A Flight Thrust Deck for the F100 Turbofan of the F-16 Aircraft

P. Hendrick*, K. Bourdiaudhy & J-F. Herbiet****
***Université Libre de Bruxelles (ULB), **Royal Military School of Belgium**

Keywords : turbofan, installed thrust, flight tests, validated model

Abstract

A physical model, called a Flight Thrust Deck, of the F100 turbofan of the F-16A/B fighter aircraft, based on engine parameters measurements in flight through the whole F-16 flight envelope is presented.
Such a model can be used and is adequate to open the flight envelope for new "uncleared" aircraft configurations and is a mandatory tool when developing and testing new methodologies for engine health monitoring systems.
The necessary parameters have been measured using the acquisition system RADA FACE of the F-16 through data picked up on the 1553 bus of the aircraft. Only results at subsonic speeds are presented here, without or with the afterburner on.

Nomenclature

C_D	Aircraft drag coefficient
DEEC	Digital Electronic Engine Control
EPR	Engine Pressure Ratio (-)
FTIT	Fan Turbine Inlet Temperature (K)
FN	Engine net thrust (kN)
FNs	Engine installed net thrust (kN)
ISA	International Standard Atmosphere
Ma	Flight Mach number (-)
N	Rotation speed (RPM)
P	Pressure (kPa)
TSFC	Thrust Specific Fuel Consumption (kg/daN.h)
T	Temperature (K)
W2	Total air mass flow rate (kg/s)
WF	Fuel Flow (kg/s)

1 Introduction

A physical model of a modern turbofan engine is never available if you are not an engine or aircraft manufacturer. Even if for large operators of military and civil engines, such a model may be included in some software, it is just available as a black box for the user and is therefore totally unknown to him and, as such, useless for research activities and work on new methods that need a validation before proving their real interest.

In this paper, a physical model of the F100 low by-pass ratio turbofan with afterburner that is used on the F-16 MLU fighter is presented, as well as the methodology used for its development and its validation.

The development of the model is based on measurements of the engine parameters in flight, through the whole flight envelope in dry and in afterburning regimes, at subsonic and supersonic speeds. It is what is called a Flight Thrust Deck of the engine, i.e. a software delivering the net thrust F_N (i.e. taking into account the installation effects, thus developed for a particular application or aircraft, in this case the F-16 MLU fighter) and the TSFC (Thrust Specific Fuel Consumption) for any set of the physical parameters fixing a working point (steady state point) of the engine, for example the altitude, the Mach number, the throttle position and the ambient air temperature.

The model takes also into account the variable geometry of this particular engine: the variable stator vanes of the fan, the variable stator vanes of the high pressure compressor and the convergent-divergent exhaust nozzle ([1]).

Such a model can be used in very different ways. For an aircraft operator or an upgrading company that is not aware of all models for the aircraft and its engine(s), it can be used to open the flight envelope for new “uncleared” aircraft configurations, as a military fighter equipped with new weapons, auxiliary fuel tanks or specific pods (in fact, in this application, the engine Flight Thrust Deck allows to estimate rather precisely the aircraft total drag). For researchers and universities, it is a mandatory tool when developing and testing new methodologies for health monitoring logic, engine monitoring systems or engine control systems (like adaptive fuel control systems).

The model shown in this paper has been developed based on flight test measurements of the F100 engine installed in a F-16 fighter aircraft, flown with different (drag) configurations in order to change the parameter “engine throttle” (or in fact the engine TIT) for a given triplet altitude, Mach, Outside Air Temperature. The necessary parameters have been measured using the acquisition system RADA FACE of the F-16 through data picked up on the 1553 bus of the aircraft mainly in steady state engine ratings but also during engine transients (a total of 22 parameters of the aircraft or of the engine have been measured simultaneously). These test data have also been used to define the real compressor and turbine maps of the engine, which are mandatory elements to obtain a realistic physical engine model.

Hereunder, as an example, the Table 1 shows the first specifications fixed for the engine in SLS ISA conditions at different engine ratings (the FTIT is the total temperature between the HPT and the LPT and W_2 the total air mass flow rate).

