ADAPTIVE JET ENGINES WORK ANALYSIS AND CONTROL

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Abstract

The paper describes major designs of adaptive jet engines as well as their structural and operational advantages. Attention is paid to actual thermodynamic cycles of such engines and energy balance of flows. Particular attention paid to a double-rotor engine designed by Pratt & Whitney, where a portion of air is bled from downstream of the compressor and then supplied to the area downstream the turbine when the engine is operated at its maximum performance (turbine bypass engine). Then attention is paid to actual thermodynamic cycles of such engines and energy balance of flows. It was shown that real working cycles of these engines represent figures with variable surface areas, which is the reason for the second name of these units – engines with variable thermodynamic cycle. It is explained how basic parameters of such engines affect sensitiveness of operating cycles and controllability. The analysis has been conducted separately for internal and external channel. The sensitivity analysis for the working cycle makes it possible to select parameters that are potentially controllable and adjustable. To sum up the foregoing deliberations one has to state that operation of turbojet adaptive engines is the topic that needs much more investigation. Even the design solution of the engine itself, although being really exciting and promising, is troublesome in the aspects of the design and process engineering, and will lead to a series of operation and maintenance problems.

Keywords: *adaptation engine, parameters of the engine air, sensitivity of the work cycle*

1. Introduction

The common use of turbine jet engines as basic drive units for both military and civil aircrafts as well as tremendous increase of demands to cost-effectiveness, noise and emission of toxic pollutants has led to drawing up of new research directions for their further development.

One of the most innovative and original direction of research is devoted to designs of so-called turbine adaptive engines (also referred to in literature sources as engines ‘with variable thermodynamic cycle’). The basic aim of such developments is to fill the existing gap between the single-flow and double-flow engines. The characteristic properties of such structures is the ability to simulate operation of a double-flow engine when flights are performed with subsonic or near sonic speeds or to behave as a single-flow engines for flights with supersonic speeds values.

The most promising designs of that type include:

- VCE (variable cycle engine) from General Electric, referred also to as the engine with a double external channel (Fig. 1);

  That engine implements the concept of switching between the single-flow and two-flow modes and to adjust the double-flow degree depending on the aircraft speed and altitude (e.g. under takeoff conditions both the switching gate of operation mode (3) and the front control gate (7) are open in order to reduce intensity of air flow via the internal channel, whilst the both gates are fully closed when flight is performed with supersonic speed).
- VSCE (variable stream control engine) from Pratt and Whitney (Fig. 2).

Control to variable flow of fuel in that engine is achieved by repositioning of all the guide vanes of the fan (1) and the compressor as well as by variation of cross sections of the both outlet jets.

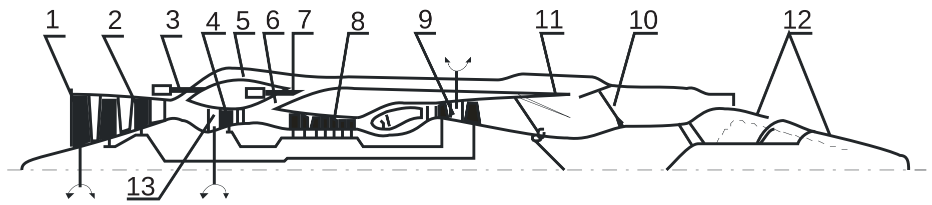


Fig.1. Longitudinal section of the VCE engine from General Electric [3]: 1 – adjustable inlet guide vanes, 2 – two-stage front section of the fan, 3 – switching gate of operation mode 4 – rear, single-stage section of the fan, 5 – external bypass channel, 6 – internal bypass channel, 7 – front control gate, 8 – compressor, 9 – adjustable inlet guide vanes for the low-pressure turbine, 10 – real control gate, 11 – ribs designed to fix the central cone of the outlet jet, 13 – adjustable inlet guide vanes for the rear section of the fan

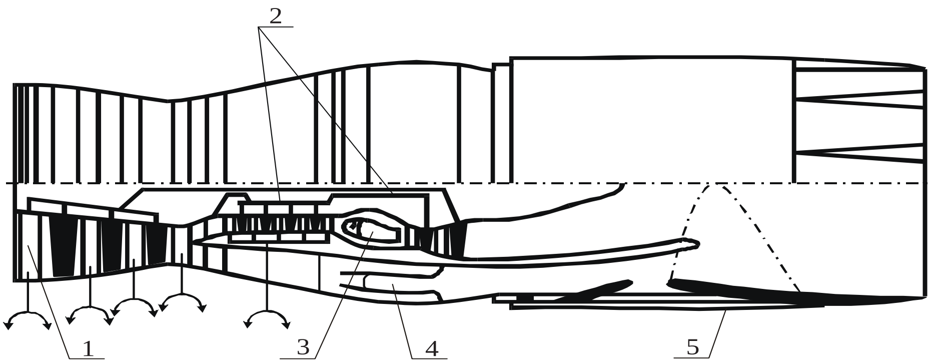


Fig.2. Engine VSCE from Pratt and Whitney [3]: 1 – fan with adjustable guide vanes, 2 – high pressure rotor unit, 3 – combustion chamber for the internal channel, 4 – combustion chamber for the external channel, 5 – outlet jet with thrust reverser

