APPLICATION OF "VIRTUAL" CONTROLLERS FOR INTEGRATED PROPULSION AND AIRCRAFT CONTROL

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Abstract

A new method of the gas turbine engine (GTE) control is discussed. It is based on the use of a mathematical engine model incorporated into an engine control system (ECS). This approach allows to enhance engine performance through a deeper integration of a powerplant and aircraft control. Simulation results of engine control system operation with the use of parameters calculated with the help of the on-board engine model (OEM) are presented. Those parameters fully describe GTE efficiency but are not directly measurable.

1 Introduction

The modern GTE control is performed according to the fan rotor speed (n_1), the high pressure compressor (HPC) rotor speed (n_2) and the engine pressure ratio (*EPR*) that are indirect presentation of key engine parameters needed for aircraft (thrust, specific fuel consumption) as far as a direct measurement of these parameters is not possible.

Nevertheless the relationship between the rotor speed and thrust varies over the engine operation due to the influence of ambient conditions beyond the area of condition similarity, engine component degradation and change of component performance resulting from their ageing. In this case the probability is that the engine is no longer able to provide thrust necessary for the aircraft whereas the thrust deviation in operation is not checked.

Modern electronic control units allow to incorporate a sufficiently accurate engine model ("a virtual engine") into the control system software making possible to perform calculating a real value of engine thrust [1, 2]. One of the contributory factors is the model validation in operation that allows the model correction dependent on the engine performance variation.

The engine power management control in accordance with the calculated engine thrust which required value is set by the control unit in the flight control system will increase the engine efficiency as of an aircraft propulsion part.

Being so, the traditional control parameters physically measured in the engine control system are used for the main control unit envelope generation taking into account aerodynamic stability and engine endurance criteria.

In the present paper the possibility of this type of system build-up is studied and its efficiency assessment is given.

2 The gas turbine engine control using on-board engine model

The calculation power of the modern digital gas turbine engine control systems makes possible to enhance engine performance and to improve engine reliability through the application of different control methods. One of the means to achieve this goal is the use in the engine control system of an on-board engine model that is in fact a thermoaerodynamic model, based on the description of processes occurring in the engine with the help of aerodynamic, thermodynamic, hydraulic and mechanic equations. The improvement of calculation methods used for solution of equations on which are based these models enabled now engine electronic units performing calculations over a time significantly shorter than real time and consequently to use such models as on-board ones.

In case of use of the on-board model the engine can be controlled in accordance with calculated parameters inherent in the engine operating process but not directly measurable, such as engine thrust, compressor surge margin, combustion chamber temperature, air/fuel ratio in the combustion chamber, etc. [1].

A control system with control loops using measured engine parameters and with those using parameters calculated with the help of the on-board model is schematically shown in Fig.1.

