JOURNAL OF THEORETICAL
AND APPLIED MECHANICS
50, 4, pp. 913-921, Warsaw 2012
50th Anniversary of JTAM

PHASE MAPPING IN THE DIAGNOSING OF A TURBOJET ENGINE

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This paper describes possibilities of using the phase portrait for the diagnosis of the turbojet engine AŁ-21F3 type. Attention is paid to description of the theoretical basis of application of this method to identify the engine fuel system. The identification of the engine fuel system was conducted for each operating adjusting point according to the mono-selection 3r plan with variable data sampling period with a frequency equal to a constant submultiple of the engine rotation frequency. It is explained how the settings of the operational control of the AŁ-23F3 engine fuel system influence the shape of the phase characteristics of engine rotation speed. Additionally, the location of the phase portrait distinctive points is determined. Moreover, there are shown examples of phase portraits for selected ranges of engine operation. It is shown, as an example of using the phase mapping, the ability to monitor parameters of the automatic engine start up using the adjusting machine screw of the altitude corrector of the start-up automaton and changes of the diameter of the start-up automaton nozzle. It is also shown that the qualitative analysis of the adjustment of specific ranges of engine operation is sufficient to determine the influence of the individual adjusting points for those operating ranges.

Key words: aircraft engine diagnostics, phase mapping of engine parameters

1. Introduction

The presentation of solutions of the systems of linear and nonlinear equations on the plane with coordinates $(x : dx/dt)$ gives the so-called phase trajectory, when the list of families of solutions (trajectories) at different initial conditions creates a phase portrait of the system. Each point of a phase plane corresponds to a certain state of the system. Thus, phase portrait are a graphical way to illustrate the dynamic features of either the first or second rank linear and nonlinear objects.

The method of phase portrait in application for the diagnosis of turbine engines is based on the following assumptions and inference rule:

a) assumptions:
   - analysis of the technical state of the object is performed with a minimum number of observers/key parameters of the process
   - mapping of the instantaneous operating parameters of the object in the state space is limited by the defined vector of the state

b) inference rule (Kowalski, 2009; Kowalski *et al.*, 2000)

$$\forall i \in (1,2,\dots,m) \quad \mathbf{CV} = \Big[Par_i, \frac{dPar_i}{dt}, \frac{d^2 Par_i}{dt^2}\Big] \in \mathrm{TS} \;\Rightarrow\; \text{OBJECT EXPLOITABLE}$$

where **CV** is the state vector, TS – technical specifications, Par_i – i-th parameter of the state of the engine, m – number of diagnosed parameters.

It can be concluded that the phase portrait method allows detection of the hidden malfunction of the object and allows one to analyse its operation in actual working conditions.

In the diagnosing process of the state of the object, using the method of phase portrait is essential to select the adequate observer (parameter) of its operational state. This parameter for a turbojet engine is its rotation speed which is the primary output parameter in the assumed engine fuel system (Fig. 1).

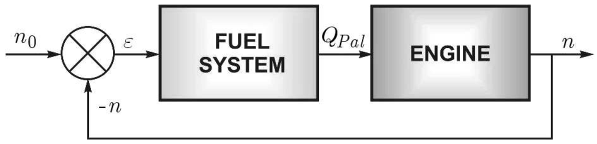

Fig. 1. Assumed model of the fuel system of the AŁ-21F3engine

The transfer function $G(s)$ of the jet engine can be described by the following relation (Kowalski, 2011; Orkisz, 1995)

$$G(s) = \frac{G_{UP}(s)Q_{TSO}(s)}{1 + G_{UP}(s)Q_{TSO}(s)} \tag{1.1}$$

where $G_{UP}(s)$ is the transfer function of the fuel system, $Q_{TSO}(s)$ – transfer function of the engine.

