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Turbofan thrust control on flight information in aircraft engine diagnostic system

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Abstract

In the paper it is shown that the statistical data of throttling characteristics of turbofan by thrust parameter can be presented in the form of linear non-dimensional dependence that simplifies the generalization of such characteristics for various flight configuration. At that, as measuring (basic) thrust values it is suggested using values measured in similar power conditions of engine module by rather simple derived formulas. Thus, the method of the airborne thrust control of turbofan by the measured thermogas dynamic parameter in flight is considerably simplified.

Keywords: flight, thrust, characteristics, control.

Introduction

The aeroengine is the most loaded part of an aircraft. The main parameters of efficiency of an aircraft engine are its thrust and the fuel consumption, therefore their current in-flight monitoring with the help of onboard computer is the major and actual task of flight support and diagnostics of a technical condition of an aircraft engine. However in flight these values can't be measured.

The problem of determination of flight thrust is the fact, that conventional calculation of high-altitude-speed characteristics of gas-turbine engines usually are made on the base of toilful and complex mathematical model (MM) using sequence-approximate method. Such exact enough method is applied only for the exploitation's operational characteristics analysis on the computer for engine parameters selection. Then these characteristics are approximated for their use in an onboard computer, but such values are comparable only with initial (formulary) data. At deterioration of the engine in exploitation there is a wide difference between real values and results of calculations using MM. To choose the acceptable MM it is necessary to compare results of calculations on it with real engines characteristics of different schemes and the parameters.

One of the most significant tasks of the aircrfat engine monitoring system is the control of its thrust. In the used monitoring systems thrust is evaluated only during the take-off, however, the aircraft engine control function is the maintenance of the assigned thrust level in flight, which is impossible to be measured directly on board. Usually, the thrust control is performed by indirection – by the assignment of the rotational speed of rotor n_{HP} or n_{LP}, using a complex linear dependence between thrust $\overline{R}$ and speed of rotor $\overline{n}$. At that, the degrees of engine throttling in flight are evaluated relatively maximum values of thrust, and their calculation demands the application of complex mathematical models. For the increase of the thrust control objectivity one must pass on from the human control to computer control with the use of other functional dependences.

In new aircrafts the thrust is evaluated by the control factor value – a pressure difference out of turbine and at the engine input p_T^* / p_H^* (in many old engines this value is not measured) [1, 2]. In the given paper it is shown that the statistical data of throttling characteristics by this value can be presented in the form of linear non-dimensional dependence that simplifies the generalization of such characteristics for various flight configurations. Besides, as an alternative principle it is suggested controling and monitoring the engine power condition by the new thrust parameter of the turbofan – the measured values of air pressure raise ratio in the fan, $\pi_F^* = p_F^* / p_H^*$, correlated with the engine thrust. The reason for the basis of this value choice is the fact that in the modern turbofans with the hight level of bypass a major part of thrust is created in the outer contour.

Estimation method of flightning characteristics of turbofan

The turbofan thrust *R* at any speed *M* and altitude *N* of flight can be defined on the generalized formula:

$$R = R_0 \cdot \overline{R}_{MH} \cdot \overline{R}_{thr_{MH}}, \qquad (1)$$

where R_0 is bench thrust on the ground; $\overline{R}_{MH}$ is relative maximum turbofan thrust at *M* and *H*; $\overline{R}_{thr_{MH}}$ is relative drosseling (throttle ratio) turbofan thrust at *M* and *H*.

Below there are described the approaches of definition of basic performances of turbofan different schemes with convergent constant-geometry nozzles (for subsonic airplanes) using a similar mode of engine module (EM) [3]. It is suggested as parameter of monitoring the operational mode of turbofan with low bypass ratio to apply the engine pressure ratio (EPR) of air pressure raise ratio in the fan (on pressure measurement in an external contour on an input in the mixing chamber) $\pi_{R_{MH}} = \pi_F$. Pressure measurement in external contour of turbofan is more preferable because the air is cleaner than products of combustion (there is no danger of sensor choked), besides the value of pressure is a little bit higher and twist of a stream is less there, than behind the turbine. Besides at bypass ratios $m \geq 4$ the most part of thrust (3/4 and more) is formed in an external contour. The relative change of maximum thrust on speed and altitude (M and H correspondently) on a mode of EM can be calculated by the simple and convenient formula (corresponding plots are given in Fig.1):

