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EXAMINATION OF OPERATIONAL DEPENDABILITY DEMONSTRATED BY TURBINE REACTIVE ENGINES

EKSPLOATACYJNE BADANIA STANU ZDATNOŚCI TURBINOWEGO SILNIKA ODRZUTOWEGO

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Abstract: *The paper presents course and results of operational examination carried out for engines with particular consideration of land-based tests. It has been suggested that available, already recorded signals from the automatic and control systems can serve as a basis for assessment of the engine operability. The recorded signals can be analyzed in various manners, including the method that is based on the phase trajectory superposed with the Lyapunov function. It has been shown that analysis of signal interrelations presents substantial advantages, where the movement of the phase trajectory vector over the time period is subject to analysis and is related to successive values of the Lyapunov function that is calculated for subsequent moments of time (possibility to analyze both linear and non-linear systems, simultaneous analysis of three signals: operational, environment and feed), therefore the proposed method prevails over other approaches to analysis of signals. The final part of the paper deals with analysis of signals obtained from recorded waveforms from the automation and control systems of the K-15 engine.*

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

Streszczenie: *W pracy przedstawiono badania eksploatacyjne silnika ze szczególnym uwzględnieniem prób naziemnych. Zasugerowano, że podstawą oceny zdatności silnika są dostępne, zarejestrowane sygnały automatyki (regulacji). Przedstawiono różne metody analizy zarejestrowanych sygnałów, w tym metodę opartą na trajektorii fazowej z naniesioną funkcją Lapunowa. Wykazano przewagę analizy relacji między sygnałami, której podstawą jest badanie ruchu wektora trajektorii fazowej w czasie, względem kolejnych w czasie różnych wartości funkcji Lapunowa (możliwość badania układów liniowych i nieliniowych, jednoczesna analiza trzech sygnałów: użytkowego, otoczenia i zasilania) nad innymi metodami analizy sygnałów. Podano przykłady analizy sygnałów na podstawie zarejestrowanych przebiegów sygnałów automatyki (regulacji) silnika K-15.*

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

1. Introduction

Any system intended to handle avionic engines incorporates two major activities: regular operation and technical maintenance (Fig. 1). The diagram shows that the maintenance function comprise adjustments, diagnostics and reliability, respectively derived from the fundamentals of automatic control, diagnostic rules and theory of reliability [9, 10].

The necessary theoretical knowledge on the areas of automatic control, diagnostics and reliability provides the information that is introduced into the system and therein, in accordance with the principles of cybernetics, it is transformed onto tangible features (savings on material, power consumption and also time [6,11]).

Finely tuned engines, with use of the best available knowledge, demonstrate optimized wear, typical for normalized operating conditions. Any new variable that represents alteration in technical condition (degree of wear) should be calculated in accordance with diagnostic rules and immediately responded with simultaneous updating (following the reliability theory) of reliability parameters, which is then translated into changes in operation mode of the equipment.

Therefore, the comprehensive assessment of the operation dependability of avionic engines covers simultaneous assessment of its operation (static and dynamic characteristics), technical condition (parameters of wear and tear, degree of technical resource consumption), and reliability conditions (reliability characteristics). All the above issues (adjustment, diagnostics and reliability) are mutually interleaved and complete each other. Operation practice demonstrates that particular attention should be paid to the issues of appropriate adjustments as the tuning processes, owing to the sensitivity of machinery to control the parameters, provides information on technical condition of the engine and any alterations of that condition are associated with further reliability of the machinery [2, 10. 15].

Specific role of the decision maker (Fig. 1) is also worth mentioning. Based on acquired information it consists in improving the organization of the system (with increasing of the system redundancy) and therefore its efficiency [6, 11].