The fuel system of the jet engine AŁ-21F3 as the object of identification is described by the set of equations (Szczepanik *et al.*, 2003

$$\begin{aligned} Q_{Pal} &= [G_{UP1}, G_{UP2}, \ldots, G_{UPZ}]_Z \begin{bmatrix} U_1 \\ U_2 \\ \vdots \\ U_Z \end{bmatrix}_Z \\ \begin{bmatrix} G_{UP1} \\ \vdots \\ G_{UPZ} \end{bmatrix}_Z &= \begin{bmatrix} Q_{11} & \cdots & Q_{1R} \\ \vdots & \vdots & \vdots \\ Q_{Z1} & \cdots & Q_{ZR} \end{bmatrix}_{R,Z} \begin{bmatrix} S_1 \\ \vdots \\ S_R \end{bmatrix}_R \end{aligned} \tag{1.2}$$

where: Q_{Pal} is tge fuel expense, $\mathbf{G}_{UP}$ – matrix function (technical condition) of the fuel system, $\mathbf{U}$ – matrix of thermodynamical parameters of the engine (control and feedback signals) – of technical condition of the engine, $\mathbf{Q}$ – matrix of the structure of the fuel system, $\mathbf{S}$ – matrix of elements of the adjustment of the structure of the fuel system (of identification of causes of the incompatibility), Z, R – ID badge of the dimension of the matrix (matrix size).

The diagnosing of AŁ- 21F3 engine with using the phase portrait consists in determining the unanimity of the value of elements of the matrix $\mathbf{G}_{UP}$, $\mathbf{U}$ and $\mathbf{S}$ with their standard values determined earlier for the engine in working order.

2. Identification of distingtive points of the phase portrait

The described above method was used to test the fuel system of the turbojet engine AŁ-21F3 type exploited in Su-22 aircraft. The objective was to determine the effect of setting operational adjustments of the engine fuel system on:

- shape of phase characteristics of the engine rotation speed
- location of distinctive points of the phase portrait.

The adjustments of all units of the engine fuel installation were set according to technical specifications (TC) for this type of engine during the first engine test. The waveforms were recorded while testing. Then, based on recorded waveforms, the level of interference contributed by the measuring track at the re-modulation of the rotation speed of the transmitter PME and by the torsional vibration of the lay-shaft and by the backlash of gearing was examined. There is a phase portrait based on data taken from the conducted engine test (Fig. 2) and characteristic subranges of the engine operation shown, see Figs. 3-5 (in the figures, the rotation speed **n** is related to the real maximum value).

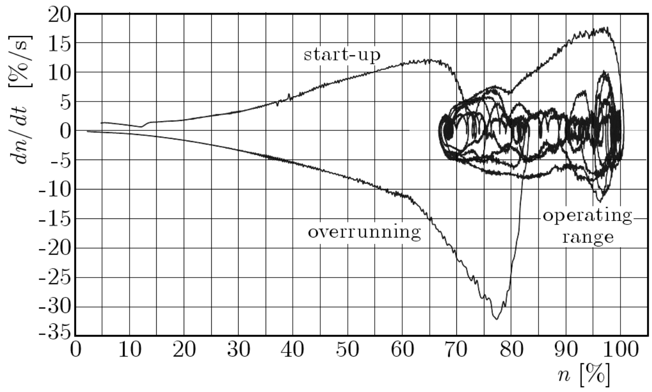

Fig. 2. Phase portrait of the rotation speed of AŁ-21F3 engine: start-up and operation range, overrunning

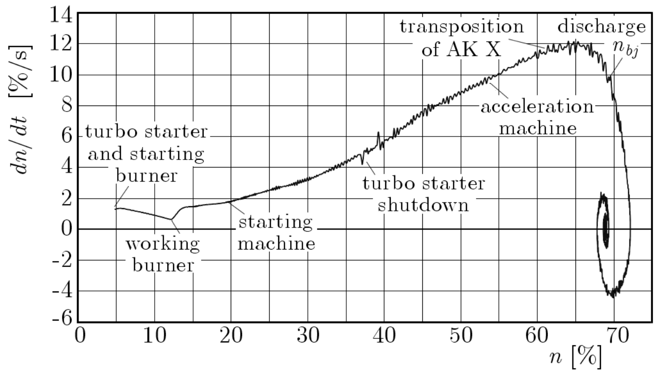

Fig. 3. Phase portrait of the rotation speed of AŁ-21F3 engine during its start-up (AK X-: compressor stator blades of the tenth stage of compressor)

