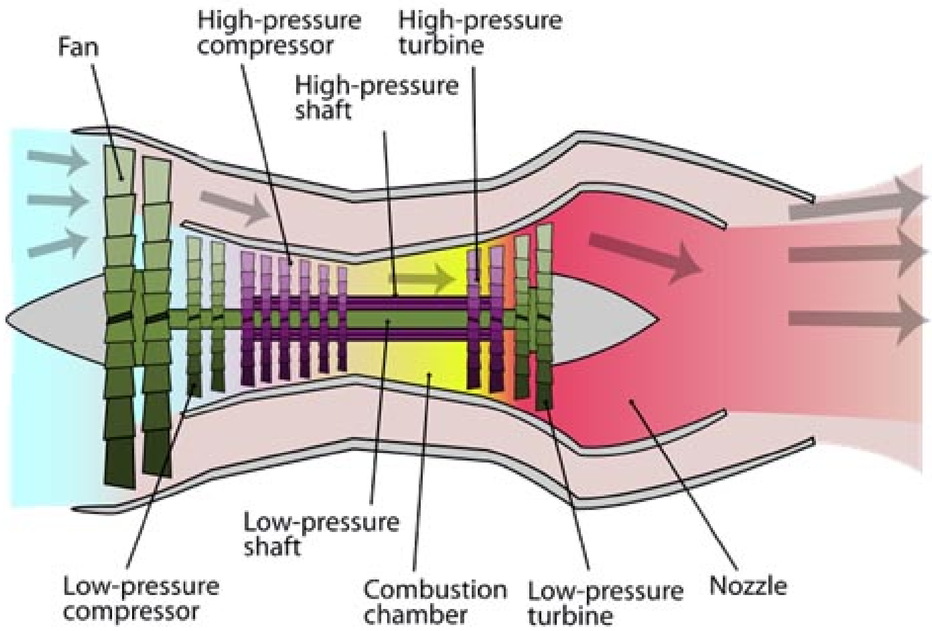

Figure 1 Twin spool turbofan scheme

We chose to model the engine using altitude (H), Mach number (M) and throttle lever angle (TLA) as inputs, and the thrust and fuel flow as outputs.

Model Identification

As mentioned previously, the purpose of this study was to create an engine model able to predict thrust and fuel flow for all flight conditions (H, M) and any pilot commands (TLA). To obtain this model, an identification and validation procedure was used. The identification process applied to the engine system is presented in the following figure:

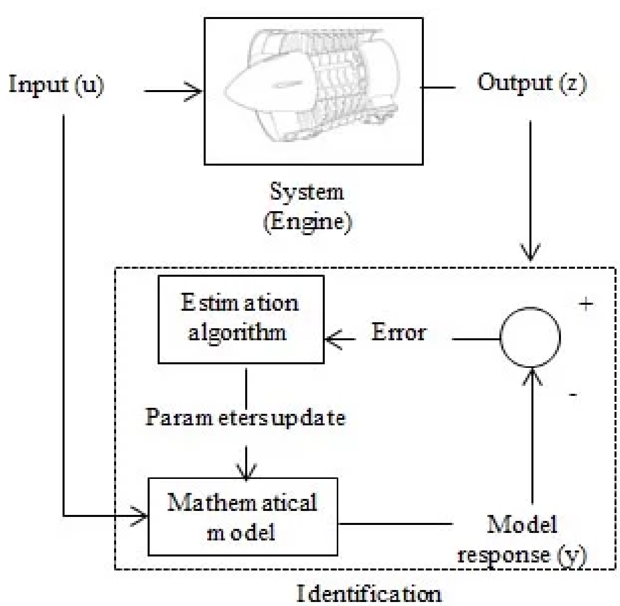

Figure 2 System identification principles applied to the engine.

As shown in Figure 2, the identification process requires a mathematical model, which can be given by an equation, for example. Then, the numerical model response is compared to the actual experimental output of the system. The difference between these two outputs, e.g. the error, is used by an estimation algorithm. The purpose of this algorithm is to fine-tune the equation parameters in order to reduce the error between the output of the identified model and the system output. The model accuracy is verified with a validation procedure.

Data Acquisition

The identification process requires a set of data to identify the model, and another set of data to validate it. In this study, the data were provided by flight tests executed on the Cessna Citation X Level D Research Aircraft Flight Simulator (RAFS) developed by CAE Inc. Level D is the highest certification level delivered by the certification authorities for flight dynamics modelling, according to the Federal Aviation Administration (FAA).

Figure 3 Cessna Citation X Level D Research Aircraft Flight Simulator (RAFS)

Ce niveau a été choisi pour effectuer des tests en vol adaptés au modèle choisi. Le modèle ne considère que la phase de croisière, ce qui signifie une altitude constante. En outre, seul l'état stationnaire est étudié où aucunes variations de position de la manette des gaz ne sont permises. Par ailleurs, le TLA doit également demeurer constant. Les tests en vol ont été effectués pour différentes valeurs de TLA et d'altitude, comme indiqué au tableau 1. Pourtant, on note que l'échelle des TLA varie en fonction des valeurs d'altitude. Par exemple, 35 degrés est la valeur minimale requise pour éviter le calage à 45 000 pi d'altitude.

TLA (deg) Alt (ft)	35	37.5	40	42.5	45	47.5	50	52.5	55	57.5	60	62.5	65
5000	X	X	X	X	X	X	X	X	X	X	X	X	X
10000	X	X	X	X	X	X	X	X	X	X	X	X	X
15000	X	X	X	X	X	X	X	X	X	X	X	X	X
20000	X	X	X	X	X	X	X	X	X	X	X	X	X
25000	X	X	X	X	X	X	X	X	X	X	X	X	X
30000	X	X	X	X	X	X	X	X	X	X	X	X	X
35000	X	X	X	X	X	X	X	X	X	X	X	X	X
40000	X	X	X	X	X	X	X	X	X	X	X	X	X
45000	X	X	X	X	X	X	X	X	X	X	X	X	X

Table 1 Identification (25) and Validation (92) Flight Tests Distribution

As seen in Table 1, a total of 25 flight tests were used to identify the model (red), and 92 flight tests were used to validate it (blue).