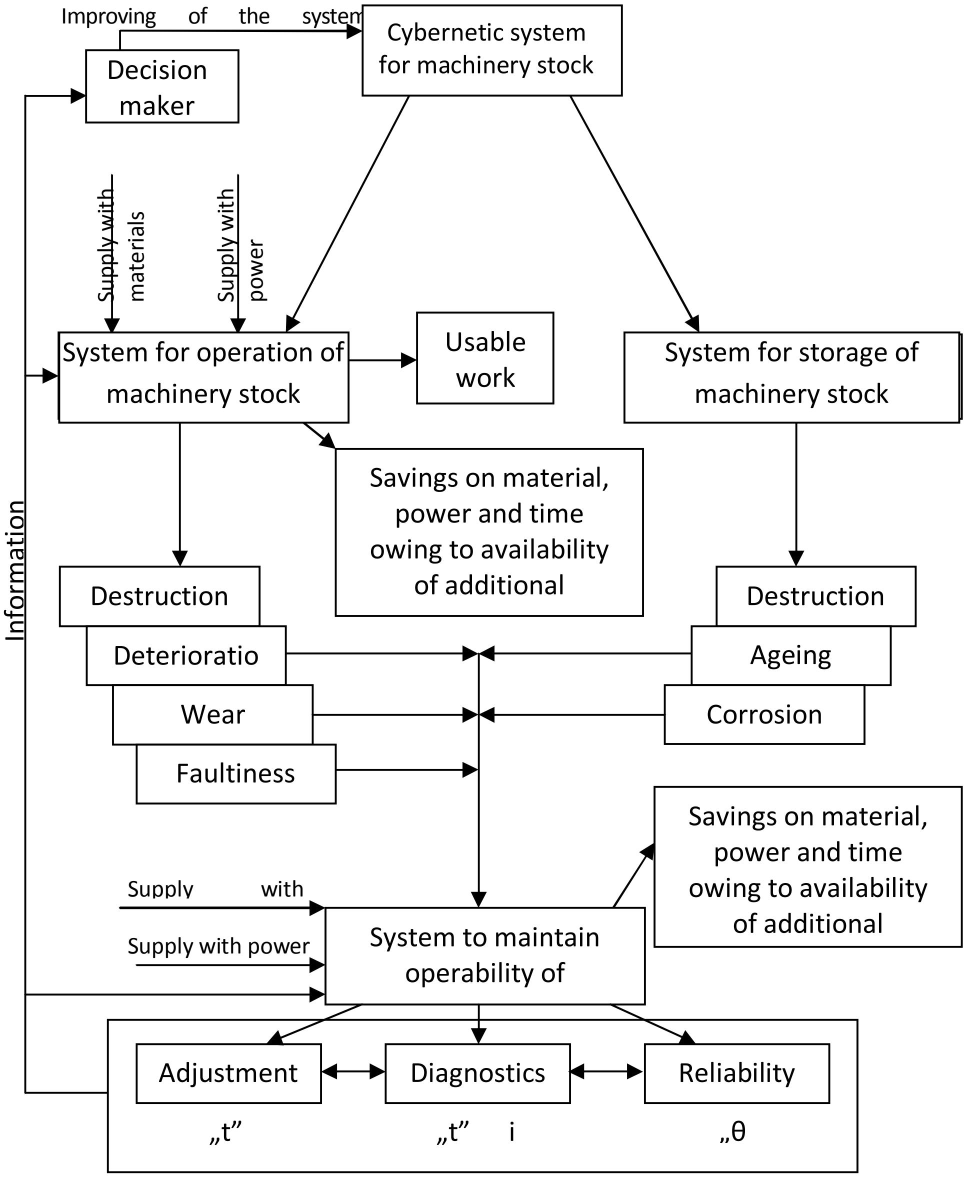

Fig. 1 Major components of a system dedicated to handle the machinery stock: t – passing time (the time by Newton), θ – operation time (time by Bergson)

2. Operational examination of turbine engines

Turbine reactive engines (Fig. 2) represent non-uniform (due to their physical properties) and very sophisticated technical facilities that involve high-tech procedures of manufacturing, overhauls, operation and maintenance. It is why the process of operational examination of such engines and then the process of tuning of them is really difficult (huge number of various adjustment controls) and must be carried out strictly in accordance with maintenance manual developed by the engine manufacturer and with use of specialized instrumentation and tools, i.e. facilitates that are purposefully dedicated to carry out all the maintenance operations: special tools, measuring instruments, measuring equipment, recorders and computers.

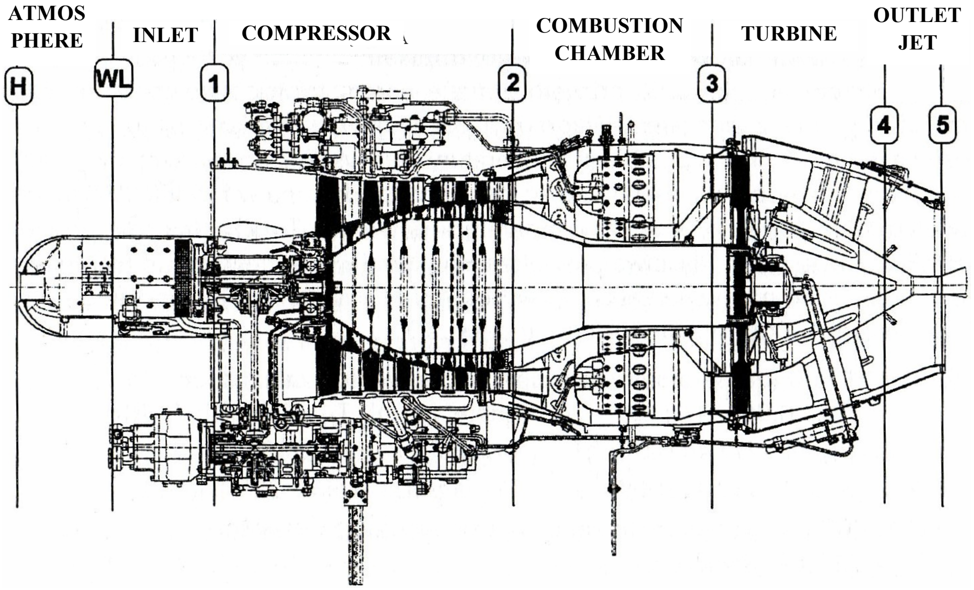

Fig. 2 Operation diagram of a reactive engine: H, WI, 1, 2, 3, 4, 5 – cross-section of the engine [2].