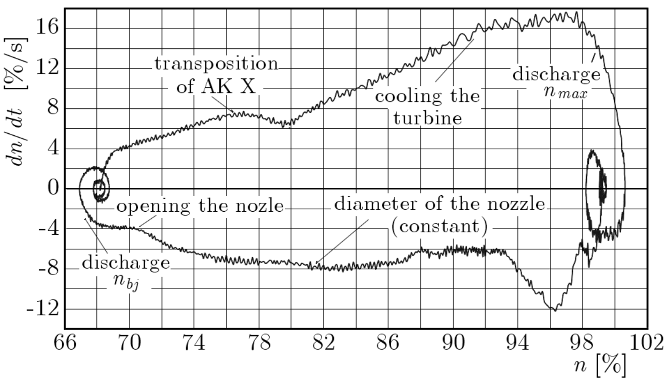

Fig. 4. Phase portrait of the rotation speed of AŁ-21F3 engine during its acceleration and deceleration

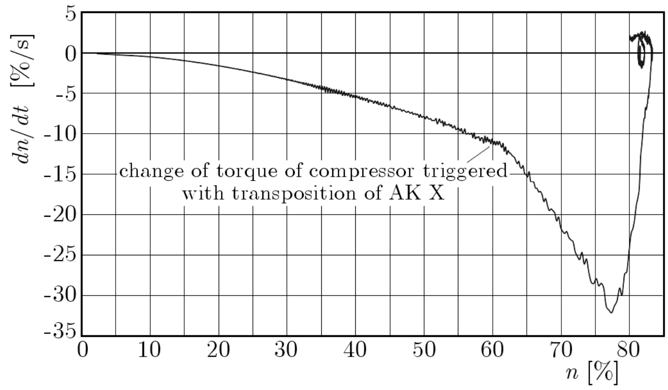

Fig. 5. Phase portrait of the rotation speed of AŁ-21F3 engine during its rotation speed overrunning

For the purpose of analysis of the distinctive points on phase portraits, the following phases of the engine operation were sorted out: start-up, acceleration, deceleration, afterburning, control SUNA (adjustable steering mechanism of the setting compressor stator blades), shutdown. Examples of partial phase portraits of the mentioned phases are presented in Figs. 3-5.

3. Example of monitoring of parameters of the engine automatic start up

An example of the way of adjustment of the automatic process of the engine start-up using the adjusting machine screw of the altitude corrector of the start-up automaton and diameter changes of the start-up automaton nozzle is shown in Fig. 6 (⑥, ⑪).

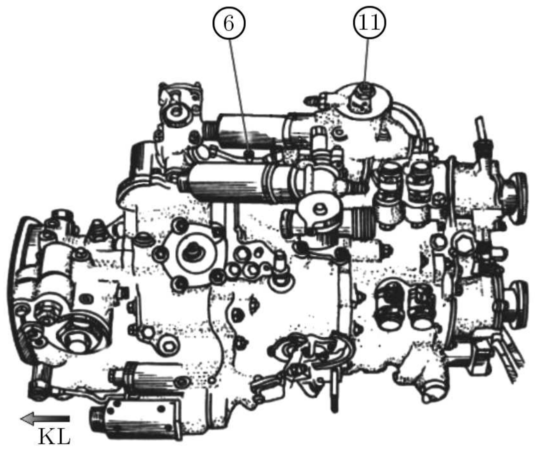

Fig. 6. NR-53D Unit – side view (left hand): 11 – adjusting machine screw of the altitude corrector of the star-up automaton (SA) and diameter changes of the start up automaton nozzle, 6 – p_2 output nozzle of the start-up automaton (SA) [5]

3.1. Adjustment of the altitude corrector of the engine start-up automaton

The regulation of the altitude corrector of the engine start up automaton consists in changing the fuel pressure during the dummy start-up (no fuel delivered).

The impact of such adjustment on changing the phase portrait shape during start-up phase is observed mainly in the middle phase of the start-up (Fig. 7). However, in the engine operating range represented by the process of acceleration and deceleration (Fig. 8) no significant impacts of the adjustment made at that point (altitude corrector) on the phase portrait shape care observed.

Slight differences in the shape of phase portraits, which are visible during deceleration, come out from differences in the way of engine control – pace of displacement of the engine control lever (ECL).