	F (lb)	SFC (lb/hr/lb)	N_1 (rpm)	N_2 (rpm)	FTIT (K)	W_2 (lb/s)
Maximum (5 minuten)	23840	2,17	10160	12960	1205	228
Maximum[1]	21360	2,29	10100	13020	1208	210
Intermediate	14690	0,72	10200	12980	1205	228
Maximum Continuous	12410	0,69	9810	12560		
90% Maximum Continuous	11170	0,68	9600	12360		
75% Maximum Continuous	9300	0,67	9260	12020		
Ground Idle	670	1040[2]	4540	9130		

Table 1 - F100 turbofan SLS ISA specifications

A first result of this physical engine model is already shown hereunder in Figure 1 with the working line for SL static conditions.

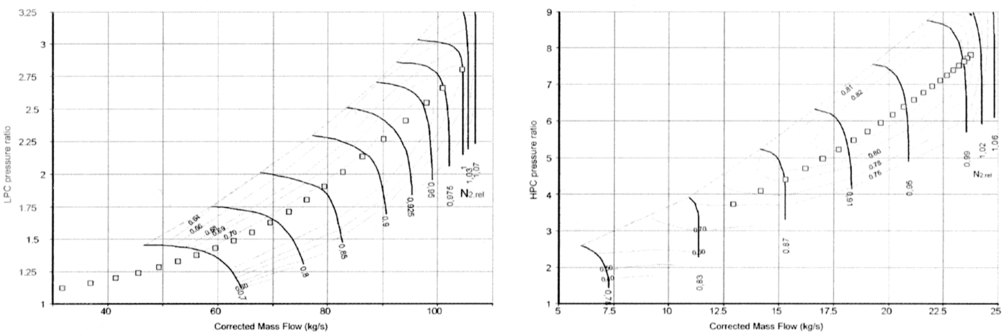


Fig. 1 – Steady state line on the LPC (fan) and HPC maps

The rational behind this engine installed performance prediction tool is to use as much as possible sensors already available on board the aircraft and collect their values thanks to a system also available on board as the MUX bus of the aircraft (this is a 1553-bus) and an adequate software linked with the data collection unit used by the pilot, the so-called FMU (Flight Monitoring Unit) with the Rada Face software.

2 Development of the Flight Thrust Deck

2.1. The F100 and its installation effects

The F100 is installed in the F-16 with a belly-mounted position and is receiving its air via a rather long normal shock supersonic external compression intake profiting of some pre-turning and pre-compression at, respectively, subsonic and supersonic speed. That is illustrated in Figure 2.

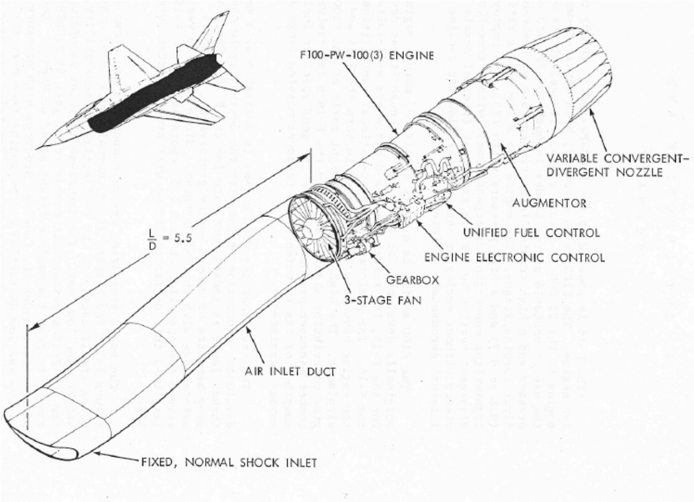


Fig. 2 – The F100 in the F16 with its belly-mounted intake

The installation effects needed to be considered in the Flight Thrust Deck development are :

- the inlet ram recovery;
- the inlet spillage drag;
- the nozzle/aftbody drag;
- the customer bleed air;
- the power off-take.

The reference working point of the F100 turbofan (its “design point”) is considered to be at 30.000 ft ISA at maximum engine power rating (without the afterburner).

