Сербезов В. Моделювання витрат пального турбовентиляторного двигуна на компенсацію споживання енергії системою обладнання / Сербезов В. // Вісник ТНТУ. — 2011. — Том 16. — № 4. — С.137-142. — (машинобудування, автоматизація виробництва та процеси механічної обробки).

УДК 629.7.036

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МОДЕЛЮВАННЯ ВИТРАТ ПАЛЬНОГО ТУРБОВЕНТИЛЯТОРНОГО ДВИГУНА НА КОМПЕНСАЦІЮ СПОЖИВАННЯ ЕНЕРГІЇ СИСТЕМОЮ ОБЛАДНАННЯ

Резюме. *Побудовано математичну модель, яка враховує вплив відібраної від турбовентиляторного двигуна пневматичної потужності та потужності на валу генератора на витрати пального. Модель дає добрі результати в усьому літальному діапазоні й на всіх основних режимах двигуна. Реалізація виконана як підпрограма в програмному середовищі Matlab і призначена для доповнення вже існуючої моделі двигуна. Вона являє собою детерміновану чисельну модель ідентифікації. Дані для неї генеровані чисельними експериментами в софтверному продукті Gasturb. Перевірку моделі виконано шляхом порівняння результатів повної моделі польоту літака, в якій інтегровані розглядувана модель двигуна з даними з літальної документації та літальних записів.*

Ключові слова: *математичне моделювання турбовентиляторних двигунів, витрата пального на компенсацію споживання енергії.*

V. Serbezov

TURBOFAN ENGINE MODEL FOR ESTIMATION OF THE FUEL CONSUMPTION FOR COMPENSATION OF AUXILIARY ENERGY SUPPLY

The summary. *The presented model is suited for estimation of the influence on fuel consumption of the pneumatic and generator shaft power will be off-take from turbofan engine. It is made to be applicable for the entire aircraft flight envelope and engine operating modes. The model is realized in Matlab environment and is intended to complement the performance model of the engine, that is already developed [2]. The model is based mainly on polynomial interpolation. The data, used for the synthesis of the model is generated by simulation with Gasturb software. The model is validated by comparison with data published in the relevant Aircraft Flight manual and flight data records.*

Key words: *turbofan engine mathematical modeling, gas turbine fuel consumption, aircraft systems power supply.*

1. Introduction. The assessment of the incremental fuel consumption of the aircraft power plant, for aircraft systems pneumatic and electric power generation is a key for the evaluation of the effectiveness of these systems. In the specialized literature, however (as [1] for example) the point is mostly on comparing the effectiveness of the systems in certain flight conditions for the most common flight phase e.g. cruise flight. This approach allows the use of simplified methods of calculating the engine efficiencies and fuel consumption. For the task of evaluating new possible architectures of the aircraft power generation it is necessary to assess their performance also in other phases of the flight. The main difficulty is that the engine performance characteristics that are needed for this in the most cases are not publicly known.

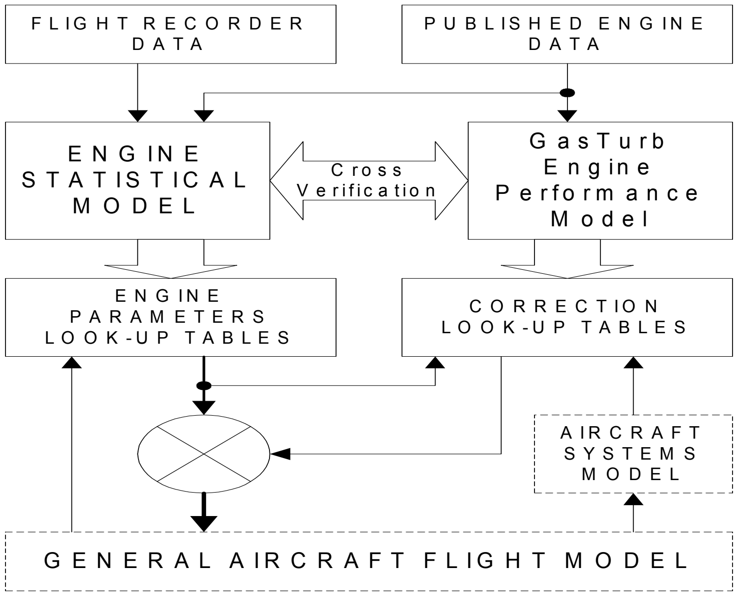

Figure 1. General structure of the developed model

The solution proposed by the author is to use a combined approach. The flight performance characteristics of the engine for the flight simulation can be derived statistically from flight recorder data [2]. The internal engine efficiencies and other parameters that are needed for estimating fuel spent for additional power generation can be obtained from an engine model produced by specialized engine performance software. In this particular case GasTurb 11 software is used. A general block-diagram of the combined model is given in figure 1.

