Journal of KONBiN 4 (16) 2010
ISSN 1895-8281

PREMISES FOR COMPREHENSIVE PARAMETRIC EVALUATION OF THE CONDITION OF TURBOJET ENGINE REGULATION

PRZESŁANKI KOMPLEKSOWEJ PARAMETRYCZNEJ OCENY STANU REGULACJI TURBINOWEGO SILNIKA ODRZUTOWEGO

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Abstract: *In his paper a basis of new approach to evaluate the condition of turbojet engine has been presented. The model in the form of the four transmittances has been reduced to one comprehensive model with such a desirable property that the operating quality of the engine determined during the ground tests also provides sufficient information about its performance during flight. A model involves a input of the engine (signals* p_2 *and* $\dot{m}_p$*) with the output of the engine (*n *and* t_4^**) has been given. It can be set the theoretical model* $|G_{kompleks}(j\omega)|^2$ *and its parameters then compare the parameters of the experimental model (ground test) within the parameters of the standard model.*

Keywords: *performance tests, serviceability assessment, engine adjustment*

Streszczenie: *W tym artykule zostało przedstawione nowe podejście do oceny stanu działania turbinowego silnika odrzutowego. Model w postaci czterech transmitancji został zredukowany do jednego kompleksowego modelu z taką pożądaną właściwością że ocena stanu działania silnika podczas jego prób naziemnych daje także możliwość oceny jego wartości użytkowej w locie. Został przedstawiony model wiążący sygnały wejściowe silnika (*p_2 *i* $\dot{m}_p$*) z sygnałami wyjściowymi (*n *i* t_4^**). Został wyznaczony teoretyczny model silnika* $|G_{kompleks}(j\omega)|^2$ *i jego parametry które następnie można porównywać z parametrami uzyskanymi podczas próby naziemnej.*

Słowa kluczowe: *badania eksploatacyjne, ocena zdatności, regulacja silnika*

1. INTRODUCTION

The proper adjustment of aircraft engines (technical systems, machinery, equipment, hydraulic and pneumatic installation, etc.) is essential to allow the engine or any object to use, which must be secure and reliable (e.g. maximum rotation speed of turbine jet engine must gain 100 ± 0.2%, and the excess of 0.5% for example, leads to a rapid engine wear, and the situation that the use of this engine is becoming dangerous and unreliable). Currently in the process of assessing the state of aircraft engine, signals waveforms and the assumed values of the quality indicators of these waveforms in very specific moments determined by engine ground test program are investigated. This way of assessing the quality of the engine is very time and material consuming, and often unreliable because of the ability to make a mistake resulting from a different environment (temperature, pressure) acting on the engine while trying to land in relation to the environment acting on the fly easily. But it is mainly due to the fact that the mechanic performing the engine test is only able to enter to the controller using the DSS (lever engine control) of different preset values for the main usable signal (n and T4), and there is no possibility of introducing different and unknown disturbances acting on the engine in flight. For this reason, engine tests during the ground test are incomplete and unreliable because it can be properly aligned on the basis of ground tests engine but it can have insufficient utility value in flight. [3, 4] Hence the need for researching a new methods for defining the condition of the engine.

One of these methods is comprehensive (simultaneous analysis of four main signals arising from the working of the engine), parametric (condition of engine is expressed by parameters of engine model based on his four signals) a method of assessing the condition of the engine during ground testing also gives the opportunity to assess its value in flight.

2. THEORETICAL BASIS FOR PARAMETRIC EVALUATION OF THE CONDITION OF TURBOJET ENGINE

Currently, assessment of aircraft engine control is carried out on the basis of the quality of automation engine waveform signals identifying during ground tests. Method is not universal. It turns out that the indicators set during ground tests do not always coincide with the quality indicators that may arise during the flight. Hence the need to amend designated quality waveform signals witch the additional parameter – potential regulator set of equations of state that binds the state of the quality to its technical conditions. [1, 3, 4, 5]

It was notice that these difficulties may be resolved by automation processing signals (input and output) on the system parameters (coefficients of reinforcement and time constants of the mathematical model of the engine). Designated parameters have the peculiarity which are determined during ground testing and allow to assess the value of other parameters which occur during the flight of the aircraft.