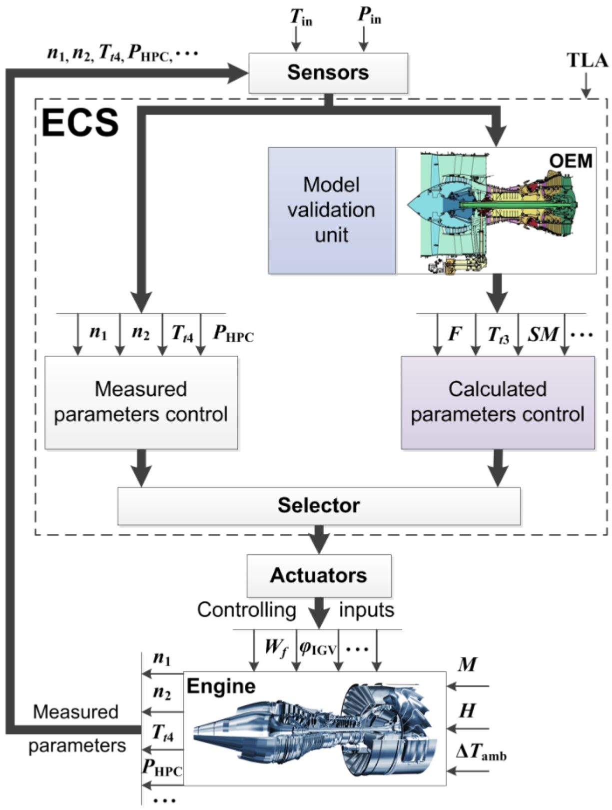

Fig. 1. Engine control system with an on-board engine model

In addition to "virtual" control loops in such a control system there are "real" control loops that use measurable parameters indirectly involved into the operating process description. Controllers of this type have up-graded settings and are used as redundant ones for the "virtual" control loops. Differences between the measured and the calculated in the on-board model parameters are introduced into algorithms for the on-board model validation.

This type of systems meets one of major requirements for modern GTE control systems, namely the adaptation to flight conditions and to the performance decrease of engine with its degradation.

3 Study of the component wear effect on engine performance

3.1 Compressor performance alteration while wearing

Within the framework of our study a number of scientific works devoted to the effect of engine component deterioration on engine performance have been analyzed with a goal to introduce it in the engine model and to simulate degradation thereby.

So, in the reference [3] it is noted that the nearest to the real compressor performance alteration due to degradation is determined by all the three major compressor parameters decrease: the compressor pressure ratio (PR_C), the flow capacity (FC_C) and the efficiency (η_C) (see Fig.2).

Being so, the operating point on the efficiency curve leaves its optimum location to move to the right beyond the local maximum η_{Cmax} (A'–B').

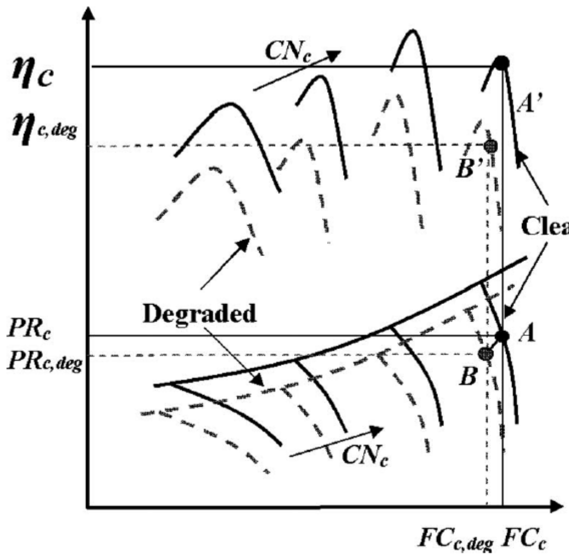

Fig. 2. Compressor performance alteration due to wear [3]

Studies devoted to this subject and carried out before at the Central Institute of Aviation Motors (CIAM) with a turbofan of the fourth generation revealed as well that the compressor degradation led to a proportional PR_C, FC_C and η_C drop. As for the take-off operating point on the airflow curve, it moves upwards along the pressure ratio branch, closer to the surge line as it is shown in Fig.3.

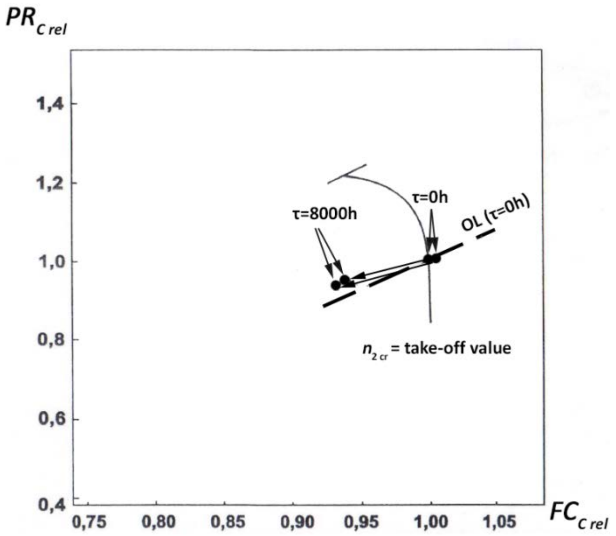

Fig. 3. Change of the operating point location on the airflow curve with progressive compressor degradation

In another experimental CIAM work devoted to the assessment of HPC surge margin in a turboshaft engine subject to erosion it was shown that:

- while wearing, the HP compressor pressure ratio curves move to the left and downwards becoming smoother;
- the surge margin of a deteriorated engine goes decreasing by more than 10% and moves below the curve of a required margin.