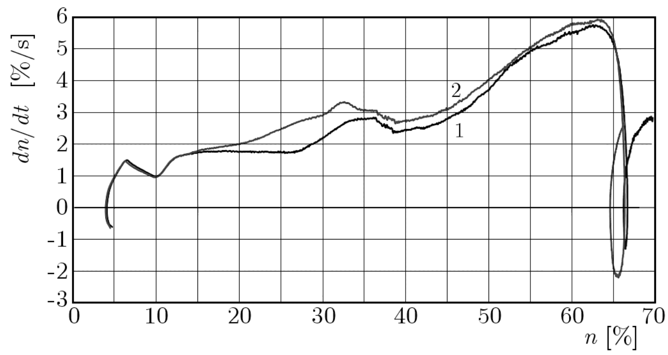

Fig. 7. Nature of changes in the shape of the phase portrait during AŁ-21F3 engine start-up as a result of adjusting fuel pressure at the start-up using screw 11: 1 – unscrewed by a half-turn, 2 – screwed by a half-turn

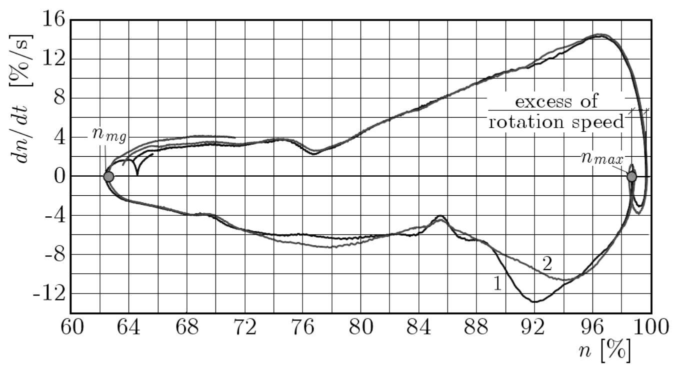

Fig. 8. Nature of changes in the shape of the phase portrait during AŁ-21F3 engine operating range as a result of adjusting the fuel pressure at the dummy start-up (no fuel delivered) using screw 1: 1 – unscrewed by a half-turn, 2 – screwed by a half-turn

3.2. Adjustment by changing the diameter of the nozzle of the start-up automaton

Changing the diameter of the nozzle of the start-up automaton (6) results in changing the air pressure at the inlet of the engine start-up automaton. That is a way to regulate the second phase of the engine automatic start-up process. It is the primary method of regulation of the length of the engine start-up period and excess of the temperature T_4 of the exhaust gas. The nozzles that are in use have diameters ranging from 0.8-3 mm. It was found that changing the nozzle diameter by 0.1 mm changes the start-up period of 1-2 s and the temperature T_4 drops by 15°C-20°C. The length of the engine start-up period is directly proportional to the diameter of the nozzle. While the excess of the exhaust gas temperature is inversely proportional to the diameter of the nozzle.

It was observed that increasing the diameter of nozzle (6) increases the growth of dynamics of the start-up process – rotation speed increases faster while the length of the start-up period decrease (Fig. 9). Analysis of the second derivative of the rotation speed shows that due to increased dynamics of the rotation speed growth, during the final start-up phase rapid slowing down occurs (too rapid dynamics of the increase of the rotation speed results in appearing of short considerable excess of the rotation speeding and extending time of its stabilization (Fig. 10).

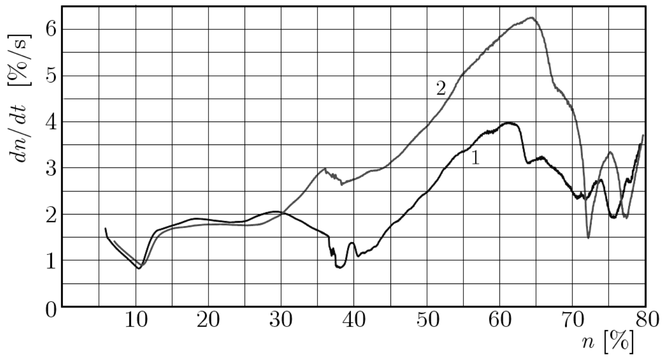

Fig. 9. Nature of changes in the shape of the phase portrait during AŁ-21F3 engine start-up the period by regulation of the nozzle of the start-up automaton: 1 – nozzle with diameter 0.9 mm, 2 – nozzle with diameter 2.6 mm