Figure 1. represents simplified scheme system of control engine speed.

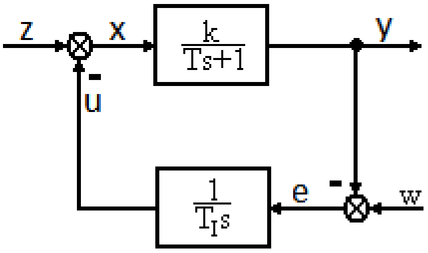

Figure 1. Simplified diagram of aircraft engine regulation; k – object gain; T, TI – engine time-constant, PI regulator time-constant, w – setting value, u – signal of regulator impact on object, z – disturbance, y – operational signal, x – excitation signal, e – error, s – complex variable

Assessment of the quality of the engine is determined by the transmittance [5, 10, 13]:

- open system H_O:

$$H_O = \frac{u}{z} = \frac{k}{T_I s(Ts+1)} \tag{1}$$

- closed system from the set point (on ground tests) H_W:

$$H_W = \frac{y}{w} = \frac{\frac{k}{TT_I}}{s^2+\frac{1}{T}s+\frac{k}{TT_I}} \tag{2}$$

- closed system from the interference (work during the flight) H_Z:

$$H_Z = \frac{y}{z} = \frac{\frac{k}{T}}{s^2+\frac{1}{T}s+\frac{k}{TT_I}} \tag{3}$$

Parameter $\frac{k}{T}$ occurring in transmittance H_Z describing the engine during the flight can be easily determined from the transmittance H_W in which parameters are determined during ground tests. It is sufficient to multiplied the coefficient of the sample ground by current regulation sample T_I control setting:

$$\frac{k}{T} = \frac{k}{TT_I}T_I \tag{4}$$

This possibility gives the advantage to the state of parametric methods assessment beyond the existing methods of regulation on the quality based on waveform signals. [4, 5]

3. THEORETICAL BASIS FOR COMPREHENSIVE EVALUATION OF THE REGULATION CONDITION OF TURBOJET ENGINE

In the evaluation of the condition of the engine regulation (see Figure 2) in which 4 basic signals are considered: n – rotational speed; p2 – pressure behind the compressor; $\dot{m}_p$ – mass concentration of the fuel flow; t_4^* – temperature behind the turbine. [1, 4, 10, 12, 13]