In Fig.4 are shown compressor performance for a new such engine in comparison with those for an engine operated under desert climate conditions.

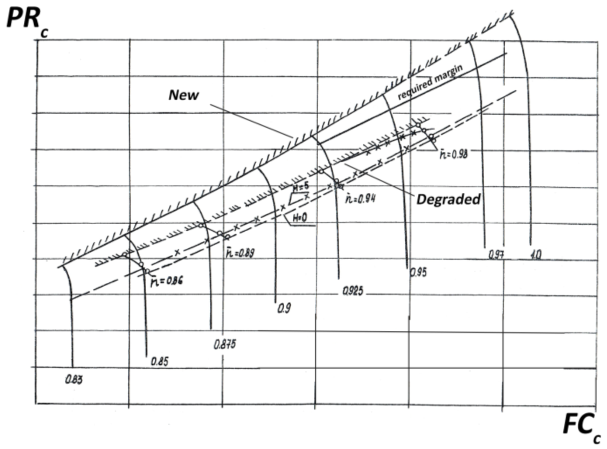

Рис. 4. HPC performance variation under erosion

In most of the considered works the deterioration in the performance of an aged engine is expressed in a 5% decrease, and in some cases even in a 10% decrease of all major compressor characteristics.

Mathematical modeling of the compressor degradation in application to a high by-pass ratio turbofan is based on the results of these studies.

3.2 Turbofan compressor degradation simulation

To simulate degradation a complex "Engine – ECS" model, which already existed at CIAM [1] and that had been elaborated for a modern engine on the commercial aircraft, was modified. For this purpose appropriate deviations were introduced in component characteristics of the engine model.

The specified HPC performance decrease due to degradation and the corresponding change of the operating line (OL) location are presented in Fig.5. In the performed calculations HPC pressure ratio branches and its efficiency curves were moved to the left and downwards with the similar 10% decrease of PR_C, FC_C and η_C compared to their initial values. 10% deterioration is chosen to obtain a clearer picture of the OL location change on the compressor map.

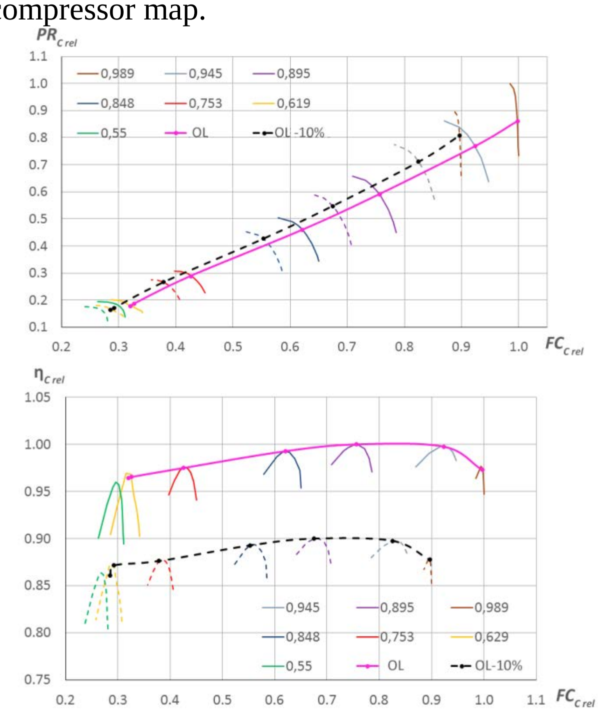

Fig. 5. HPC performance map with simulated degradation

HPC operating line with such a simulated degradation level moves upwards, closer to the flow stability limit. Being so, corrected airflow and pressure ratio values go decreasing. On the efficiency map the operating points go out of their optimum location corresponding to the local efficiency maximum. This leads to a further efficiency decrease. The calculation results of similar simulations for fan and booster are presented respectively in Fig.6 and Fig.7.