2.2. Development rational

The rationale behind the development of this Flight Thrust Deck is that we need to fly through the whole flight envelope of the aircraft/engine. That means that different configurations for the F-16 must be considered in order to be able to fly at a given couple altitude & speed (or Mach) with different engine ratings (or RPM). Three configurations have been selected: light, medium and heavy.

Some extra elements had also to be added to those considerations: the influence of using or not and at what level the afterburning section, the sideslip and the angle of attack (through the aircraft Gross Weight).

For the in-flight measurements, the Rada Face system available on board some of the Belgian F-16 has been considered to be more than adequate with very low cost modifications. This system is presented on Figure 3 (see also ([2] and [3]).

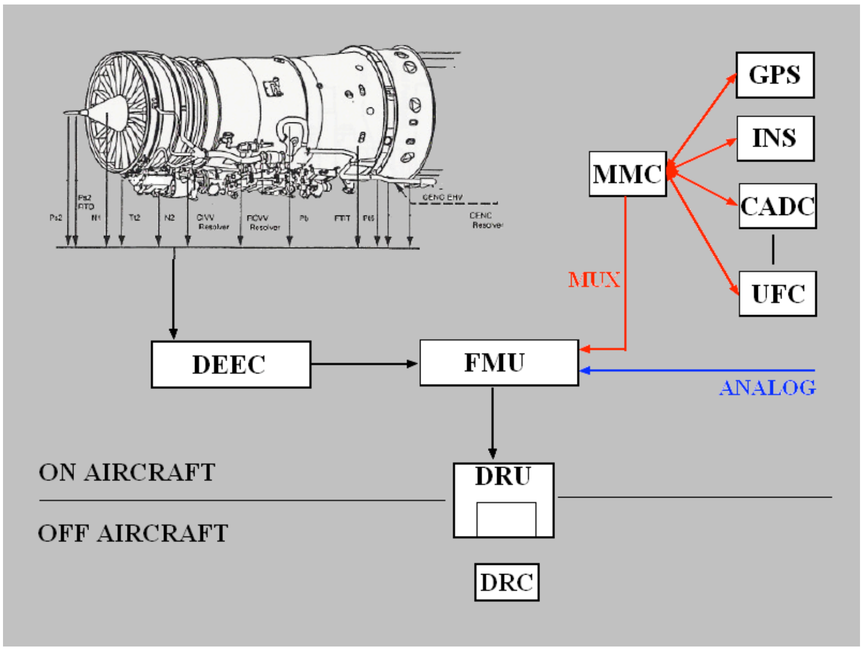


Fig. 3 – The Rada Face system installation on the F-16 A/B

In total, twenty aircraft parameters and eighteen engine parameters were measured during the different flight tests that were realised for the three configurations (and aircraft Gross Weights) at different altitudes, different flight Mach numbers, without or with the afterburner and without or with sideslip in some cases. Only subsonic flights were done until now. Supersonic flight are planned for this fall.

Based on those in-flight measurements and on reference performance ([4] and [5]) available for this engine in this aircraft, the physical model of the engine taking into account its installation effects has been derived from simulations.

2.3. Simulations for the establishment of the engine installed model

The necessary simulations were executed in the software GasTurb 10 ([6]). An example of performance curves required for those simulations is shown on Figure 4. Those simulations were realised for on-design conditions and off-design cases. A control law for the variable area convergent-divergent exhaust nozzle has of course also been introduced into the simulation model.