The group of adaptive engines includes also a two-rotor engine designed by Pratt & Whitney, where a portion of air is bled from downstream of the compressor and then supplied to the area downstream the turbine when the engine is operated with the maximum performance (turbine bypass engine). For the maximum performance of the engine it is possible to bleed up to 25% of the air stream that passes through the compressor. The more the flow is throttled, the less percentage ratio of the air is bled downstream the compressor in order to maintain the flow intensity of flue gas that passes the turbine. It makes possible to keep the engine rpm of the motor at the predefined level of 100% within the sufficiently wide variation range of both the total and unit trust

Common research studies carried out by Boeing and Pratt & Whitney have led to the design of a single-rotor engine with application of the bleed as described above (Fig. 3).
A peculiar feature of such a solution is implementation of external (with circular cross-section) bypass channels as well as a system that is capable to control air bleeding depending on the aircraft speed. Such a solution enables to improve efficiency of the engine, decrease its noise emission and emission of toxic compounds in flue gas. The additional advantage of the presented solution is the relatively lowly sophisticated standard solution and possibility to apply the solution to engines that already have been in use.

2. Energy balance

Real working cycles of these engines represent figures with variable surface areas, which are the reason for the second name of these units – engines with variable thermodynamic cycle.

Working cycles for adaptive engines of VCE or VSCE types are typical cycles of a double-flow engine, where the working area is split between bypass channels, depending on the aircraft flight conditions and operation range of the engine (Fig. 4).

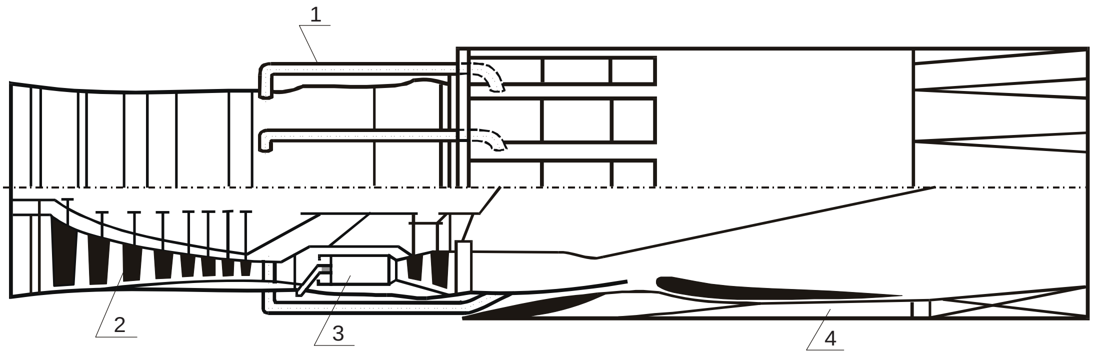


Fig.3. Cross-section diagram of the turbine jet engine of 'bypass' type: 1 – bypass channel of air delivered from downstream of the compressor to the area downstream the turbine, 2 - controllable and adjustable compressor, 3 – combustion channel with low-emission of toxic components in exhaust gas, 4 – outlet jet with thrust reverser.

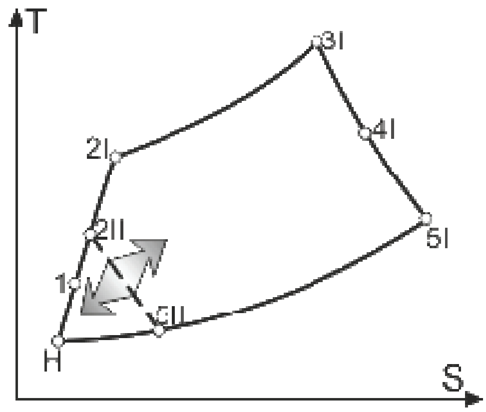
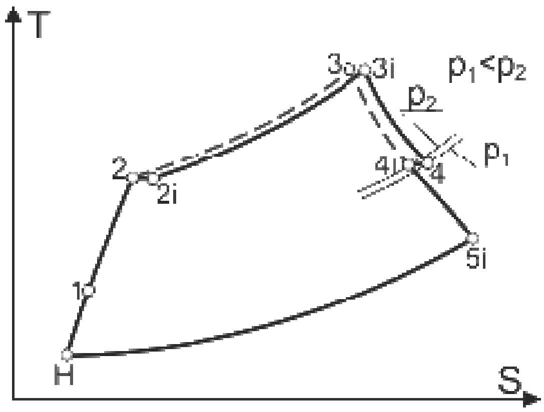