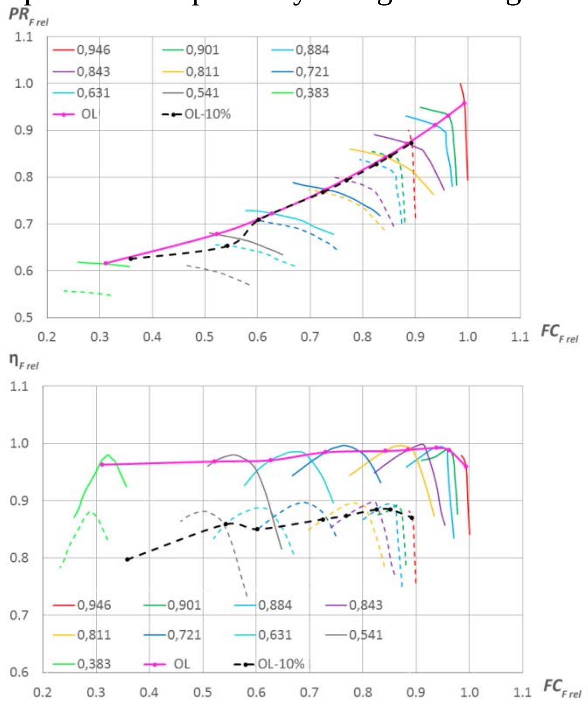

Fig. 6. Fan performance map with simulated degradation

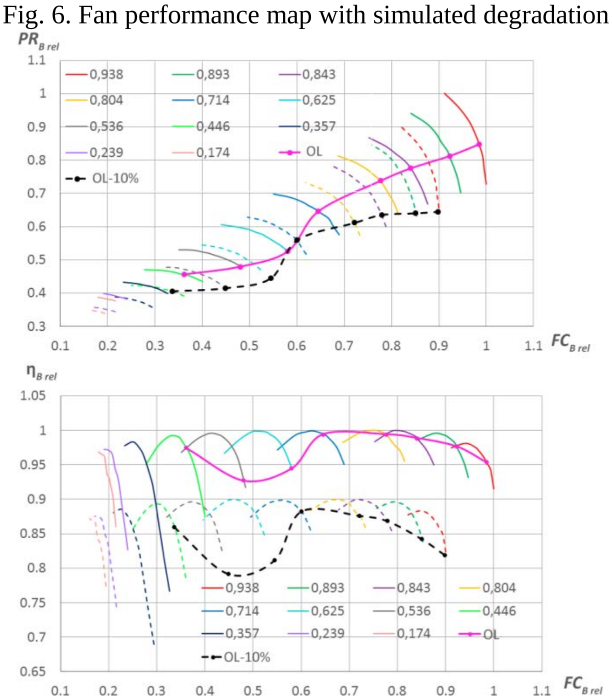

Fig. 7. Booster performance map with simulated degradation

3.3 Engine component deterioration impact on key engine parameters in case of typical control

The modified complex model allows performing calculation to assess the degradation impact on commercial aircraft engine key parameters.

The calculation showed that with the use of the traditional fan rotational speed control schedule the fan deterioration impact on engine thrust was more pronounced than the deterioration of other engine components (see Fig.8). Being so, at lower operating modes the thrust decrease is first of all determined by the drop of the fan outlet pressure whereas at ratings close to take-off one can see that thrust is impacted by the fan flow capacity decrease. The effect of the efficiency decrease on thrust at any operating modes is not significant.