The examination process consists in recording of signals from automation (adjustment) systems of the engine: input, output and auxiliary ones. Full set of recorded signals from automatic systems of avionic reactive engine (K-15) is listed in Table 1 with waveforms of recorded signals plotted in Fig. 3 and Fig. 4 [12, 13].

Waveforms of signals obtained from automation systems of the engine for various operation ranges (which is associated with the recording time) serve as a basis to assess its level of dependability.

Table 1. List of signals from automatic (adjustment) systems that are used for operational examination of the K-15 engine

DProb [kG/cm^2]	16	Differential pressure of fuel in the engine
DSS [deg]	8	Position of the engine control lever
N [% Pm]	16	Rotation speed of the engine overhead shaft
PC2 [atm]	64	Absolute air pressure downstream the compressor
PC4[atm]	8	Pressure of gases across the inlet nozzle of the engine
T4 [Cels]	16	Temperature of the exhaust gas downstream the turbine
WIBR [m/s]	32	Level of crosswise vibrations of the engine
TH	8	Ambient temperature
		and the following set of binary signals
DProb	16	Flow of fuel to the motor
SMCO	8	Low oil pressure in the engine
SMCP	8	Low pressure of fuel supplied to the engine
SZFP	8	Fuel filter contaminated (clogged)
UALUP	16	Air bleeding valve in on
UROZ	16	Valve of start-up fuel (turbo mode) is on

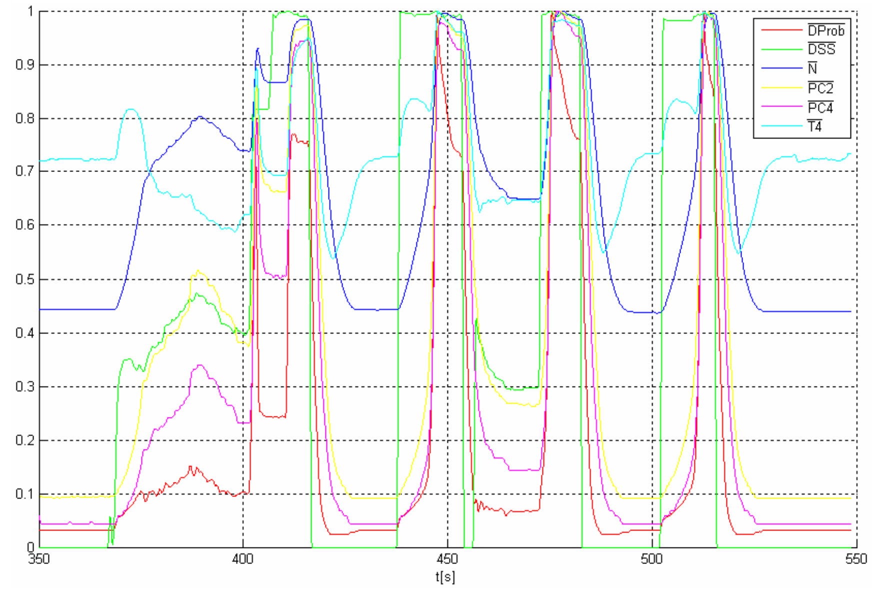

Fig. 3 Waveforms for control signals of the engine
(recording time of the signals 350 – 550 [s])

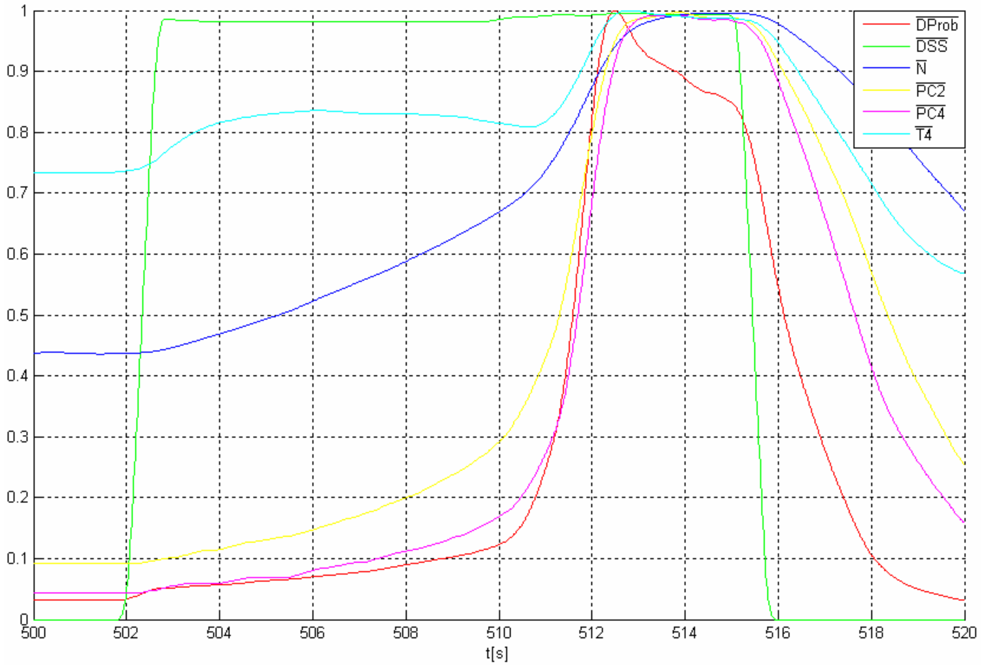

Fig. 4 Waveforms for control signals of the engine (recording time of the signals 500 – 520 [s])