Fig.4. Real cycle of a turbojet adaptive engine



Rys.5. Real cycle of a turbojet engine of the 'bypass' type

On the contrary, the working cycle of the 'bypass' engine is a typical cycle of a single-flow engine with variable area of the corresponding thermal cycle. The curve shape depends on the amount of air that is bled from downstream of the compressor and fed downstream the turbine (Fig. 5).

Based on [1, 8], the work during a full cycle of adaptive engines can be determined for individual channels with use of the following formulas:

$$l_{obI} = (1-\beta)\, l_{ob}\,, \tag{1}$$

$$l_{obII} = \frac{\beta}{\overline{m}} l_{ob}\,, \tag{2}$$

where: l_{ob} - effective work for a cycle of an equivalent single-flow engine,

β - split ratio for shared work of two engine channels,

$\overline{m}$ - degree of double-flow operation, equal to the ratio between intensities of air flow through the external channel $(\dot{m}_{II})$ and the internal channel $(\dot{m}_{I})$.

For an adaptive engine that incorporates a mixer of streams, the relationship between the effective work of the external cycle on one side and the η_M mixer efficiency and φ_M ratio of velocities of air stream to be mixed can be expressed in the following form:

$$l_{obII} = \frac{2\beta(\eta_M - 1)\varphi_M^2}{2\varphi_M - (1+\varphi_M^2)\eta_M} l_{ob}\ . \tag{3}$$

Whilst the corresponding relationship for the engine with an afterburner in the external channel is the following:

$$l_{obIIdp} = \left(1 - \beta + \beta\Delta^{*}_{dp}\right) l_{ob} \ , \tag{4}$$

where: $\Delta^{*}_{dp} = \dfrac{T^{*}_{dpII}}{T^{*}_{2II}}$ - the degree of heating the air stream in the internal channel with the afterburner.

The work of the full cycle executed by the engine of the 'bypass' type can be expressed in the form that exemplifies the difference between the work during a cycle executed by a turbojet engine without bleeding facilities and the working cycle of the 'bypass' engine, i.e.

$$l_{obi} = l_{ob} - \nu\varphi^{2}_{D} c'_{p} T^{*}_{H} \left\{ \Delta^{*} - \frac{B\left[\left(1 + \bar{l}_{s}\right) c_{p} - c'_{p} \eta_{m} \bar{l}_{s}\right]}{c'_{p} \eta^{*}_{s} \eta_{m}} - 1 \right\}, \tag{5}$$

where: $\nu = \dfrac{\dot{m}_{up}}{\dot{m}}$ - relative amount of air that is bled from the downstream area of the compressor ($\dot{m}_{up}$ - the portion of air that is bled from the downstream area of the compressor to the area downstream the turbine).

φ_{D} - coefficient for loss of gas velocity in the outlet jet (usually φ_{D} =0.97-0.99);

c_{p}, c'_{p} - respective values of specific heat for air and exhaust gas;

T^{*}_{H} - stagnation temperature across the outlet of the compressor;

η_{m}, η^{*}_{s} - respective values of mechanical efficiency for the engine and the compressor;

Δ^{*} - the degree of heating for an equivalent single-flow engine;

$\bar{l}_{s} = \dfrac{L'_{s}}{L_{s}}$ - split ratio for the operation of the compressor with air bleeding, e.g. according to (L'_{s} - portion of the compressor work that is necessary to compress the bled air, L_{s} - overall work of the compressor);

$B = \Pi^{*\frac{k-1}{k}}_{s} - 1$ - constant coefficient that depends on the compression value Π^{*}_{s} (k – exponent of the isentropic curve for air equal to 1.4).

2. Sensitivity of the work cycle

The sensitivity analysis of a mathematic model is understood as estimation of increments exercised by variables of the model caused by variations of its parameters [11]. Increments of variables are usually evaluated by differential approximations.

The sensitivity analysis for the work cycle makes it possible to select parameters that are potentially controllable and adjustable. Such an analysis can be used for the needs of modelling software dedicated to jet engines. In addition, sensitivity of the work cycle serves as the measure how individual design and operational parameters of the engine affect its internal and external characteristics. The sensitivity can be determined when the relationship that determines the work cycle is expanded into the Taylor series, where only two first terms of the expansion are taken into account:

$$l_{ob} = l_{ob0} + \frac{\partial l_{ob}}{\partial x_{1}} dx_{1} + \frac{\partial l_{ob}}{\partial x_{2}} dx_{2} + ... + \frac{\partial l_{ob}}{\partial x_{n}} dx_{n}, \tag{6}$$

where: $x_{1}...x_{n}$ - selected status parameters;
index '0' refers to the expansion point.