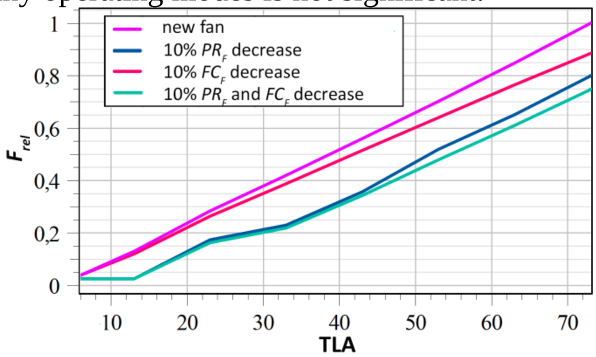

Fig. 8. Impact of the fan performance decrease on thrust (operating line, $H = 0$, $M = 0$, ISA)

In case of other component performance decrease the engine control system keeps thrust unchanged through increasing fuel consumption in order to maintain the specified n_1 value. This leads in its turn to the combustor gas temperature increase by approximately 100-150 K (see Fig.9).

The calculated curves of engine thrust and the combustion chamber temperature variation on the operating line at ambient conditions $H = 0$, $M = 0$, ISA are shown in Fig.9 as $F = f(n_{1\,cr\,rel})$ and $T_{t3} = f(n_{1\,cr\,rel})$ functions. Versions with deterioration of different engine components are considered.

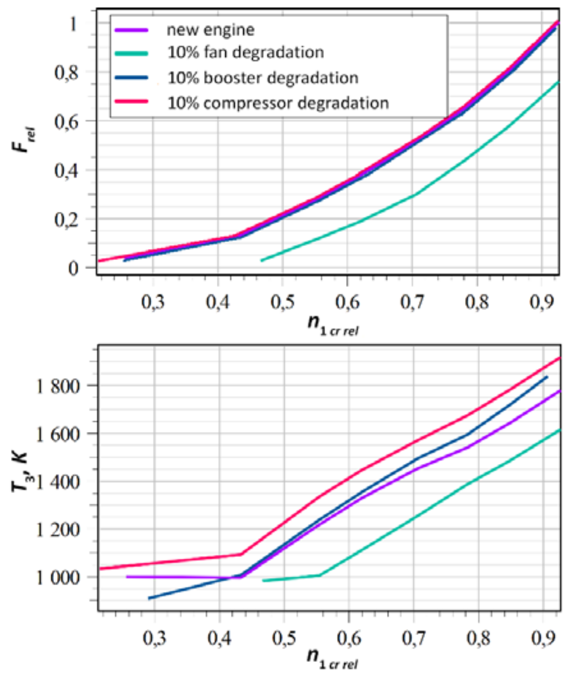

Fig. 9. Impact of various engine component deterioration on key engine parameters (operating line, $H = 0$, $M = 0$, ISA)

Similar calculations were performed for four different engine degradation levels defined as 3, 5, 10 and 15% deviations of engine component characteristics from original ones. Table 1 gives the above mentioned calculation results showing the impact of the LPC and HPC wear level (a common decrease of compressors characteristics) on key turbofan parameters.

Table 1. Impact of the degradation level on engine parameters

Degradation, %	F_{rel}	*TSFC*	T_{t3}, K
	Engine mode		
	Take-off	Cruise	Take-off
0	1	0.535	1776.8
3	0.927	0.557	1783.9
5	0.87	0.575	1792
10	0.753	0.63	1817.7

The analysis of the obtained results shows that with compressor performance drop the take-off thrust decrease is somewhat more significant than the SFC increase in cruise (by 5% on average). So, degradation not only makes higher the specific fuel consumption but also reduces the flight envelope and makes worse the aircraft flight safety because of impossibility to provide take-off thrust while the go-around flight manoeuvre. As for the combustion chamber gas temperature T_{t3} it sees itself increased by 67.5 K even at a maximum 15% degradation level. This allows to conclude that it exists a temperature margin that could be used for reducing a negative influence of engine degradation because, as a rule, engines are designed with a T_{t3} margin as high as approximately 150 K.

4 Engine thrust control

4.1 Thrust control loop design

In the preceding part of the paper it was shown that the engine possessed a potential to compensate the impact of component performance degradation on thrust and specific fuel consumption (i.e. approximately 80 K combustor gas temperature margin available even in case of decrease of all the compressors performance). The use of the thrust value, calculated by means of the on-board engine model introduced in the control system software, is one of the ways of such compensation.