Methodology

The model used in this study was adapted from the "Component Level Modelling" (CLM) method. It consists in identifying a model for each component of the engine. Yet, the simulator does not provide enough information on the different temperature and pressure values for each component of the engine. The model was only divided in three sub-modulus as shown in Figure 4.

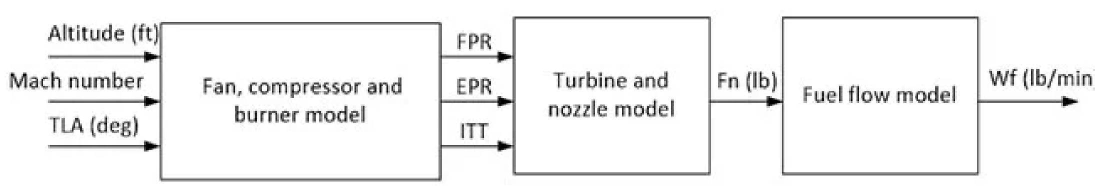

Fig. 4 Engine model sub-modulus scheme

Two different approaches were used: "Black Box" and "Grey Box". A "Grey Box" consists in identifying a model with a combination of mathematical model and estimation algorithm. The "Black Box" only uses an estimation algorithm. The fan, the compressor and the burner model were identified as a "Black Box" using a combination of the method of Least Squares and the Levenberg-Marquardt estimation algorithm. The principle behind the method of Least Squares is to express a cost function as the squared error between model response and actual experimental data. The algorithm tunes the model parameters in order to reduce this cost function. This algorithm has the benefit of providing accurate results quickly. Concerning the "Black Box" approach, the mathematical model is identified as a polynomial function. Consequently, the algorithm identifies the different coefficients of a polynomial function. A polynomial function depending on the three inputs (H, M and TLA) was identified for each output of the model (FPR, EPR, ITT, Fn and Wf). FPR is the Fan Pressure Ratio, EPR, the Engine Pressure Ratio, ITT, the Interstage Turbine Termperature, Fn, the net thrust, and WF, the fuel flow.

Regarding thrust and fuel flow outputs, there are much more theoretical models in the literature than for the FPR, EPR and ITT. Mattingly and Torenbeek's models are two of the most often used. Yet, our approach consisted in modelling the two turbines and the nozzle using a thermodynamics equation for each component, according to the "Component Level Modelling". The fuel flow was modelled as proportional to the thrust. However, the equations of the "CLM" method cannot be used on the simulator data. The flight simulator is an extremely useful tool in acquiring data but it does not give the measures of all the parameters involved, for example the ones characterizing the efficiency of different engine components. The solution was to identify these unknown parameters with the Levenberg-Marquardt (LM) algorithm. Therefore, the thrust and fuel flow are identified with a "Grey Box" approach using the LM algorithm.

Results

In order to verify the fluid dynamics model accuracy, the FAA validation criteria was used. The FAA criteria stands if a validation success is obtained when thrust and fuel flow are predicted within a 5% mean absolute relative error.

	Identification Success (%)	Validation Success (%)	Mean Absolute Relative Error (%)
Black Box	100	81.72	2.70
Grey Box	100	96.33	1.62

Table 2 Thrust obtained with 25 identification flight tests and 92 validation flight tests

	Identification Success (%)	Validation Success (%)	Mean Absolute Relative Error (%)
Black Box	100	67.90	4.84
Grey Box	100	64.90	5.23

Table 3 Fuel flow obtained with 25 identification flight tests and 92 validation flight tests

The criterion is applied on all flight tests used for model validation, thus the mean absolute relative error is obtained for these tests data.

Conclusion

The thrust "Black Box" approach provided only 81.7% validation success while the "Grey Box" approach gave 96.33%. These differences are dues to the efficiency of the mathematical model. However, concerning the fuel flow, the results were not as accurate as those obtained for the thrust. The main reason for these differences was that the fuel flow model depended on the results obtained with the thrust model. Consequently, the error on the thrust model led to an error in the fuel flow models. For the same reason, the thrust model error increases due to the error obtained on the FPR, EPR, and ITT predictions. For example, it was noticed that if the actual FPR, EPR and ITT are used with the "Grey Box" model, the validation success increases to 100% instead of 96.33%. The error multiplication is an issue of the "CLM" modelling. Thus, using this "CLM" modelling, an improvement on the FPR, EPR and ITT predictions might lead to a huge improvement of the thrust and the fuel flow prediction.

Besides, another difference between the thrust and the fuel flow results is due to the mathematical models itself: the thrust model used is much more developed than the fuel flow model, which depends on the thrust model results. It also explains that the "Grey Box" and "Black Box" approaches present similar results for the fuel flow output. To improve the results, other mathematical models might be used, for example the "stage-stacking" method for the FPR and EPR modelling, or Mattingly's and Torenbeek's models for the thrust and fuel flow modelling. Other estimation algorithms might improve these results such as the Particle Swarm Optimization (PSO).

Additional Information

For more information on this research, please read the following article:

BARDELA, Paul Alexandre, BOTEZ, Ruxandra M. Identification and Validation of the Cessna Citation X Engine Component Level Modeling with Flight Tests. In : *AIAA Modeling and Simulation Technologies Conference*. 2017. p. 1942.

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