Next, it is necessary to find out appropriate relationships between the partial differentials and selected status parameters.

When the formula for the effective work of the cycle (e.g. from [1]) is introduced to (1), the following relationship can be obtained for the internal channel circuit of the adaptive engines (in the form of the mathematic functions):

$$l_{obI} = f\left(\beta, \Pi_s^*, \Delta^*, \eta_{prs}, \eta_{prr}\right). \tag{7}$$

Respective partial differentials for the equation (7) adopt the following forms:

$$\frac{\partial l_{obI}}{\partial \beta} = -c_p T_H^* \frac{e-1}{\eta_{prs}}\left(\frac{\overline{k}\Delta^* \eta_{prs}\eta_{prr}}{e} - 1\right), \tag{8}$$

$$\frac{\partial l_{obI}}{\partial \Pi^*} = (1-\beta) R T_H^* \frac{\overline{k}\Delta^* \eta_{prs}\eta_{prr}\Pi^{*^{-\frac{1}{k}}} - \Pi^{*^{\frac{2k-3}{k}}}}{\eta_{prs}\Pi^{*^{\frac{2(k-1)}{k}}}}, \tag{9}$$

$$\frac{\partial l_{obI}}{\partial \Delta^*} = (1-\beta) c_p T_H^* \overline{k}\eta_{prs} \frac{e-1}{e}, \tag{10}$$

$$\frac{\partial l_{obI}}{\partial \eta_{prs}} = (1-\beta) c_p T_H^* \frac{e-1}{\eta_{prs}^2}, \tag{11}$$

$$\frac{\partial l_{obI}}{\partial \eta_{prr}} = (1-\beta) c_p T_H^* \overline{k}\Delta^* \frac{e-1}{e}\cdot \tag{12}$$

The foregoing relationships (8), (10) and (12) give the background to infer that the sensitivity of the work cycle for the internal channel adopts the constant value and for the case (8) is independent on the split ratio of work, in case of (10) is independent on the heating degree of the stream in that channel and for the case (12) is independent on efficiency of the decompression process.

According to (9), any increase of the engine compression results in continuous drop of the work cycle sensitivity to variation of the given parameter (Fig. 6 – the sensitivity of the work value within the operation cycle is related to the work value for the specific channel at the point of expansion). However, the effect is very weak, so that parameter is not used as a control factor.

According to (11) the work cycle sensitivity of the internal channel decreases in pace with increase in efficiency of the compression process (Fig. 7) but again, the sensitivity within the range of compression values that are commonly applied (i.e. $\eta_{prs}>0.80$) is insignificant, which confirms only slight effect of that parameter on the work value within the operation cycle.

For more precise evaluation, how parameters of the engine thermal cycle affect efficiency of its operation, the information should be sought by estimating values of natural derivatives for specific parameters.

For the external (bypass) channel the relationships between the work value of the thermal cycle and functional parameters of the cycle adopts the following form:

$$l_{obII} = f\left(\overline{m}, \beta, \Pi_S^*, \Delta^*, \eta_{prs}, \eta_{prr}\right). \tag{13}$$

Comparison between (7) and (13) makes it possible to conclude that for the external channel the sensitivity of the work value to variations of such parameters as β, Π^*, Δ^*, η_{prs} and η_{prr} is quite similar as for operation of the internal channel. However, there is one more parameter that contributes to the work value within the thermal cycle of the external channel, i.e. the degree of double-flow operation $\overline{m}$.

To estimate that effect quantitatively one has to calculate the partial derivative l_{obII} against $\overline{m}$, i.e.:

$$\frac{\partial l_{obII}}{\partial \overline{m}} = -\frac{\beta}{\overline{m}} c_p T_H^* \frac{e-1}{\eta_{prs}} \left(\frac{\overline{k}\Delta^* \eta_{prs} \eta_{prr}}{e} - 1 \right). \tag{14}$$