Further upgrading of the combined "Engine – ECS" model was undertaken to assess such a thrust control system capacities. The upgrading included:

- the introduction into the control system of the on-board engine model with an validation unit;
- the development of a logic and an algorithmic content for the thrust control system;
- the selection of control law coefficients for thrust control loops at steady and transient engine modes.

In Fig.10 the developed system architecture is presented.

Controlled parameters traditionally used and physically measured on the engine are used for specifying the main "virtual" controller envelope and serve as redundant ones.

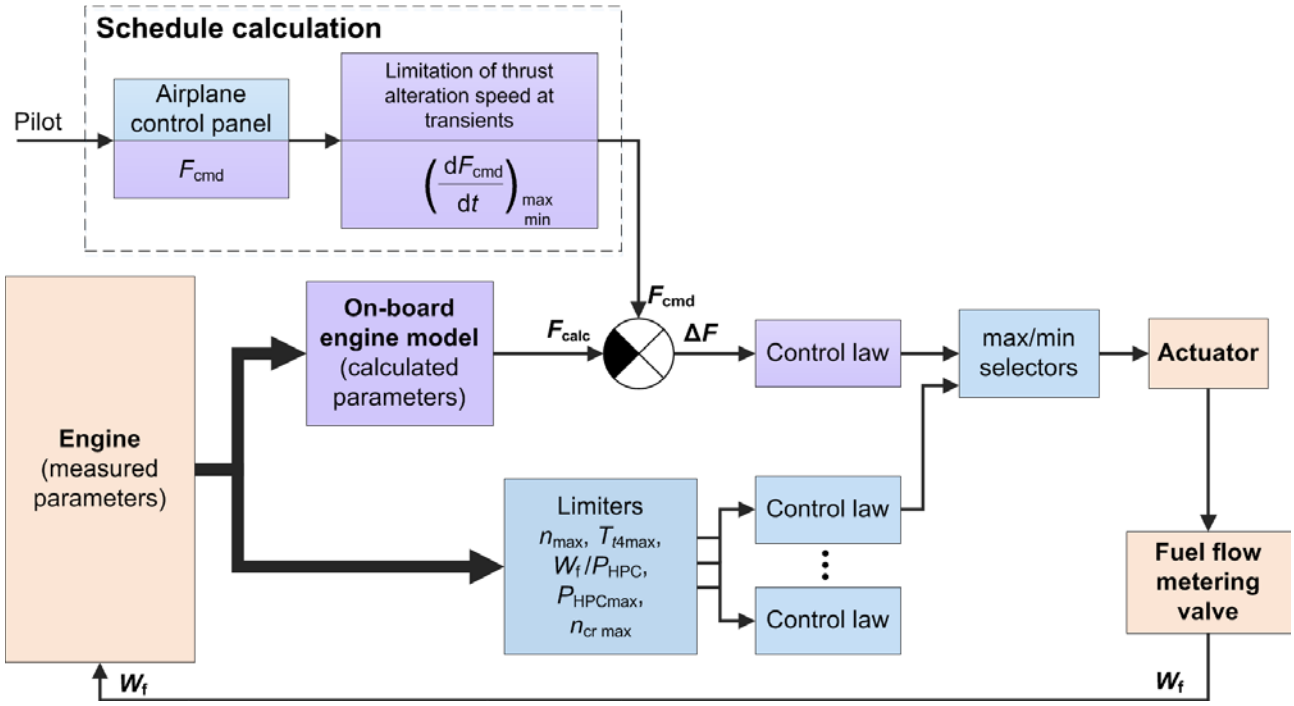

Fig. 10. Architecture of the thrust control loop

Typical control schedules for steady-state $n_1 = f\,(\mathrm{TLA}, T_{\mathrm{in}}, P_{\mathrm{in}})$ and transient engine modes $\dot{n}_2 = f\,(P_{\mathrm{in}})$, in this architecture are replaced by control schedules regulating calculated thrust $F = f\,(\mathrm{TLA}, T_{\mathrm{in}}, P_{\mathrm{in}})$ and $F = f\,(t)$ respectively.