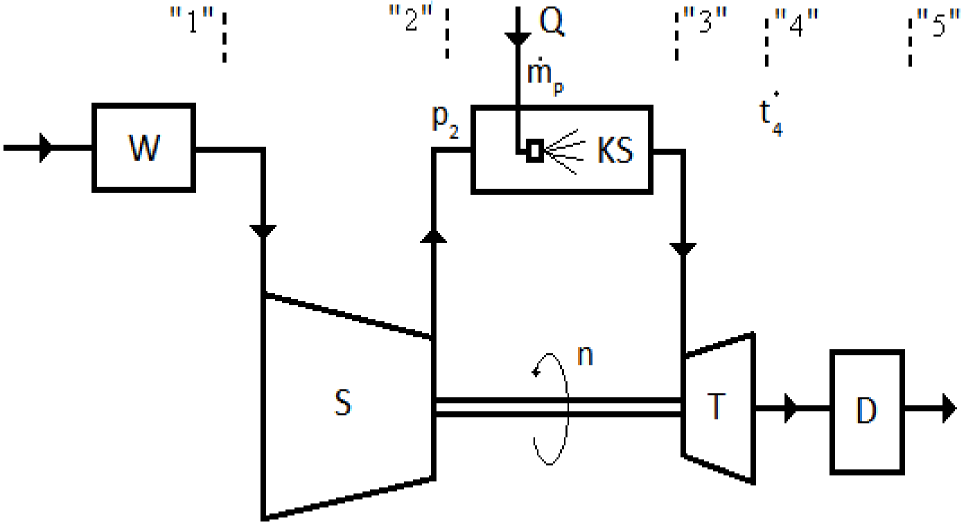

Figure 2. Diagram of engine regulation (W – inlet; S – compressor; KS – combustion chamber; T – turbine; D – nozzle, exhaust; 1,2,3,4,5 – specific cross sections)

In order to evaluate the operating quality of the engine, all interactions between the basic signals are analyzed. The signals relationships are defined by the following transmittances [1, 5, 13]:

$$G_{1\dot{m}_p} = \frac{\Delta n}{\Delta \dot{m}_p} \tag{5}$$

$$G_{1p_2} = \frac{\Delta n}{\Delta p_2} \tag{6}$$

$$G_{2\dot{m}_p} = \frac{\Delta t_4^*}{\Delta \dot{m}_p} \tag{7}$$

$$G_{2p_2} = \frac{\Delta t_4^*}{\Delta p_2} \tag{8}$$

The model in the form of the four transmittances has been reduced to one comprehensive model with such a desirable property that the operating quality of the engine determined during the ground tests also provides sufficient information about its performance during flight.

The delivery volume of output signals Δn and Δt_4^* is made in the first step and then equations 5÷8 are replaced by the following:

$$G_{1\dot{m}_p p_2} = \frac{\Delta p_2}{\Delta \dot{m}_p} \tag{9}$$

$$G_{2\dot{m}_p p_2} = \frac{\Delta p_2}{\Delta \dot{m}_p} \tag{10}$$

The delivery volume of input signals $\Delta \dot{m}_p$ and Δp_2 is the second step and then also the equations 5÷8 are replaced by the following:

$$G_{1nt_4^*} = \frac{\Delta n}{\Delta t_4^*} \tag{11}$$

$$G_{2nt_4^*} = \frac{\Delta n}{\Delta t_4^*} \tag{12}$$

Finally the model is created as a quotient of transforms the output signals relative to the ratio transforms input signals:

$$G_{kompleks}(s) = \frac{G_{1nt_4^*}}{G_{1\dot{m}_p p_2}} = \frac{G_{2nt_4^*}}{G_{2\dot{m}_p p_2}} \tag{13}$$

Depending account (10) and (12) is obtained:

$$G_{kompleks}(s)=\frac{\dfrac{\Delta n}{\Delta t_4^*}}{\dfrac{\Delta p_2}{\Delta \dot{m}_p}}=\frac{\Delta n \Delta \dot{m}_p}{\Delta t_4^* \Delta p_2} \tag{14}$$

When applying the inverse Laplace transformation is determined: [6, 11]

$$g_{kompleks}(t) * \Delta t_4^* * \Delta p_2 = \Delta n * \Delta \dot{m}_p \tag{15}$$

The dependence (14, 15) shows that there is a comprehensive (one) model of the engine corresponding to 4 classic models used so far in the assessment process of engine state regulation. This model is the relation between convolution of signals t_4^*, p_2, with impulse respond $g_{kompleks}(t)$ and convolution of signals n and $\dot{m}_p$.
Analyzing complex models $G_{kompleks}(s)$ and $g_{kompleks}(t)$ it is concluded that the complex variable "s" and a time variable "t" are not sufficiently sensitive to deal with relations between four signals. Therefore, in accordance with the principles of automation from the complex variable "s" goes to the frequency variable "ω" to produce a signal analysis and the possibility of a single signal on the basis of cross-power density and self-signals recorded during engine tests.
From relation (14) is obtained:

$$G_{kompleks}(j\omega)=\frac{\dfrac{\Delta n(j\omega)}{\Delta t_4^*(j\omega)}}{\dfrac{\Delta p_2(j\omega)}{\Delta \dot{m}_p(j\omega)}}=\frac{\dfrac{S_{nt_4^*}}{S_{t_4^* t_4^*}}}{\dfrac{S_{p_2\dot{m}_p}}{S_{\dot{m}_p\dot{m}_p}}} \tag{16}$$

where: $S_{nt_4^*}$ - mutual spectral power density of signals n and t_4^*,

$S_{t_4^* t_4^*}$ - own spectral power density of signal t_4^*,

$S_{p_2\dot{m}_p}$ - mutual spectral power density of signals p_2 and $\dot{m}_p$,

$S_{\dot{m}_p\dot{m}_p}$ - own spectral power density of signal $\dot{m}_p$.

Then designate the square of module and argument of the transmittance $G_{kompleks}(j\omega)$:

$$|G_{kompleks}(j\omega)|^2 = \frac{\dfrac{S_{nn}}{S_{t^*_{4t}t^*_4}}}{\dfrac{S_{p_2p_2}}{S_{\dot{m}_p\dot{m}_p}}} = \frac{\Delta n \Delta \dot{m}_p}{\Delta t^*_4 \Delta p_2} = \frac{A^2_{nnt^*_4t^*_4}(\omega)}{A^2_{p_2p_2\dot{m}_p\dot{m}_p}(\omega)} \tag{17}$$

$$ArgG_{kompleks}(j\omega) = \Delta\varphi_{nt^*_4p_2\dot{m}_p} = \Delta\varphi_{nt^*_4} - \Delta\varphi_{p_2\dot{m}_p} = Arg\,\frac{\dfrac{S_{nt^*_4}}{S_{t^*_4t^*_4}}}{\dfrac{S_{p_2\dot{m}_p}}{S_{\dot{m}_p\dot{m}_p}}} \tag{18}$$

where: S_{nn} - own spectral power density of signal n,
$S_{p_2p_2}$ - own spectral power density of signal p_2,
$A^2_{nnt^*_{4t}t^*_4}(\omega)$ - square amplitude gain of output signals n and t^*_4,
$A^2_{p_2p_2\dot{m}_p\dot{m}_p}(\omega)$ – square amplitude gain of input signals p_2 and $\dot{m}_p$.

Spectral power density functions S signals determined on the basis of the correlation function to which the Fourier transformation is used. When the signals $n(t)$, $t^*_4(t)$, $p_2(t)$ and $\dot{m}_p(t)$ are known, auto and cross correlation together with own and mutual spectral power density can be estimate. Subsequently square amplitude gain of input signals $A^2_{p_2p_2\dot{m}_p\dot{m}_p}(\omega)$ and square amplitude gain of output signals $A^2_{nnt^*_{4t}t^*_4}(\omega)$ can be computed. Quotient of this functions is the comprehensive model of engine what was looked for. Amplitude gain $|G_{kompleks}(j\omega)|^2$ and related to it phase shift $\Delta\varphi_{nt^*_4p_2\dot{m}_p}$ can be estimate from this model. [6, 11]

4. A COMPREHENSIVE PARAMETRIC ANALYSIS OF THE STATE OF REGULATION THE ENGINE ON THE BASIS OF OPERATIONAL ENGINE K-15 TEST

Recorded signals automation of turbojet engine (K-15) is shown in Figure 3 and Figure 4. [7]
Additionally it is assumed that the course DP_{rob} corresponds to the conduct of the signal $\dot{m}_p$, the signal T- to the signal t^*_4, N signal n and $P2$ to the signal p_2.