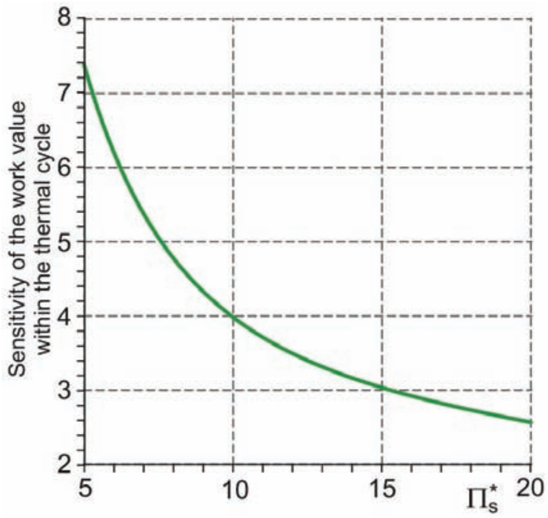


Fig.6. Sensitivity of the work value within the thermal cycle to variations of the engine compression (β=0.5, Δ^*=5)

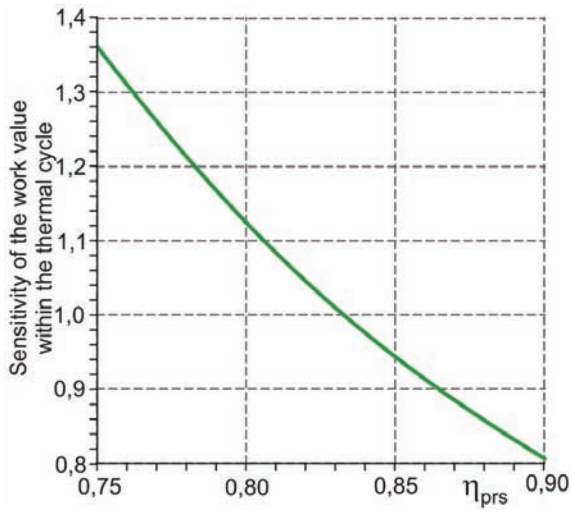


Fig.7. Sensitivity of the work value within the thermal cycle to variations of the compression process efficiency (β=0.5, Δ^*=5)

The foregoing relationship demonstrates that increase of the split factor (degree of double-flow operation) $\overline{m}$ between two streams always leads to drop of the work value for the thermal; cycle in the external channel (Fig. 8).

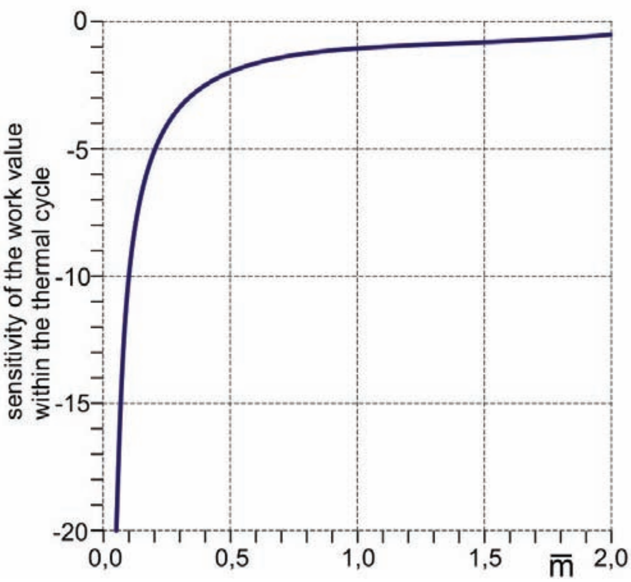


Fig. 8. Sensitivity of the work value within the thermal cycle to variation of the double-flow factor (β=0.5, Δ^*=5)

However, the nature of the curve reveals very high sensitivity of the work value within the thermal cycle to variations of that parameter within low range of the parameter values, whereas as early as from $\overline{m}$ >1.5 the dependence is really insignificant. All the above serves as a proof that further increase of the $\overline{m}$ value above the mentioned threshold, no longer decides about the work values within the thermal cycle of the external channel. It may be the reason for the fact that for all the already examined adaptive engines the air bleeds via the external channels not more than 15 – 20%, i.e. within the limits of the highest sensitivity of the work value within the thermal cycle to that parameter.

For adaptive engines with mixers it is additionally necessary to find out, how the value of work within the thermal cycle is sensitive to variation of the mixer efficiency η_M and mutual ratio of velocities demonstrated by air streams to be mixed φ_M, as:

$$l_{obII} = f\left(\eta_M, \varphi_M, \beta, \Pi^*, \Delta^*, \eta_{prs}, \eta_{prr}\right). \tag{15}$$

After having calculated the partial derivatives of the foregoing function with regard to η_M and φ_M one can obtain:

$$\frac{\partial l_{obII}}{\partial \eta_M} = -2\beta l_{ob} \frac{\varphi_M^2(\varphi_M - 1)}{[(\varphi_M + 1)\eta_M - 2\varphi_M]^2}, \tag{16}$$

$$\frac{\partial l_{obII}}{\partial \varphi_M} = 4\beta l_{ob} \frac{(1-\eta_M)(\eta_M - \varphi_M)\varphi_M}{[(\varphi_M + 1)\eta_M - 2\varphi_M]^2}. \tag{17}$$