4.2 Assessment of the thrust control system efficiency for the degraded engine control

The elaborated mathematical complex that allows the engine component deterioration simulation and includes the engine thrust control system enabled us to calculate the alteration of degraded engine parameters in case of the typical control and control with the use of the thrust value calculated by the on-board engine model.

The engine parameter change on the operating line in flight conditions $H = 0$, $M = 0$, ISA for new and degraded engine (the compressor performance is turned worse by 5%) with a traditional fan rotational speed controller and with the developed engine thrust control loop is shown in Fig.11.

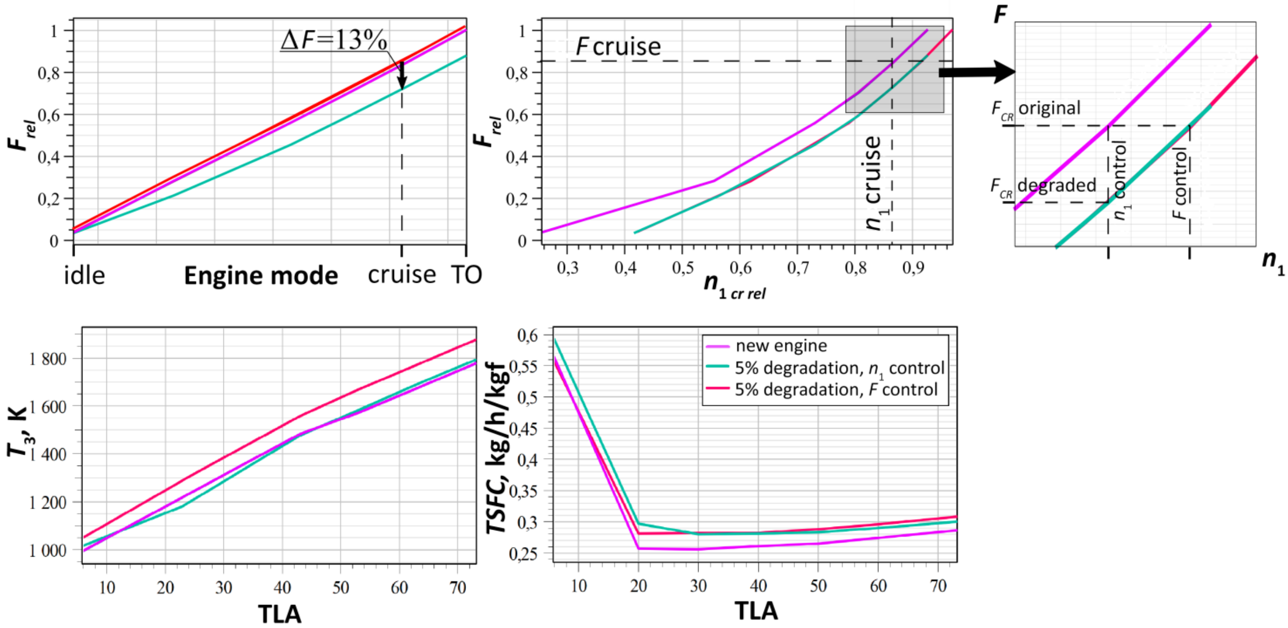

Fig. 11. Degraded engine parameters change in case of different control methods (operating line, H = 0, M = 0, ISA)

It is evident that with the degradation simulation there is a considerable deviation of the thrust as a function of the corrected fan rotational speed curve (see the first diagram in the right corner). As a result, while controlling the engine in a traditional way (n_1 control) the thrust shortage at take-off and cruise engine modes is in the region of 13%.

When the "virtual" thrust control loop is active the degraded engine operating line practically coincides with the new engine one (the original thrust value is maintained) but the combustor gas temperature margin sees itself additionally reduced: T_{t3} goes increasing by approximately 100 K.

Calculations carried out for cruise flight conditions (H = 11000 m, M = 0,8) with various ambient temperature deviations from ISA (T_{amb} = −40°C, T_{amb} = +40°C) provide similar results and confirm the possibility of required thrust maintaining by the engine thrust controller what makes it different from the traditional controller.