$$\overline{R}_{MH} = \overline{p}_H \left\{\left[\left(k_{MIX}+1\right)\left(1+0{,}2M^2\right)^{3{,}5} - k_{MIX}\sqrt{\frac{1{,}2}{\tau_{Dz_0}}} \times M\left(1+0{,}2M^2\right)^3\right]\frac{\pi^*_{F_0}}{\pi_{S(kr)}}\sigma_{II} - 1\right\} \Big/ \left(\left(k_{MIX}+1\right)\cdot \pi^*_{F_0} / \pi_{S(kr)} \cdot \sigma_{II} - 1\right), \qquad (2)$$

where k_{MIX} is an adiabatic parameter of a gas mix in the mixing chamber; $\pi^*_{\mathrm{F}_0}$ is air pressure raise ratio in the fan, identical on a similar mode in the flight and on the ground; $\pi_{\mathrm{S(кр)}}$ is a pressure drop in the nozzle of the engine at a critical mode of the efflux; σ_{II} is a loss coefficient in the channel of the second contour; τ_{Dz_0} is relative temperature parameter of a gas mix on the engine exit.

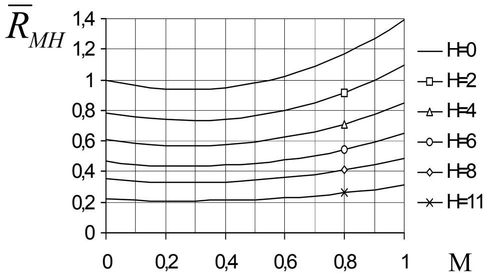

Fig.1. **Relative maximum thrust relation of engine RD-33 on flight conditions (at EM similarity)**

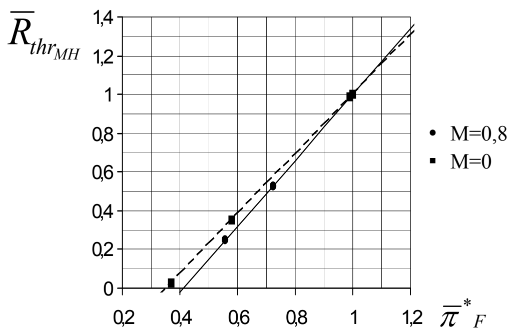

Fig.2. **Relative drosseling engine RD-33 thrust relation from pressure drop in the fan (at EM similarity)**

Feature of representation of experimental throttling characteristics (on an example of engine RD-33 statistical characteristics) depending on offered parameter is strictly linear character of engine thrust (see Fig.2) from maximum bench value down to the minimal value on an earth idle power. It confirms unequivocal correlation between thrust R and π^*_{F}, including in flight and at presence of an air bleed, similarly to the Eq. 3.

Apparently, stratification of straight lines becomes appreciable in case of deep throttling. The equation of relative throttle ratio of turbofan thrust is deduced in the following view:

$$\overline{R}_{thr_{MH}} = 1 - k_{thr_{MH}} \cdot (1 - \overline{\pi}_F), \qquad (3)$$

where $k_{thr_{MH}}$ is the factor which consider throttle ratio, $\overline{\pi}_F$ is relative air pressure raise ratio in the fan.

In an approximation equation value of a Mach number influence was expressed through particular factor k_M :

$$k_{thr_{MH}} = k_M \cdot k_{thr_0}, \qquad (4)$$

where k_{thr_0} is the factor which consider throttle ratio on the ground at a zero Mach number.

Value k_M on a Mach number is offered to approximate as:

$$k_M = 1 + k_V \cdot M, \qquad (5)$$

where k_V is the speed coefficient of engine.

For engine control in an onboard computer by aerodynamic characteristics required thrust R_{req} is determined on different M and H, on which it is possible to define absolute value of throttling thrust $R_{dr} = R_{req}$. Relative throttling thrust further is determined using similar operational mode of GG, $\overline{R}_{thr_{MH}} = R_{thr} / \left(R_0 \cdot \overline{R}_{MH}\right)$. Then it is possible to define engine operational modes using the following formula:

$$\overline{\pi}_F = 1 - (1 - \overline{R}_{thr_{MH}}) / k_{thr_{MH}}, \qquad (6)$$

It is determined, that relation of the specific fuel consumption C_R from π^*_{F} it is curvilinear, however strongest increase of C_R occurs at π^*_{F} below critical value 1,89. At these π^*_{F} values the turbine ceases to be closed, and pressure drop in it π^*_T is decreased at the further throttling. Then relations of gas temperatures before and behind the turbine cease to be linear from π^*_{F}. However in flight taking into account a dynamic pressure raise ratio π_v supercritical pressure drops ensuring similarity of EM are observed in all range of throttling modes, including the mode of a flight idle power. Thus for any earth mode with the critical efflux from the nozzle it is possible to establish flight similar operational mode of EM (at any altitude and speed of flight), appropriate to a constancy of rotational speed of a turbocompressor.