The analysis of the relationship (16) makes it possible to conclude that sensitivity of the work value within the thermal cycle varies within vast limits, depending on the φ_M proportion between the velocity values of gas streams that leave individual channels (Fig. 9). Moreover, in pace with increase of φ_M the graph starts approach to asymptotes, which is also the proof that the value of work within the thermal cycle is highly sensitive to that parameter nearby the asymptotes. The asymptotes move towards higher values of mixing efficiency η_M for the assumed values $\varphi_M > 0$. For $\varphi_M = 1.0$ the sensitivity is equal to zero or even falls below zero for $\varphi_M > 1.0$. Therefore it is impossible to unambiguously determine, how the mentioned parameter affects the value of work within the thermal cycle as the interrelationship changes in pace with variation of φ_M.

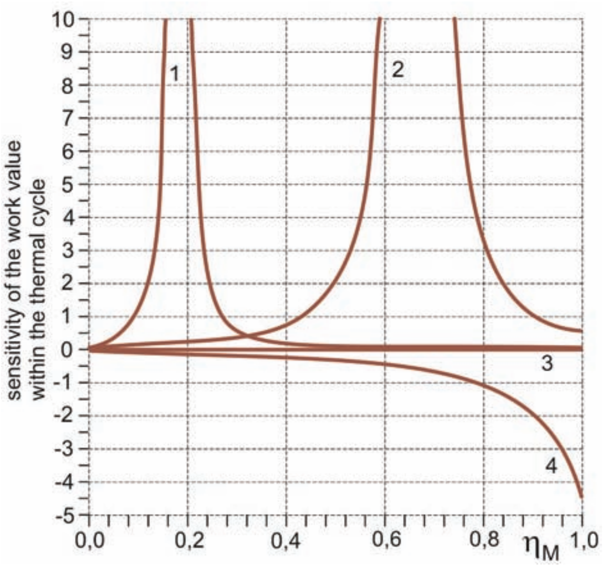


Fig. 9. *Sensitivity demonstrated by the value of work within the thermal cycle to variations of the mixing efficiency η_m (β=0.5, 1 - φ_M =0.1, 2 - φ_M =0.5, 3 - φ_M =1.0, 4 - φ_M =1.5)*

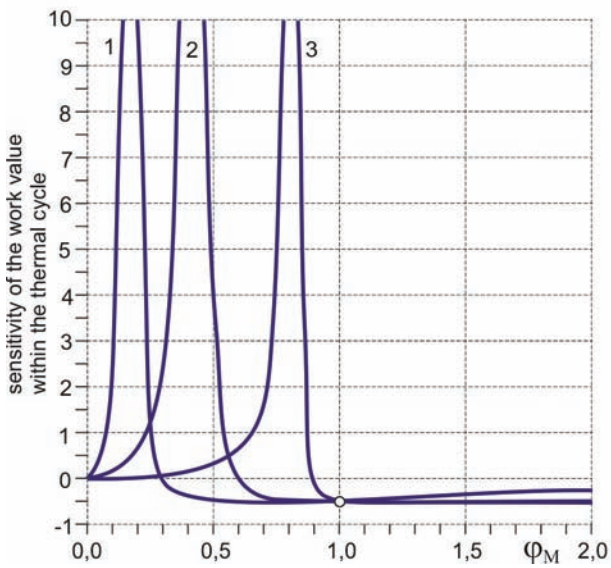


Fig.10. *Sensitivity demonstrated by the value of work within the thermal cycle to variations of the ratio φ_M between velocities of gas streams (β=0.5, 1 - η_M=0.1, 2 - η_M=0.3, 3 - η_M=0.6)*

Similar (variable) nature is demonstrated by the waveforms of the relation (17) – Fig. 10. The completed analysis makes it possible to find out the highly variable effect of variations in the ratio φ_M between velocities of flows from the both channels onto the value of work as the effect depends on efficiency of the mixing process. A very distinctive component of the mentioned relationship is sensitivity of the work value within the thermal cycle at the point $\varphi_M = 1.0$, where the value is constant, regardless the value η_M. of the mixing efficiency.