3. Methods for analysis of signals from automation (adjustment) systems of the engine

3.1. Direct method – visual inspection

This method consists in direct visual observation and assessment of waveforms for major signals obtained from automation systems associated with operation of the engine [4, 10]. For the case considered, the signals listed in Table 1 are subjected to successive analysis. The method is based on reference waveforms (curves) already recorded for the major signals of the engine automation and stored separately for the engine in sound operating condition and for the engine with typical defects. The essence of this method is included in visual and direct comparison between waveforms currently recorded during operational examinations and the reference signals stored for both defect-free engine and for the engine with typical defects. It is the method that abstains from deterministic examination of the relationship between the signal curves (e.g. $n=f(m_p)$, *etc.*), although such examination is required by the rules of automatic processes. The encountered difficulties associated with this method (it requires to record reference signals for defect-free engine and for typical defects) gave the reason to seek for new and better methods to analyze signals obtained from automation (adjustment) systems of the engine.

3.2. The method based on the impulse and step responses of the engine

This method is based on the analysis of the impulse and step responses calculated for various mathematical models (transmittances) of the engine. The adopted models define relationships between appropriately selected signals, where the selection is approved by an expert [1, 5, 14, 16].
For the case in question it is necessary to examine relationships between the following signals: N=f(DProb); N=f(PC4); T4=f(DProb); T4=f(PC4); PC2=f(N) and additionally DProb=f(DSS).
The necessary characteristic curves are determined from respective transmittances that bind together the following signals from the automatic system:

$$G_1 = \frac{N(s)}{DProb(s)};\ G_2 = \frac{N(s)}{PC4(s)};\ G_3 = \frac{T4(s)}{DProb(s)};\ G_4 = \frac{T4(s)}{PC4(s)};\ G_5 = \frac{PC2(s)}{N(s)};\ \text{etc.,}$$

On the other hand the necessary transmittances are calculated after previous determination of the transform for the recorded signals from the automatic systems, where the calculations are carried out on the basis of the original waveform for the considered automation signal for various ranges of the motor operation (objects with insignificant deviations from linearity were modelled by means of several linear objects).
It may be particularly interesting to consider the relation between the signal from the N input and the PC2 output (rotation speed and pressure downstream the compressor) [7, 8, 10]. That interdependence can be determined from the already recorded waveforms for these signals and may enable assessment of operation stability (pumping efficiency) of the gasodynamic channel of the engine. For instance, from the waveform curves presented in Fig. 2 for the recording time 500 ÷ 520 [s] one can find out that respective transorms PC2 and N amount to:

$$PC2(s) = \frac{k_P}{s(T_{2P}^2 s^2 + T_{1P} s + 1)} \tag{1}$$

$$N(s) = \frac{k_N}{s(T_{2N}^2 s^2 + T_{1N} s + 1)} \tag{2}$$

or, after rough approximation (case 1):

$$PC2(s)=\frac{k_P}{s(sT_{OP}+1)(sT_{ZP}+1)} \tag{3}$$

$$N(s)=\frac{k_N}{s(sT_{ON}+1)(T_{ZN}+1)} \tag{4}$$

or (case 2):

$$PC2(s)=\frac{1}{s}e^{-T_{OP}s}\frac{k_P}{sT_{ZP}+1} \tag{5}$$

$$N(s)=\frac{1}{s}e^{-T_{ON}s}\frac{k_N}{sT_{ZN}+1} \tag{6}$$

as well as (case 3):

$$PC2(s)=\frac{k_P}{s}\left(\frac{1}{sT_{ZP}(sT_{OP}+1)}-\frac{1}{sT_{ZP}}e^{-(T_{ZP}+T_{OP})s}\right) \tag{7}$$

$$N(s)=\frac{k_N}{s}\left(\frac{1}{sT_{ZN}(sT_{ON}+1)}-\frac{1}{sT_{ZN}}e^{-(T_{ZN}+T_{ON})s}\right) \tag{8}$$

In the first case the waveform curves are defined with use of transformers for step responses attributable for a two-inertia module, for the second case the responses are associated with serial connection of a delay and an inertia module, whilst in the third case the responses reflect parallel connection of a real integrating module and an integrating module with a delay.
Parameters k_P, k_N, T_{ON}, T_{ZN}, T_{OP}, T_{ZP} are calculated directly from curves in Fig. 4 and amount respectively to: k_P=0.9, k_N=0.58, T_{ON}=7.5 s, T_{ZN}=4.1 s, T_{OP}=9.3 s, T_{ZP}=2.0 s.