When used at acceleration, the "virtual" thrust control loop enables the degraded engine to develop a required thrust at the end of transient mode as well as to maintain original acceleration time.

Such advantages are achieved by increasing the combustor gas temperature, as well as by reducing the compressor actual surge margin (growing the compressor spent surge margin) by 5-6% (see Fig.12).

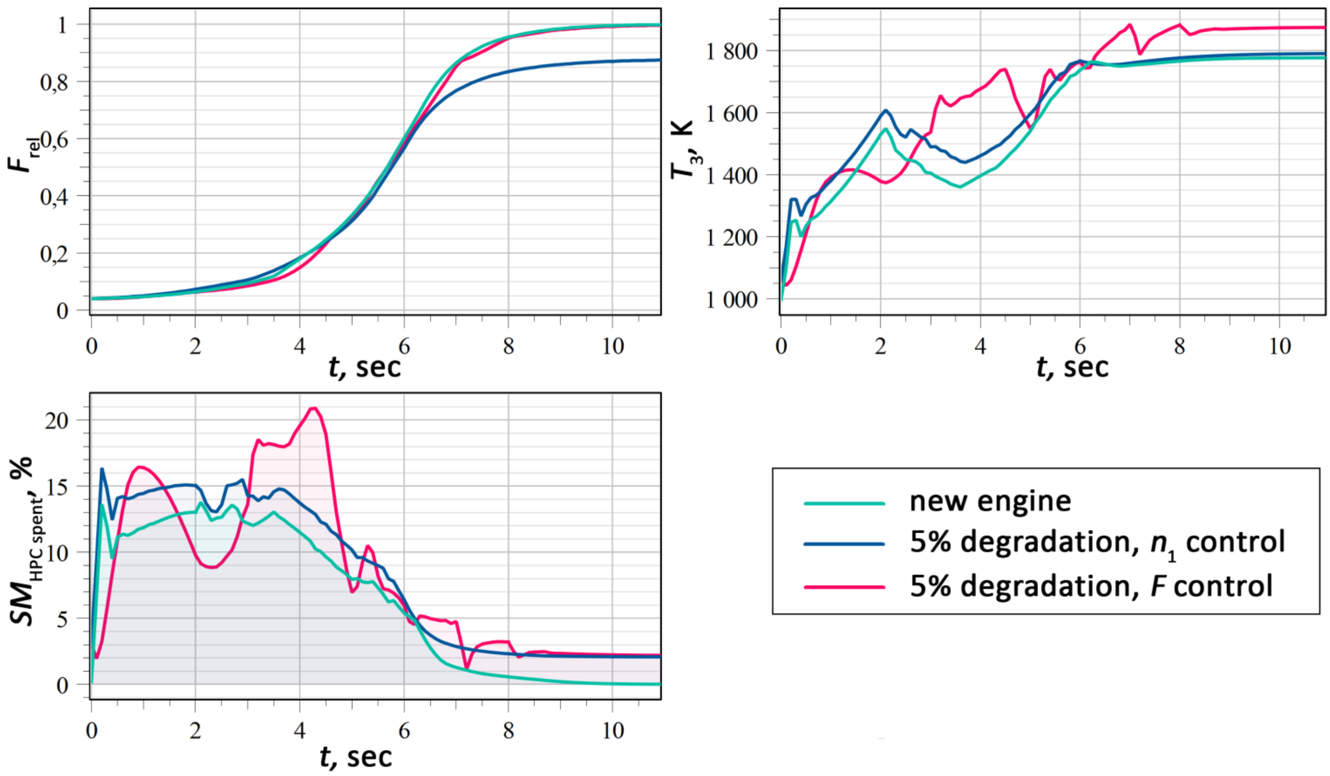

Fig. 12. Variation of engine parameters at acceleration ($H = 0$, $M = 0$, ISA)

5 Conclusion

The incorporation into the engine control system of the engine model together with the thrust control loop using the thrust value calculated with the help of the on-board mathematic model will allow to maintain the required engine thrust in operation and to improve thereby aircraft powerplant efficiency over the whole engine life cycle.

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