For adaptive motors with combustion in the external channel one has to consider one additional factor that affects efficient work of the combustion cycle. That factor is degree of stream heating Δ^*_{dp} inside the combustion channel. After using the relationship (4) that must be expanded into a Taylor series and then calculation of the partial derivative o work by Δ^*_{dp} one can obtain:

$$\frac{\partial l_{obII}}{\partial \Delta^*_{dp}} = \beta l_{ob} . \tag{18}$$

Analysis of that relationship makes it possible to find out that the sensitivity demonstrated by the value of work within the combustion (thermal) cycle for that channel is constant. It means that the effective work within that cycle shall increase in pace with the heating degree of the gas stream inside the external channel.

In case of ‘bypass’ motors, the sensitivity analysis for the value of work within the thermal cycle can be carry out with consideration to only the second term of the relationship (5) as it is the term that decides about the difference in the value of work within the thermal cycle as compared to the second motor where such air bleeds are not applied. When to express the second part of the relationship (5) in the form of functions, the following form is achieved:

$$l_{obi_2} = f\left(\nu, \Delta^*, \Pi^*_s, \bar{l}_s, \eta^*_s, \eta_m\right). \tag{19}$$

The partial derivatives of the foregoing equation are the following:

$$\frac{\partial l_{obi_2}}{\partial \nu} = -\varphi^2_D c'_p T^*_H \left\{\Delta^* - \frac{B\left[\left(1+\bar{l}_s\right)c_p - c'_p \eta_m \bar{l}_s\right]}{c'_p \eta^*_s \eta_m} - 1\right\}, \tag{20}$$

$$\frac{\partial l_{obi_2}}{\partial \Delta^*} = -\nu \varphi^2_D c'_p T^*_H , \tag{21}$$

$$\frac{\partial l_{obi_2}}{\partial \Pi^*_s} = \nu \varphi^2_D c'_p \frac{k-1}{k} T^*_H \frac{\left(1+\bar{l}_s\right)c_p - c'_p \eta_m \bar{l}_s}{c'_p \eta^*_s \eta_m} \Pi_s^{*^{-\frac{1}{k}}} , \tag{22}$$

$$\frac{\partial l_{obi_2}}{\partial \bar{l}_s} = \nu \varphi^2_D c'_p T^*_H B \frac{c_p - c'_p \eta_m}{c'_p \eta^*_s \eta_m} , \tag{23}$$

$$\frac{\partial l_{obi_2}}{\partial \eta^*_s} = -\nu \varphi^2_D c'_p T^*_H B \frac{\left(1+\bar{l}_s\right)c_p - c'_p \eta_m \bar{l}_s}{c'_p \eta_m \eta^{*^2}_s} , \tag{24}$$

$$\frac{\partial l_{obi_2}}{\partial \eta_m} = -\nu \varphi^2_D c'_p T^*_H B \frac{\left(1+\bar{l}_s\right)c_p}{c'_p \eta^*_s \eta^2_m} . \tag{25}$$

The presented relationships (20, 21 and 23) enable to conclude that for the ‘bypass’ engines the sensitivity demonstrated by the value of work within the thermal cycle is constant and in case of (20) is independent on the relative amount of air stream that is bled from the downstream area of the compressor ν, in case (21) it is independent on the heating degree of the gas stream Δ^*, whilst for the case (23) the sensitivity is also independent on the split ratio when the compressor is operated with air bleeding $\bar{l}_s$.

According to (22) any increase of the compression Π^*_s leads to continuous drop of sensitivity demonstrated by the value of work within the engine cycle to variation of that parameter (Fig. 11 - sensitivity demonstrated by the value of work within the engine cycle is referred to the value of work achievable for an equivalent single-flow motor without air bleeding, at the point of expansion). However, the effect is still weak, in particular below the compression factor of the compressor $\Pi^*_s = 10$ therefore that parameter is not used to control a turbojet engine.

According to (24), the sensitivity demonstrated by the value of work within the thermal cycle of a ‘bypass’ engine grows nearly linearly in pace with growth of the compressor efficiency (Fig. 12). However, for commonly used vales of the compressor efficiency (i.e. η_s^*>0.80) is still insignificant, which serves as a proof of only slight influence exercised by that parameter onto the value of work within the thermal cycle.