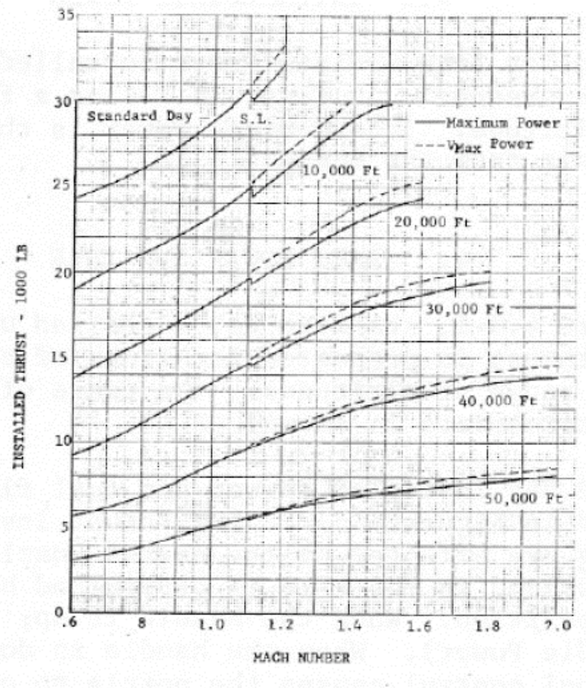


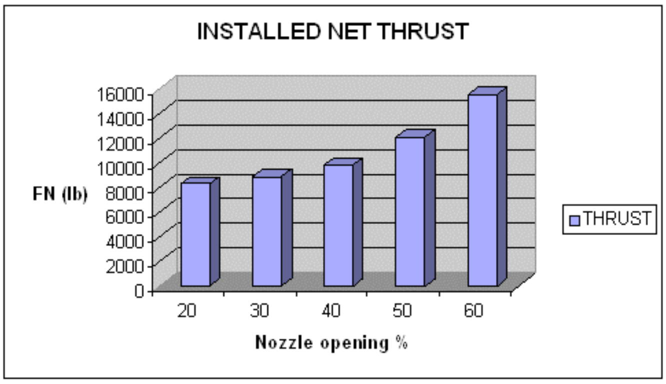
Fig. 4 – Available installed performance of the turbofan engine

An example of a simulation is shown in Table 2 for the design point. It shows also, and mainly, the comparison between the simulated results and on one hand the reference values found in the F16 literature and on the other hand the in-flight measurements.

	GT10 simulations	Reference	In-flight measurements	Error (%)
FN (lbf)	5995	--	--	
FNs (lbf)	5859	5900	--	0,6
WF (pph)	6192	5800	6196	0,06
T2 (°F)	26,4	--	26,3	0,32
P2 (psi)	7,79	--	7,797	0,1
P3 (psi)	209,6	--	209,57	0,01
FTIT (°F)	1702,6	--	1704	0,08
P5 (psi)	24,67	--	24,67	0
N1 (RPM)	10.059	--	10.059	0
N2 (RPM)	12.694	--	12.694	0
EPR (-)	3,16	--	3,15	0,3

Table 2 – Comparison at the selected engine design point

Other results with the five possible positions of the afterburner "on" are shown on Figures 5 a&b, at Mach 0,82 and 20.000 ft ISA, for the installed net thrust and the fuel flow injected into the main combustion chamber and into the afterburning section. The position of the exhaust nozzle is also indicated (different for each selection of the afterburner).



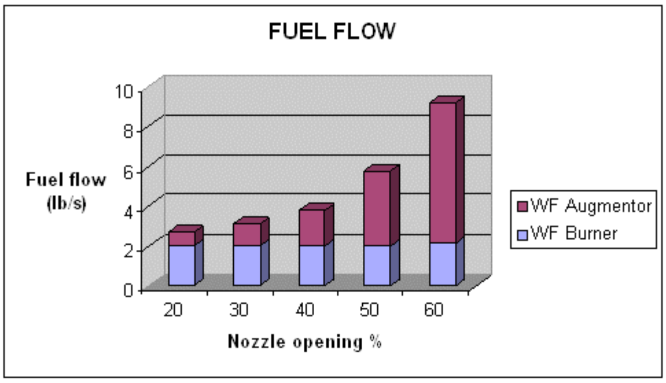


Fig. 5 – Afterburning influence on the installed net thrust and the fuel flows (Ma = 0,82, 20.000 ft ISA)

Those simulations based on three a priori selected aircraft configurations allow us to derive a model of the F100 installed in the F-16 A/B valid for all cases (all aircraft configurations). This model is approaching the physical model of the installed engine rather adequately as it has been validated in flight for various working conditions, in design and off-design.

3 Flight Thrust Deck results

This in-flight validated model of the installed engine (at subsonic speeds) can now be used to extract the value of the total drag of an aircraft flying in a given configuration and at different values of the flight Mach number and the altitude. This total drag is just equal to the requested total engine thrust calculated with the Flight Thrust Deck model that we have developed.