Transmittances that determine interrelationships between the signals PC2(s) and N(s) for various degrees of approximation (cases 1÷3) are equal to:

$$G_{5(1)}=\frac{PC2(s)}{N(s)}=\frac{k_P(sT_{ON}+1)(sT_{ZN}+1)}{k_N(sT_{OP}+1)(sT_{ZP}+1)} \tag{9}$$

$$G_{5(2)}=\frac{PC2(s)}{N(s)}=\frac{k_P}{k_N}e^{-(T_{ZP}+T_{OP})s}\frac{sT_{ZN}+1}{sT_{ZP}+1} \tag{10}$$

$$G_{5(3)}=\frac{PC2(s)}{N(s)}=\frac{k_P}{k_N}\frac{T_{ZN}}{T_{ZP}}\frac{1-e^{-(T_{ZP}+T_{OP})s}}{1-e^{-(T_{ZN}+T_{ON})s}} \tag{11}$$

Quality of interrelationships between signals PC2 and N, to which the attention is drawn for the second time, can be evaluated exclusively on the basis of determined characteristic curves calculated from transmittances $G_{5(1)}$, $G_{5(2)}$, $G_{5(3)}$. Step and impulse responses of the engine determined from transmittances 9, 10, 11 are shown in Fig. 5.

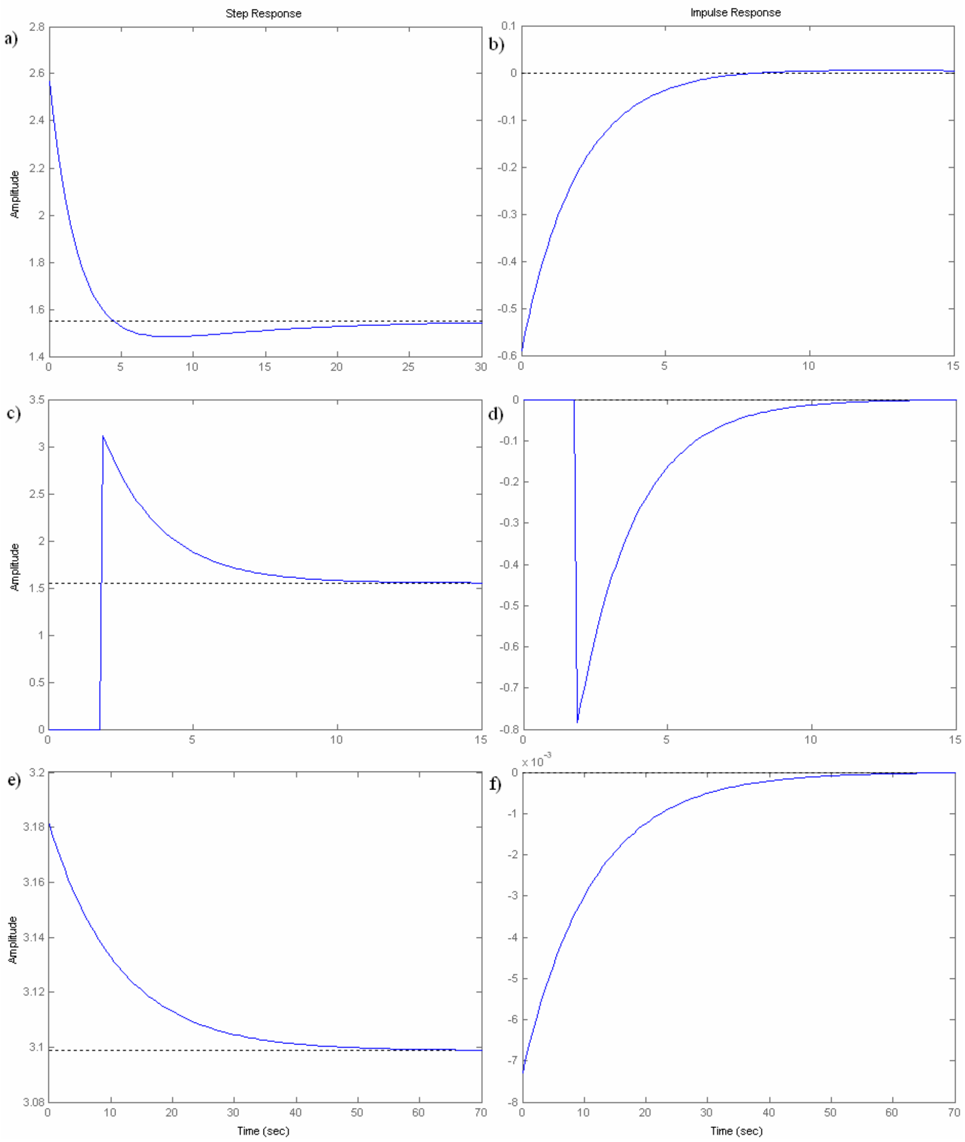

Fig. 5 a) step response of the transmittance $G_{5(1)}(s)$; b) impulse response of the transmittance $G_{5(1)}(s)$; c) step response of the transmittance $G_{5(2)}(s)$; d) impulse response of the transmittance $G_{5(2)}(s)$; e) step response of the transmittance $G_{5(3)}(s)$; f) impulse response of the transmittance $G_{5(3)}(s)$;

The analysis of the plotted characteristic curves (Fig. 5) leads to the conclusion that the examined interrelationship between the signals PC2 and N is really sophisticated, with pretty long time of transition processes until the signal values get steady. Also the effect of a ‘shot’ is significant. Occurrence of the shot effect is followed by a disadvantageous phenomenon when the signal value drops down below the value for the stationary state (‘mushing’). All the foregoing findings make it possible to formulate the conclusion that the examined engine is sensitive to instable operation (‘pumping’ effect).