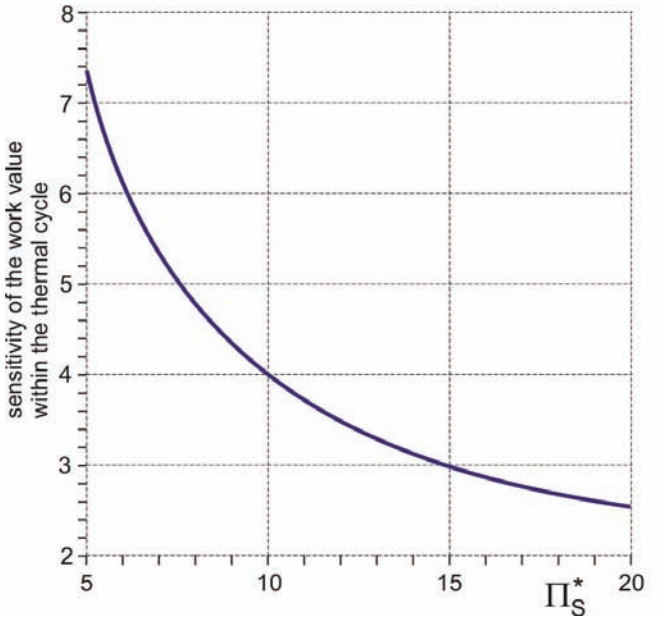


Fig.11. Sensitivity demonstrated by the value of work within the thermal cycle to variations of compression exercised by the compressor

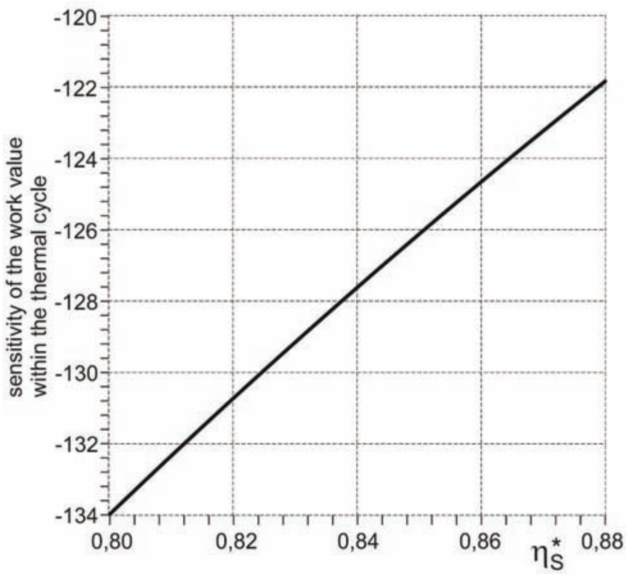


Fig.12. Sensitivity demonstrated by the value of work within the thermal cycle of a ‘bypass’ engine to variations of the compressor efficiency

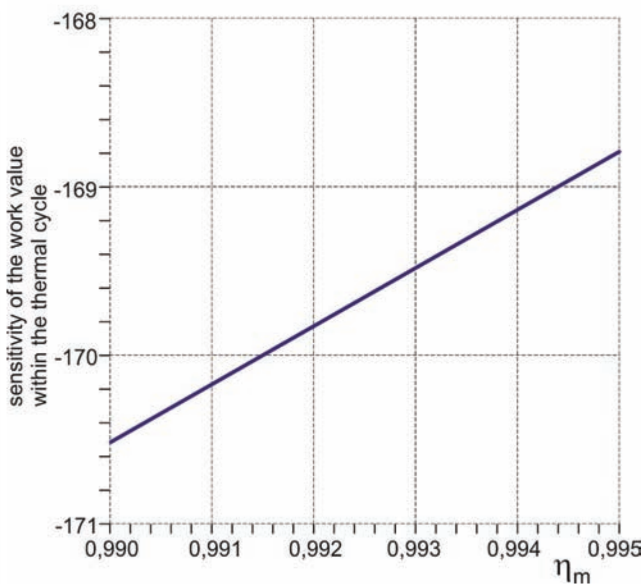


Fig.13. Sensitivity demonstrated by the value of work within the thermal cycle of a ‘bypass’ engine to variations of the mechanical efficiency

Similarly, according to (25), one can find out that sensitivity demonstrated by the value of work within the thermal cycle of the ‘bypass’ engine gradually increases in pace with the growth of mechanical efficiency achieved by the engine over the commonly applied range of that parameter (Fig. 13). However, the influence is rather weak, thus that parameter is also not used for control of the engine performance.

3. Recapitulations and conclusions

To sum up the foregoing deliberations one has to state that operation of turbojet adaptive engines is the topic that needs much further investigations. Even the design solution of the engine itself, although being really exciting and promising, is troublesome in the aspects of design, technology and shall led to a series of operation and maintenance problems. The most difficult issue seems to be a solution meant to control bleeding of air depending on the flight speed of an aircraft. Therefore future prospects for design solutions of adaptive engines are open and offer big opportunities for further development.

In addition, the degree of separation of the stream in the adaptive engines can be a parameter that adjusts the value of the working cycle engine because of its high sensitivity, especially to small values, and since $\overline{m} > 1.5$ is very small. It may be the reason for the fact that for all the already examined adaptive engines the air bleeds via the external channels not more than 15 ÷ 20%, i.e. within the limits of the highest sensitivity of the work value within the thermal cycle to that parameter.

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