Waveforms recorded $n(t)$, $t^*_4(t)$, $p_2(t)$ and $\dot{m}_p(t)$ have been multiplied by the Hanning's window then the autocorrelation was calculated. Obtained autocorrelation graphs of polynomial approximation is the general form:

$$R_{yy}(\tau) = a_1\tau^4 + a_2\tau^3 + a_3\tau^2 + a_4\tau + a_5 \qquad (19)$$

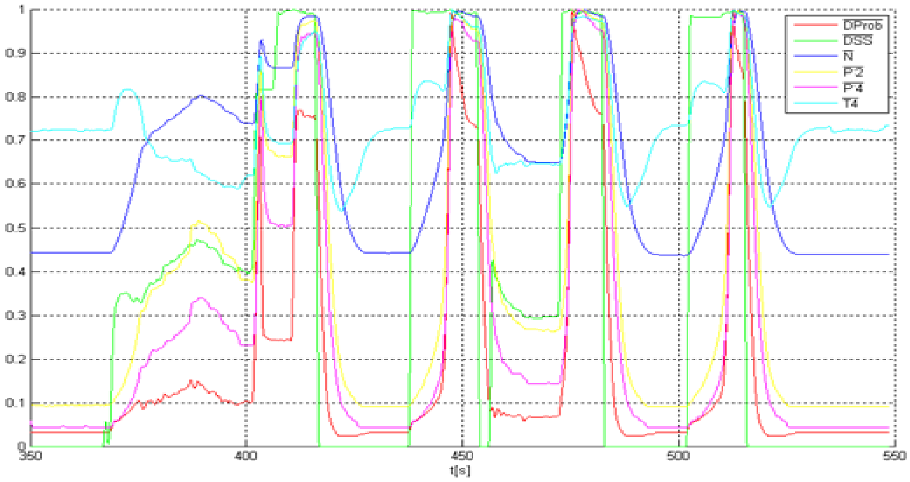

Figure 3. Waveforms of motor signals (time of observation signals 350 - 550 [s])

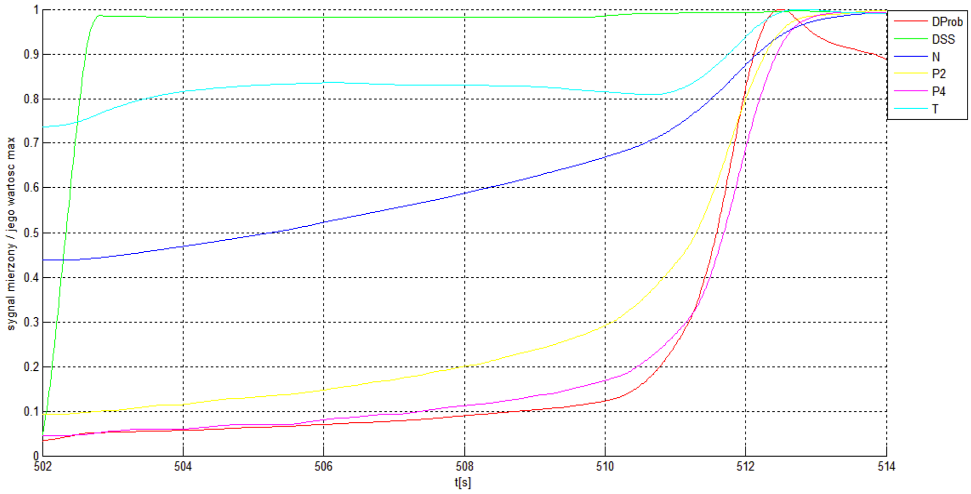

Figure 4. Waveforms of engine signals (time of observation signals 502 – 514 [s])