The discussed method is closely associated with dynamic characteristics of the engine and ambiguous interpretation of the same in accordance with the rules applicable to the automation theory of linear circuits [1, 5, 14].

The drawback of this method is the fact that it allows consideration of only sequential pairs of signals as well as the restriction that the considered system must be transformed to linear circuits.

3.3. The method based on the phase trajectory

This method consists in comprehensive analysis of the phase trajectory recorded for the engine and then application of the Lyapunov’s theory. This analysis is intended to match usable (output) signals with the power supply signals that can be expressed by Lyapunov functions.

In general, phase trajectories enable synthetic analysis of dynamic properties demonstrated by ongoing processes, the processes themselves and its environment as well as its energy balance, when the second Lyapunov method is applied. Probably the abovementioned facts have served as the reason why the phase trajectories were frequently used for stability examination of avionic engines [3, 10,16].

Phase trajectories are determined on the basis of status equations:

$$\frac{d\overline{x}}{dt} = a\overline{x} + b\overline{u} \tag{12}$$

In case of systems with built-in self-adjustment the above equation can be reduced to the following form [10, 14]:

$$\frac{d\overline{e}}{dt} = f\left(\overline{e}\right) \tag{13}$$

where: $\overline{e}$ - the signal that results from tripping of the self-adjustment system (output signal) within the system environment (input signal).

When to analyze relationships between the input signal N and the output signal of the self-adjustment system $P2$ of the engine, the following equation is obtained on the basis of (G_5):

$$\bar{e} = \overline{P2} - \bar{N} = \bar{P}_o \tag{14}$$

where additionally: $\overline{P_0}$ – the integral of the simplified differential equation [10, 14]. Then the status equation adopts the form:

$$\frac{d(\overline{P2}-\bar{N})}{dt} = f(\overline{P2}-\bar{N}) \quad \text{or} \quad \frac{d(\overline{P_0})}{dt} = f(\overline{P_0}) \tag{15}$$

Therefore the phase trajectory can be found out directly from normalized transient input waveforms P2 and N (Fig. 4). The waveform curves $\overline{P2}$, $\bar{N}$, $\overline{P2} - \bar{N}, d(\overline{P2} - \bar{N})/dt$, are shown in Fig. 6 whereas the normalized curves $\overline{P2} - \bar{N}$ and $d(\overline{P2} - \bar{N})/dt$ - in Fig. 7. The phase trajectory (Fig. 8) can be derived directly from the waveform curves in Fig. 7.

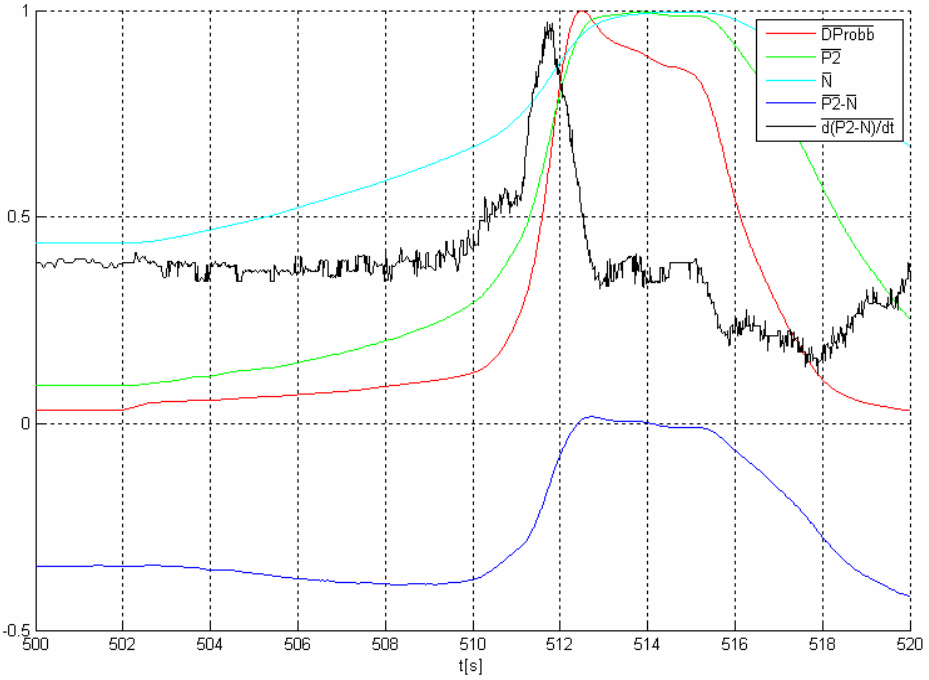

Fig. 6. Waveforms for the self-adjustment signals determined during the engine test time of 500 ÷ 520 [s]