It is established, that relative change of the fuel consumption $\overline{G}_{F_{MH}}$ on a similarity mode of EM is equally for all types of aircraft engines independently from levels of their parameters and is defined by:

$$\overline{G}_{F_{MH}} = (1 - 0{,}0226H)^{5{,}755} \cdot \left(1 + M^2/5\right)^4, \qquad (7)$$

Relative change of the fuel consumption at throttling depends on the concrete engine (see Fig. 3 and Fig. 4). For considered engine RD-33 approximation of such relationship is linear:

$$\overline{G}_{F_{THR}} = 1 - 1{,}5329(1 + 0{,}065M)\cdot\left(1 - \overline{\pi}_F^*\right), \qquad (8)$$

but for turbofan such as PS-90A for modes below critical this relationship differs a little from linear:

$$\overline{G}_{F_{THR}} = 1{,}649\cdot\overline{\pi}_F^{*\,2} - 0{,}678\cdot\overline{\pi}_F^* = 0{,}678\cdot\overline{\pi}_F^*\left(2{,}432\cdot\overline{\pi}_F^* - 1\right). \qquad (9)$$

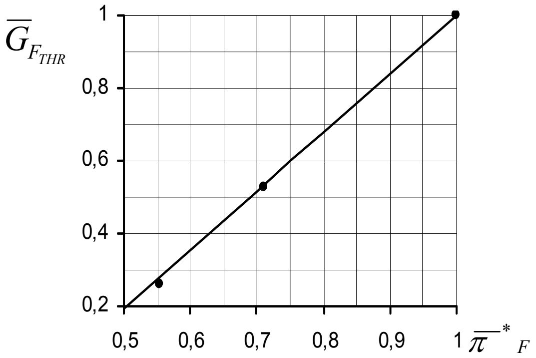

Fig.3. **Relative fuel consumption relation from relative pressure drop in the fan of RD-33 engine of M=0,8**.

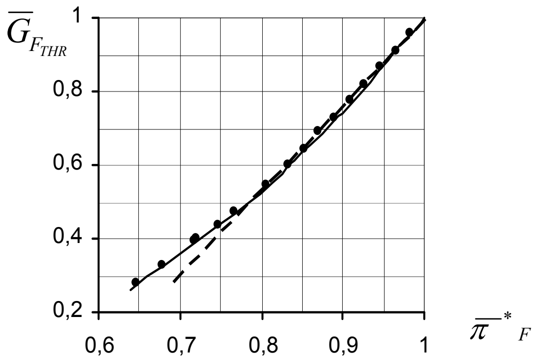

Fig. 4. **Relative fuel consumption relation from relative pressure drop in the fan of PS-90A engine of M=0,8.**

However in a flight range of throttle ratios (up to the value equals to 0.8) this relationship it is possible to accept as linear by analogy with (8). The way of definition of basic parameters (thrust and the fuel consumption) of two-shaft turbofan with the mixing chamber and with the high bypass ratio *m* is considered also, using a similar mode of EM. But it is possible only at the critical efflux from the general nozzle (at the big bypass ratio values this mode above maximum). The method of a direct presence of base high-altitude-speed characteristics of the engine in flight using the unified formula in relation to this theoretical bench mode is offered:

$$\overline{R}_{MH} = \overline{p}_H\cdot\left[\frac{k+1}{k}\cdot\pi_V - M\left(1 + 0{,}2M^2\right)^3 \times \sqrt{\frac{1{,}2}{\tau^*_{E(kr)}} - \frac{1}{k}}\right], \qquad (10)$$

where k is a parameter of an adiabatic for air; $\tau^*_{E(kr)} = T^*_{MIX\,0(kr)}/T_0$ is a temperature parameter of mixing for a critical mode. It is remarkable that it is enough to use only this one parameter for the characteristic of any concrete engine.

Results of comparison of high-altitude-speed characteristics on an example of PS-90A engine, calculated according to the conventional program on maximum thrust, with the characteristics, calculated for the program on EM similarity according to expression (10), are shown in Fig.5. It is visible that at relation of the current thrust values to maximum bench thrust the maximum cruise mode is similar to a critical mode, their values coincide on a cruise mode of flight (*M*=0,8 and *H*=11 km) and are equal to $\overline{R} = 0{,}3$.

It is remarkable, that at PS-90A engine the flight cruise (throttling) mode is similar to a maximum bench mode ($\overline{R} = 0{,}2$).