To simplify the model and in the same time to cover the entire engine operating range and flight conditions range the theory of engine modes commonality is used [3]. The power generation incremental fuel model complements the engine performance model described in ref. [2], and allows the evaluation of power generation effectiveness in wide range of flight conditions.

The model is realized for a Airbus A320 class aircraft, equipped with CFM56-5B class engines. The adequacy of the model is verified by comparison to data from the aircraft documentation [5,6].

2. Mathematical Model Requirements and Assumptions. As stated above the main requirement for the model is to give adequate results throughout the airplane flight envelope for all engine operating modes. This includes altitudes from 0 to 11887 m (Flight Level 390) and Mach number from 0 to 0.8. To satisfy the requirement and in the same time to simplify the model as possible, a number of assumptions were implied.

Engine mode-defining parameter. Particular difficulty represents the modeling of deep off-design modes of the engine such as the idle mode at different ambient conditions. As far as the original performance maps of the engine components (compressors and turbines) are not accessible, typical representative maps of these components were used. This approach allows in deep off-design modes to model some important engine parameters, such as thrust and fuel consumption but it is not applicable for evaluation of others like the rotational speed of the engine rotors. As a result the fuel flow to the engine and not the rotor RPM had to be used as a parameter that defines the engine operating mode.

Engine Operating Modes Commonality. The theory of gas turbine engine commonality is widely used for correction of the engine parameters according to the ambient conditions. It permits a significant simplification of the off-design point calculations. Detailed description of this theory is given in the literature [3].

For the present task it is suitable to use look-up tables storing the corrected values of the engine fuel flow, mechanical power off take from the engine shaft and the compressor air bleed. The corresponding equations are given in (1).

$$\begin{aligned} Wf_{corr} &= Wf\,.\frac{101300\,.Pa}{p_{t0}}.\sqrt{\frac{288\,.K}{T_{t0}}} \\ Px_{corr} &= Px\,.\frac{101300\,.Pa}{p_{t0}}.\sqrt{\frac{288\,.K}{T_{t0}}} \\ Wbl_{corr} &= Wbl\,.\frac{101300\,.Pa}{p_{t0}}.\sqrt{\frac{T_{t0}}{288\,.K}} \end{aligned} \qquad (1)$$

Were Wf is the engine fuel flow in kg/s, Px is the mechanical power off take from the engine high pressure spool in W, and Wbl is the air bleed from the high pressure compressor in kg/s, p_{t0} and T_{t0} are the total pressure and total temperature of the ambient airflow in front of the engine.

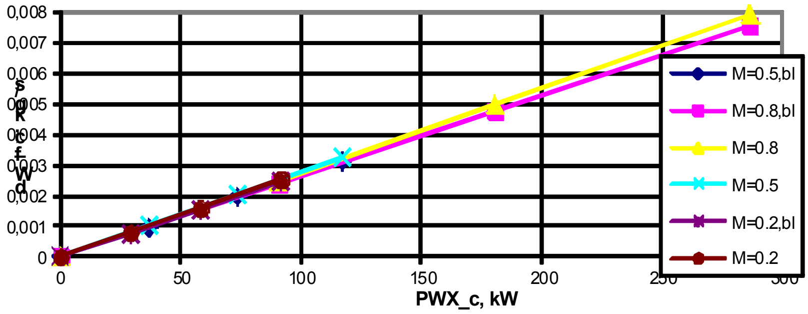

Figure 2. Relation between mechanical power off take and incremental fuel flow (booth corrected for sea level standard conditions) at different Mach numbers, with and without air bleed

Linearity Assumption. It is assumed that the electric power generation and air off take load are relatively small, compared to the total engine power (less than 5%)and these loads will not change the operating point of the engine significantly. In this way the efficiency of the power generation will not vary with variations of the power load and the relation between the power generation and the increment of the engine fuel flow will be linear.

This assumption was verified by numerical experiment with the Gasturb engine performance model. The visualization of part of the results is shown in figure 2.

Engine Control Law Assumptions. The control law of the engine has a significant effect on the way the fuel flow changes with the changes in the power off take. The control systems of modern turbofan engines use complex laws that are not known to the author. In case of flight in steady conditions and change only in power off take these laws can be reduced to three basic laws.