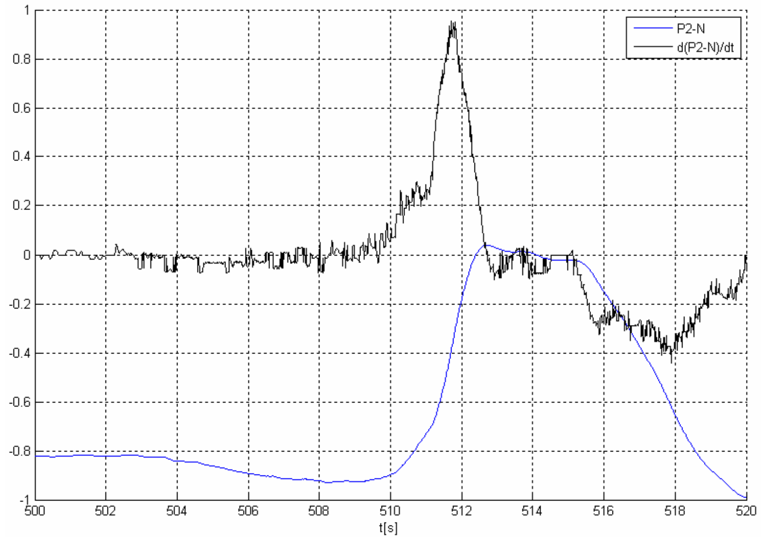

Fig. 7 Curves for synthetic signals of the motor self-adjustment

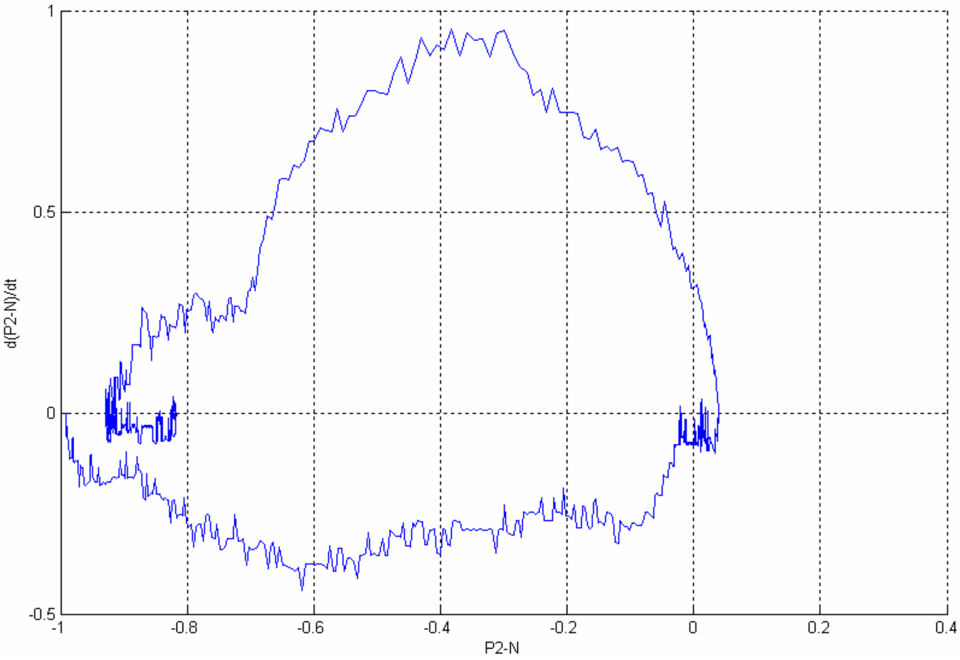

Fig. 8. The phase trajectory determined during the engine test time of 500 ÷ 520 [s]

The phase trajectory from Fig. 8 fails to meet expectations of the people who deal with technical maintenance of the engine as it is not sufficiently informative. Its interpretation and explanation requires a high level of technical expertise on automatic control. It binds only two signals, namely $\overline{P2}$ and $\overline{N}$, which is not a significant progress as compared to the previous method of signal analysis based on deterministic characteristic curves. However, the phase trajectory can be supplemented with necessary descriptions and additional information that are specific for the completed experiment (engine test).

Waveform curves from Fig. 6 have been modified to the more convenient form (Fig. 9).