The comparative analysis of drosselling thrust characteristics of PS-90A engine on different speeds of flight is carried out. Their linear character on air pressure raise ratio in the fan, and also turn on a Mach number similarly to the Eq. 3 are determined. Thus satisfactory concurrence of computational values (by conventional calculate procedure of high-altitude-speed characteristics) with statistical data of the engine is fixed (see Fig. 6).

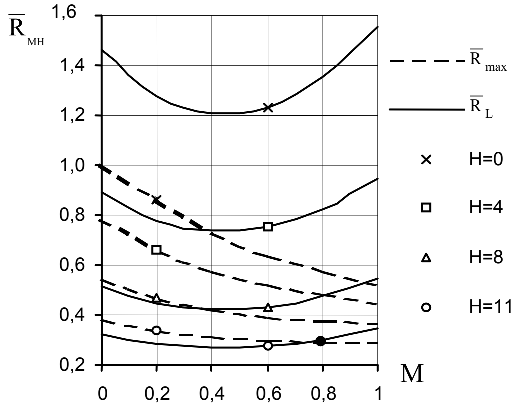

Fig. 5. **High-altitude-speed characteristics of turbofan with mixing chamber PS-90A comparison at conventional ($\overline{R}_{max}$) and similar ($\overline{R}_{S_{max}}$) calculation mode**.

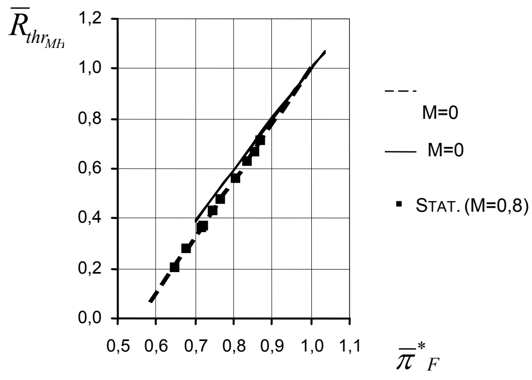

Fig.6. **Drosselling characteristics of turbofan with mixing chamber comparison with statistical data of PS-90A at M=0 and M=0,8.**

In case of the separate efflux of streams from contours of turbofan at similarity of a engine module (under condition of incomplete expansion in contours because of the critical efflux from constant-geometry nozzles) the universal formula for basic high-altitude-speed characteristics also is created:

$$\overline{R}_{MH} = \overline{p}_H \cdot \pi_V \left\{ \left(1 - \frac{1}{k \cdot \pi_V}\right) + \frac{\left(\frac{\pi_{R_0}}{1{,}85} \cdot \frac{\sqrt{\tau^*_{E_0}}}{m} + 1\right)}{k\left(1 + \sqrt{\tau^*_{E_0}} \big/ m\right)} - \frac{\frac{M \cdot (1 - 1/m)}{\sqrt{1 + 0{,}2 \cdot M^2}}}{k\left(1 + \sqrt{\tau^*_{E_0}} \big/ m\right)} \right\}, \tag{11}$$

Here $\sqrt{\tau^*_{E_0}} = \overline{C}_N$ is relation of stream speeds from nozzle of contours, at optimum distribution of energy it is equal to $\overline{C}_N = 1/\left(\eta^*_F \cdot \eta^*_{FT}\right)$; η^*_F, η^*_{FT} are accordingly efficiency of the fan and efficiency of the turbine of the fan; *m* is bypass ratio.

Conclusions

When turbofan throttling, the relationship between thrust and $\pi_F{}^*$ is linear that considerably simplifies the engine thrust control and engine monitoring. At that, as measuring (basic) thrust values it is suggested using values measured in similar power conditions of engine module by rather simple derived formulas. It is necessary to realize throttling characteristics concerning a basic similar mode of EM for each concrete engine as relations from air pressure raise ratio in the fan as they are linear concerning this parameter (similarly to Eq. 3 and 8), however they have a different inclination of lines.

Thus, the method of the airborne thrust control of turbofan by the measured thermodynamic values in flight is considerably simplified. Suggested generalized algorithms are convenient for applying instead of approximations in onboard computer, it is especial in adaptive prediction control systems of maneuverable aircraft.

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Turboventiliatorinių variklių traukos kontrolė naudojant skrydžio informaciją diagnozavimo sistemose

Reziumė

Turboventiliatorinių variklių statinių droselinių charakteristikų įvertinimas pagal oro slėgio ir traukos parametrą leidžia nustatyti gedimus variklio moduliuose. Traukos parametrų charakteristikoms įvertinti naudojami panašūs režimai pagal anksčiau taikytas formules. Taigi iš esmės supaprastinama traukos kontrolė pagal skrydyje matuojamus parametrus.

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