It is presumed that in engine take off and climb modes the control system maintains engine fan rotation speed constant. As a result there will be small changes in the engine thrust when the additional engine load changes.

In cruise flight the auto throttle system of the airplane keeps the thrust of the engines constant and compensates the changes in the additional load by varying the fan rotation speed.

At idle mode the main task of the control system is to maintain stable engine operation and for that it keeps engine high-pressure compressor rotation speed constant.

Compressor Air Off Take Assumptions. Typically the bleed air is taken from different stages of the compressor and is mixed so to maintain certain pressure and airflow. To simplify the engine model it is assumed that in all engine modes except idle the air is taken from a single point between the low pressure and high pressure points of air bleed.

At idle mode only the high pressure point of air bleed is used.

3. Model Development. The model was developed in three major steps.

First an engine performance model was created in the GasTurb 11 software. It was adjusted with engine performance data published in open access sources [7,8]. By changing the engine design point and the operating point coordinates on the compressor and turbine maps the representative engine parameters for different thrust ratings and flight conditions (Table 1) were bring within 5% margins of the published values, (Table 2). An exception is the low idle mode, were the error of the fuel flow is within 6%. The difficulty of modeling deep off-design modes was mentioned in the previous paragraph and these results are considered satisfactory.

The second step was to compute with the performance model suitable look-up tables. These tables should give the relation between the consumed electric or pneumatic power respectively and the fuel consumption of the engines in the entire operation envelope. To reduce the amount of calculated data points the linearity and mode commonality assumptions were used as described above.

Table 1. GasTurb 11 performance model of CFM56-5B engine characteristics summary

Thrust, kN	*By-pass ratio*	*Ov. Pressure ratio*	*Airflow kg/s*	*Fuel Flow kg/s*
	standard atmosphere sea level conditions			
142.35	5.5628	33.64	439.5	1.4568
133.45	5.6622	31.813	427.95	1.3221
120.11	5.7755	29.04	407.37	1.1491
104.53	5.9512	25.7	379.02	0.9868
94.7	6.0649	23.7	360.79	0.8847
	flight conditions Flight Level 350, M=0.8			
28.56		35.42		
25.98				0.4885
25.04		32.19		
	IDLE, standard atmosphere sea level conditions			
4.53				0.0915

Table 2. GasTurb 11 performance model of CFM56-5B engine verification with data from [6] and [7]

Thrust, kN	*By-pass ratio error*	*Ov. Pressure ratio error*	*Airflow error*	*Fuel Flow error*
	standard atmosphere sea level conditions			
142.35	3 %	2,6 %	0,1 %	-1,5 %
133.45	2,9 %	4,4 %	0 %	-1,3 %
120.11	1,3 %	4,9 %	0,1 %	-1,9 %
104.53	0,9 %	4,3 %	-1 %	-0,7 %
94.7	1 %	4,9 %	-1,9 %	-2,3 %
	flight conditions Flight Level 350, M=0.8			
28.56		0,1 %		
25.98				1,2 %
25.04		-1,3 %		
	IDLE, standard atmosphere sea level conditions			
				-5.7 %

The numerical experiments conducted showed that at nominal operation modes of the engine the influence of the corrected power off-take from the engine high pressure spool on the corrected fuel flow in practice do not depend from the flight Mach number the flight altitude and the compressor air bleed (fig. 2). This allowed using single dimension interpolation (table look-up). The value of the corrected fuel flow defines its derivative from the power off-take.

The compressor bleed air influence sowed more complex behavior (fig. 3). In figure 3 the parameter dFFc/dWblc is the derivative of the corrected fuel flow from the corrected air bleed. In this case a 2-dimensional lookup table is used that gives account of the flight Mach number.

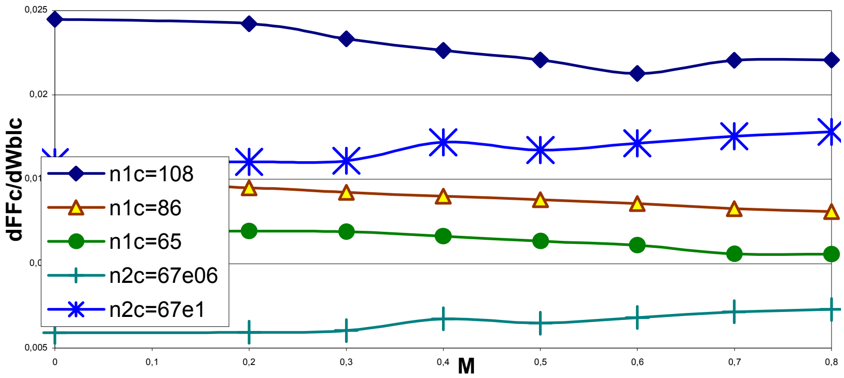

Figure 3. Relation between the derivative dFFc/dWblc and the Mach number, at different engine fan rotational speeds in percents and different points of air bleed

The final step was to realize the model in Matlab environment and to verify it. The general structure of the model algorithm is given in figure 4.