The results with the three here before selected configurations of the F-16 are shown on Figure 6 at 30.000 ft ISA. The colored dots are corresponding to in-flight measured validated points. From there, one can, for example, calculate the C_D of the F-16 with different configurations.

If one would like to know or estimate such a curve for a new unknown configuration of the aircraft, one can extrapolate the value of the C_D based on aerodynamics considerations (as the drag index) and/or one can fly this configuration during a limited time and use the Rada Face system to make a few in-flight measurements that we shall use to calculate the new requested thrust with this new configuration, thanks to the validated Flight Thrust Deck.

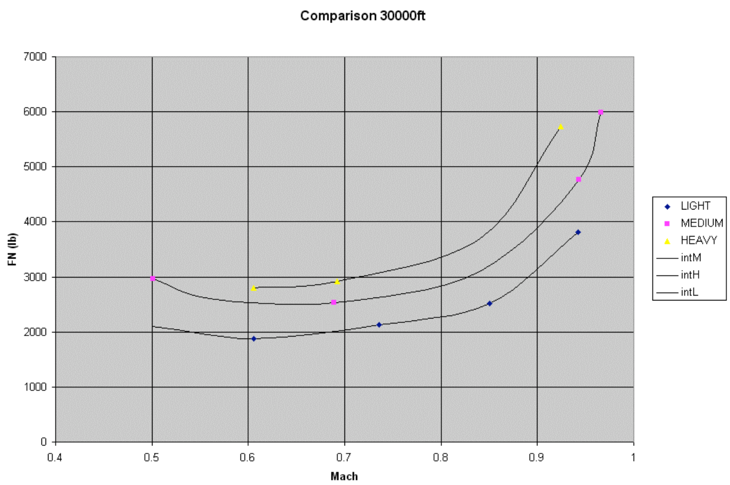


Fig. 6 – Requested thrust evolution for three different aircraft configurations

One can also use the "in-flight validated" Flight Thrust Deck of the F100 engine to calculate the maximum available thrust (and the related TSFC) and by comparing it to the calculated requested thrust, extract some possible aircraft performance in this new unknown configuration.

4 Conclusions

A Flight Thrust Deck program has been developed for the P&W F100 afterburning low by-pass ratio turbofan on board the F-16 A/B fighter aircraft. This Flight Thrust Deck is the result of flight tests throughout the F-16 flight envelope with different aircraft configurations but is currently limited to subsonic flight speeds. The supersonic part of the flight envelope will be covered as soon as possible.
The Flight Thrust Deck is covering all integration aspects of this engine installed in this aircraft. It delivers a good "physical" model of the installed engine.
Such a tool can be quite useful for non-original aircraft manufacturer or integrators in order to fix or estimate rather accurately the aircraft performance with innovative or "uncleared" aircraft configurations.
This tool can also show to be very useful for research teams and universities working on new and advanced engine health monitoring systems, as it provides a physical engine model.

Acknowledgments

The authors sincerely want to thank the Test Pilot Ph. Goffin involved in those flight tests and all the Belgian Air Force technicians involved in the preparatory work of those tests, as well as the Belgian aircraft company SABCA (Group Dassault Aviation) for the technical support of their Test Engineer Y. Scholasse who helped in realizing those flight test measurements.

References

[1] P. Buysschaert, Ontwikkeling van een Flight Thrust Deck Programma voor de Pratt & Whitney F100 motor, Vrije Universiteit Brussel (VUB), Brussels, September 2004.
[2] Lockheed Martin, Signal Interface Control document for the F-16 avionic system M3 EPAF T3", 16PP3446, 2006.
[3] RADA Technologies, Technical order BE 1F-16AM-2-31GS-FACE-00-1 & SAB-1F-16AM-2-31FI-00-1, BAF, 2006.
[4] General Dynamics, The F-16 Air Combat Fighter: Technical Description, Volume 12, Annex B, 1975.
[5] General Dynamics, The F-16 Air Combat Fighter: Technical Description, Volume 13, 1975.
[6] J. Kurzke, GasTurb 10, a program for gas turbine performance calculations, User's Manual, 2004.

Copyright Statement