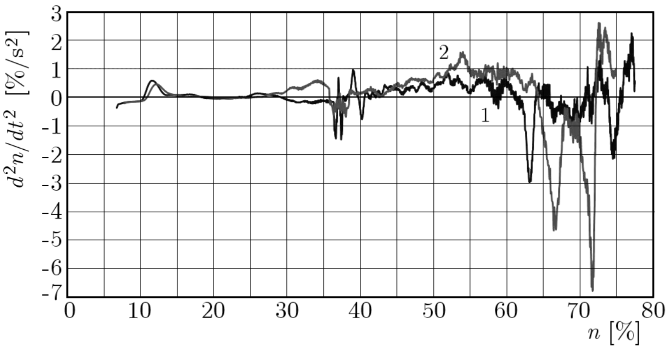

Fig. 10. Dynamics of the increase in the rotation speed of AŁ-21F3 engine during the start-up as a result of regulation of the nozzle of the start-up automaton: 1 – nozzle with diameter 0.9 mm, 2 – nozzle with diameter 2.6 mm

Figure 11 shows that within the engine working range, the adjustment made by the change of the nozzle diameter of the start-up automaton (6) slightly affects the shape of the phase portrait and mainly happens during the second phase of the acceleration.

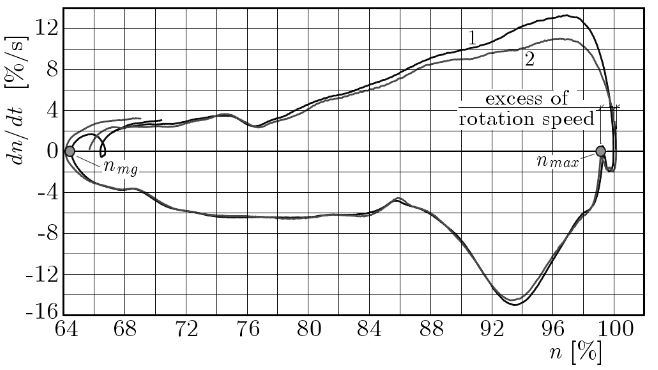

Fig. 11. Nature of changes in the shape of the phase portrait in the operating range of AŁ-21F3 engine by regulation of the nozzle of the start-up automaton: 1 – nozzle with diameter 0.9 mm, 2 – nozzle with diameter 2.6 mm

The conducted examinations allowed one to determine the impact of different kinds of adjustments on the shape of the phase portrait of the jet engine. For the qualitative analysis of the regulation of the start-up process, it is sufficient to point out the tendency of the influence of individual clauses of the adjustment – see Fig. 12 showing the difference between lines 1 and 2 in Fig. 7. The adjustment realised by machine screw (11) of the altitude corrector of the start-up automaton is effective only in the middle phase of the start-up period. However, taking into account the obtained engine acceleration records at the level lower than 0.8%/s, this method cannot be regarded as the primary method of the engine start-up process adjustment.

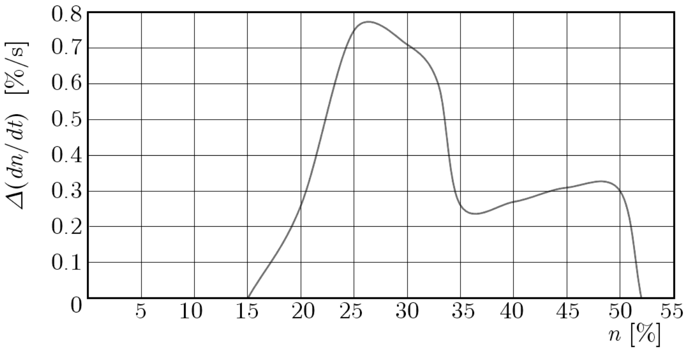

Fig. 12. Tendency of the impact of adjustment by the adjusting screw (11 – Fig. 6) of the adjusting machine screw of the altitude corrector of the start-up automaton on the shape of the phase portrait during the start-up phase