The verification of the bleed air influence on the fuel flow was performed with data from the airplane documentation [5,6]. The input information was the air mass flow at different flight conditions, taken from the Aircraft Maintenance Manuel [5].

4. Model Verification and Conclusions. The auxiliary fuel consumption model was integrated in the engine and aircraft model, described in [2]. It was compared with the fuel calculation correction data for 'normal' and 'low' modes of the air-conditioning system, that are given in the Flight Crew Operating Manual (FCOM) [6]. It must be stated that the FCOM data is tentative and conservative, as far as it is intended for quick practical calculations.

The results of the comparison for a number of aircraft take off weights and flight altitudes, that represent the aircraft flight envelope are given in table 3.

The results show good resemblance with the FCOM and fell within or close to the 10% error margin. It can be concluded that the model of the fuel consumption for air bleed is satisfactory for the most of the airplane flight envelope.

There is no evident data for similar verification of the fuel flow for electric power generation, but as far as it is directly connected with the working cycle of the engine, the reliability of the results follows from the adequacy of the model that is shown above.

Table 3. Fuel consumption correction for air bleed - comparison of the model with data from A319 FCOM[5]

Aircraft mass, kg	***Flight phase***	***Flt. level***	***Altitude, m***	***Model evaluated consumed fuel, kg***				***FCOM fuel correction, %***	***Model error,%***
				cond.-norm	***cond.-low***	***delta***	***delta,%***		
60 000	Climb to	310	9449	1328.02	1323.11	4.91	-0.369	-0.4	**-7.64**
60 000		390	11887	1739.05	1731.43	7.62	-0.438	-0.4	**9.56**
70 000	Climb to	310	9449	1692.87	1686.44	6.43	-0.380	-0.4	**-5.09**
70 000		370	11278	2155.37	2146.04	9.33	-0.433	-0.4	**8.18**
60 000	CRUISE	310	9449	5140.40	5116.90	23.50	-0.457	-0.5	**-8.57**
60 000		390	11887	4203.40	4180.50	22.90	-0.545	-0.5	**8.96**
70 000	CRUISE	310	9449	5409.70	5386.10	23.60	-0.436	-0.5	**-12.75**
70 000		370	11278	4703.40	4680.00	23.40	-0.498	-0.5	**-0.50**
65 000	Descent	390	11887	158.0977	155.133	2.9649	-1.88	-2	**-6.23**
65 000		310	9449	144.6055	142.004	2.6016	-1.80	-2	**-10.04**
45 000		310	9449	116.3125	114.262	2.0508	-1.76	-2	**-11.84**

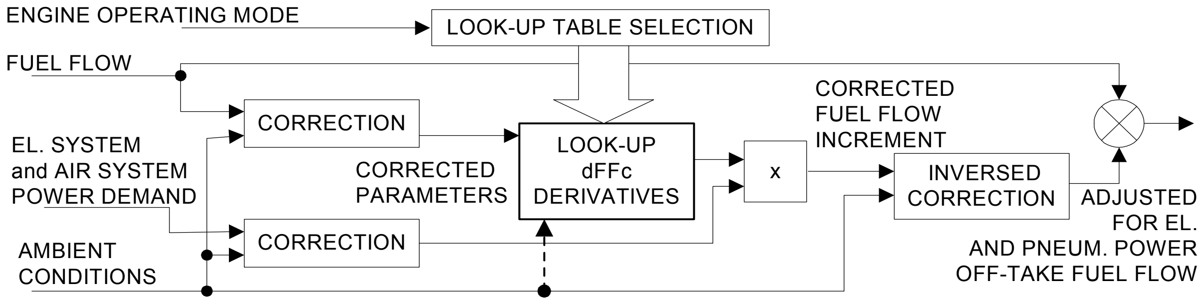

Figure 4 General structure of the model algorithm

5. Conclusions. The presented turbofan engine model evaluates the fuel consumption for auxiliary power generation from the engine. It compliments the engine performance model and enables the conduction of numeric studies of the aircraft systems effectiveness at different flight conditions. The main merit of the model is that it gives acceptable accuracy without the need of detailed information about the original engine characteristics.

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Отримано 01.12.2011