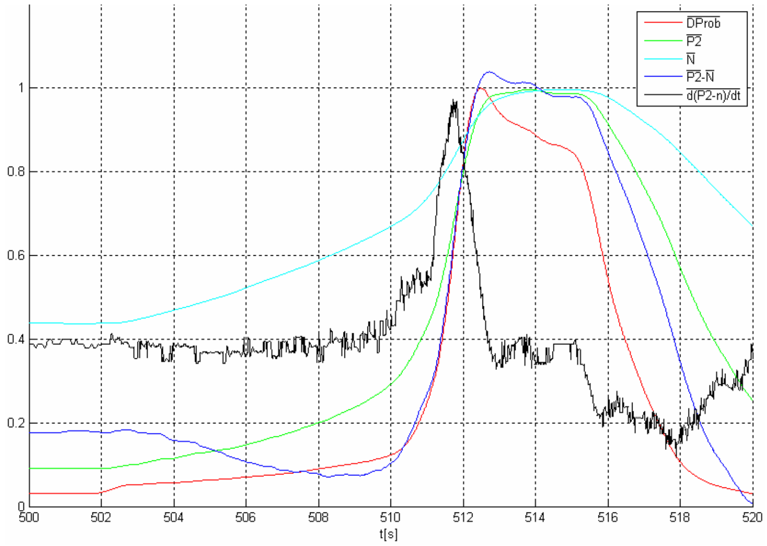

Fig. 9 Normalized waveform curves for signals: $\overline{\mathbf{DProb}}, \overline{\mathbf{P2}}, \overline{\mathbf{N}}, \overline{\mathbf{P2\text{-}N}}, \overline{\mathbf{d(P2\text{-}N\text{-}n)/dt}}$

The signal $P_0 = P2 - N$ has been transformed to its normalized value (Fig. 9)

$$\overline{P}_0 = \frac{P_0}{P_{0\max}} \tag{16}$$

And then, after introduction of status variables X_1 and X_2:

$$X_1 = \overline{P}_0 \quad \text{and} \quad X_2 = \dot{\overline{P}}_0 \tag{17}$$

as well as the Lyapunov function $V(X_1, X_2)$:

$$V\left(X_1, X_2\right) = X_1^2 + X_2^2 \tag{18}$$

finally, the phase portrait can be obtained (Fig. 10)

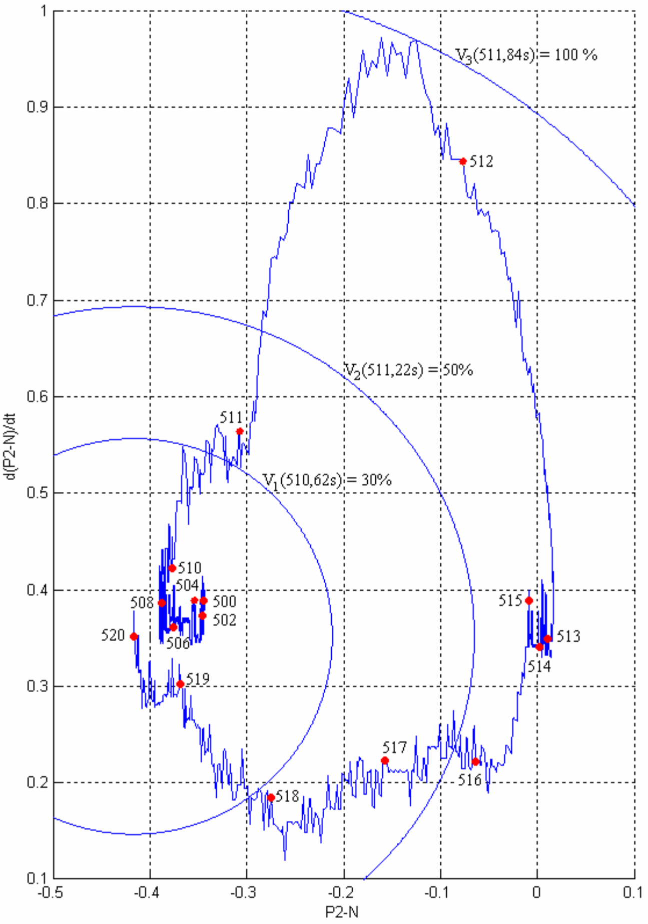

Fig. 10. The phase portrait for the system of engine self-adjustment. V(X_1 , X_2) – Lyapunov function

Values of the Lyapunov functions V_1, V_2, V_3 express the status of the system energy in quantitative terms for subsequent moments of the time t_1, t_2, t_3 and are developed on the basis of the waveform curve of the normalized signal DProb (Fig. 9). The phase portrait provides full information about the engine behaviour as it allows to analyze movements of the status vector (e.g. from the moment of 510 s up to 512 s, and then to 514 s). Further examinations may refer to the areas where the trajectory intersects individual levels of energy status as well as makes it possible to evaluate differences between theoretical status of energy [V(X_1,X_2)] and its actual value [V(DProb)]. Finally one can state that the phase portrait (Fig. 10) offers the opportunity of synthetic analysis of the process associated with operation of the gasodynamic channel of avionic engines with consideration of power supply from outside. The determined phase portrait indicates insufficiently smooth operation of the engine during transition via various levels of energy status.

Conclusions

The operational examinations of avionic motors are carried out during land-based tests of the engine and during its regular operation. They involve recording of major signals produced by the system of the engine automation and crucial for quality of its operation. The paper brings the evidence that the dependability of motors can be reliably assessed on the basis of the impulse response, the step response and the phase trajectory, whereas these characteristic functions can be found out either indirectly (the impulse and phase response) or directly (the phase trajectory) from the recorded signals from the automatic control (adjustment) system. The fact that the phase trajectory can be directly derived from the signal waveforms makes that method of operational examinations particularly suitable for the sophisticated process intended to evaluate dependability of avionic engines. The proposed method is really universal and can be applied to both linear and non-linear systems.

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