With the approximately an accuracy of R2> 0.997 coefficient of determination was obtained in the following for a functions of autocorrelation and cross correlation:

$$R_{nn}(\tau) = -0,03281\tau^4 + 0,8836\tau^3 - 6,744\tau^2 + 1,572\tau + 103,7 \qquad (20)$$

$$R_{t_4^* t_4^*}(\tau) = -0,06357\tau^4 + 1,704\tau^3 - 12,92\tau^2 + 2,72\tau + 198 \qquad (21)$$

$$R_{p_2 p_2}(\tau) = -0,004135\tau^4 + 0,1151\tau^3 - 0,8904\tau^2 - 0,1874\tau + 17,21 \qquad (22)$$

$$R_{\dot{m}_p\dot{m}_p}(\tau) = 0,0003697\tau^4 - 0,007364\tau^3 + 0,08844\tau^2 - 1,128\tau + 6,037 \quad (23)$$

$$R_{nt_4^*}(\tau) = -0,0494\tau^4 + 1,382\tau^3 - 11,35\tau^2 + 10,74\tau + 140,8 \quad (24)$$

$$R_{p_2\dot{m}_p}(\tau) = -0,00307\tau^4 + 0,06554\tau^3 - 0,1189\tau^2 - 4,924\tau + 26,37 \quad (25)$$

Fourier transform was used for estimate a power density of function:

$$F\left\{R_{yy}\right\} = \int_{-\infty}^{\infty} R_{yy}(\tau) e^{-j\omega\tau} d\tau \quad (26)$$

Fourier's transform of the polynomial (19) after moving from "jω" in the variable "s" is as follows:

$$F\left\{R_{yy}\right\} = a_1 \frac{24}{s^5} + a_2 \frac{6}{s^4} + a_3 \frac{2}{s^3} + a_4 \frac{1}{s^2} + a_5 \frac{1}{s} \quad (27)$$

After substituting the parameters from formula (20 ÷ 25) and (27) formula to (16) and (17) we obtain a comprehensive model of the engine:

$$|G_{kompleks}(s)|^2 = 0,1837 \frac{-1,928\cdot10^{-8}s^8 + 9,052\cdot10^{-7}s^7 - 1,899\cdot10^{-5}s^6 + 2,642\cdot10^{-4}s^5 - 2,818\cdot10^{-3}s^4 + 1,967\cdot10^{-2}s^3 - 5,321\cdot10^{-2}s^2 - 0,1716s + 1}{7,717\cdot10^{-8}s^8 - 4,215\cdot10^{-6}s^7 + 8,984\cdot10^{-5}s^6 - 8,814\cdot10^{-4}s^5 + 2,812\cdot10^{-3}s^4 + 1,529\cdot10^{-2}s^3 - 1,171\cdot10^{-2}s^2 - 0,0607s + 1} \quad (28)$$

$$ArgG_{kompleks}(s) = \mathrm{Arg}[0,1628 \frac{-2,138\cdot10^{-8}s^8 + 1,026\cdot10^{-6}s^7 - 2,202\cdot10^{-5}s^6 + 3,123\cdot10^{-4}s^5 - 3,397\cdot10^{-3}s^4 + 2,477\cdot10^{-2}s^3 - 8,021\cdot10^{-2}s^2 - 0,1105s + 1}{3,737\cdot10^{-8}s^8 - 1,799\cdot10^{-6}s^7 + 3,043\cdot10^{-5}s^6 - 1,426\cdot10^{-4}s^5 - 1,716\cdot10^{-3}s^4 + 2,321\cdot10^{-2}s^3 - 7,232\cdot10^{-2}s^2 - 0,1729s + 1}] \quad (29)$$

This model involves a input of the engine (signals p_2 and $\dot{m}_p$) with the output of the engine (n and t_4^*). It can be set the theoretical model $|G_{kompleks}(j\omega)|^2$ and its parameters then compare the parameters of the model within the parameters of the experimental standard model (ground test).

5. CONCLUSION

There is one comprehensive model for evaluation of the condition of turbojet engine regulation. This model allows for compute amplitude gain $|G_{kompleks}(j\omega)|^2$ and phase shift $\Delta\varphi_{nt_4^* p_2 \dot{m}_p}$ which can be physically interpreted. Parameters of the theoretical model $|G_{kompleks}(j\omega)|^2$ can be compared with parameters of the experimental standard model (obtained from ground test).

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