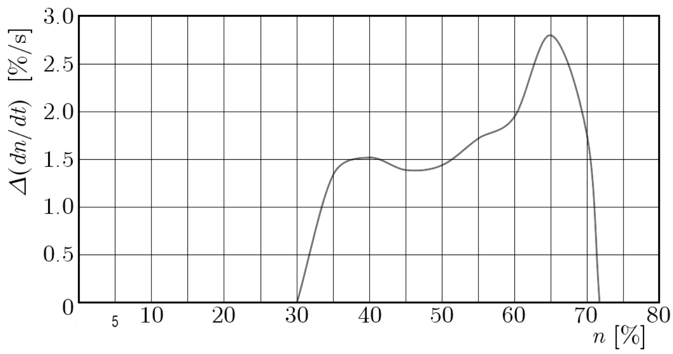

Fig. 13. Tendency of the impact of the adjustment by the nozzle (6 – Fig. 6) of the start-up automaton on the shape of the phase portrait during the start-up phase

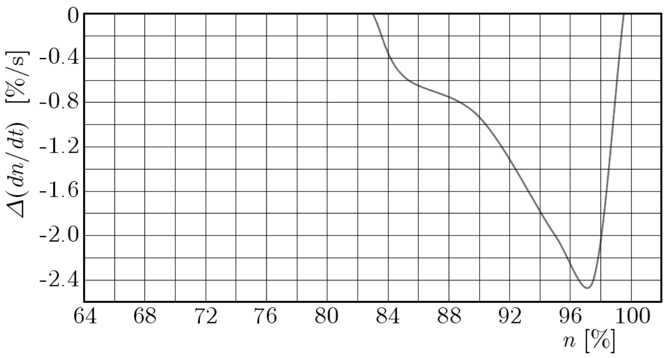

Fig. 14. Tendency of the impact of the adjustment by the nozzle (6 – Fig. 6) of the start-up automaton on the shape of the phase portrait during engine acceleration and deceleration

The impact of regulation by the start-up automaton nozzle on the shape of the phase portrait presents a somewhat different tendency. This way of adjustment has much higher efficiency, see Fig. 13 (the difference between lines 1 and 2 of Fig. 9). Besides, it is concluded that the regulation by the nozzle of the start-up automaton also affects the shape of the phase portrait in the operating range, causing a slight drop in the dynamical increase of the rotation speed during the final phase of the engine acceleration – Fig. 14 (the difference between lines 1 and 2 in Fig. 11). It must be therefore remembered that regulation which improves the start-up can affect the engine operation in other ranges of work, including the operating range. It shows that the adjustment of the start-up process by the start-up automaton nozzle changes the phase portraits in the engine operating range (during engine acceleration and deceleration). Therefore, any adjustment considered to be made in relation to the start-up process should result in an assessment regarding its impact on the engine operating parameters or other ranges of engine operation.

As the engine tests were performed only in reduced individual scopes of the adjustment, the aforementioned results have a fragmentary character.

In the framework of conducted examinations, applying similar to the described above methodology, analyses related to the adjustment of other engine parameters were carried out. These were as follow:

- rotation speed at which switching the position of the back group of compressor stator blades takes place
- rotation speed of the minimal range
- rotation speed of opening the segments of controllable nozzle
- maximum rotation speed of the engine
- maximum reduced rotation speed of the engine
- time of engine acceleration
- characteristics $\alpha_{ak} = f(n_{red})$
- rotation speed of disconnection of the turbine starter
- time of reducing the engine rotation speed
- value of excess of rotation speed and decreasing the engine rotation in transitional ranges
- diameter of the critical section of controllable nozzle on the hydraulic stand-by of RSF-53 aggregate at the arterial range
- diameter of the critical section of controllable nozzle on the hydraulic stand-by of RSF-53B aggregate at the afterburning range
- angle of transposition of the compressor stator blades when SUNA installation begins to operate.

The conducted examinations and analysis allowed one to determine the trends influencing almost all of the adjusting points of the tested engine on the obtained parameters of its work in various ranges of operation. This kind of characteristics is the basis for the development of methodology of adjustment of the engine fuel system of the turbojet engine AŁ-21F3 type during exploitation.

4. Conclusions

- The study allowed one to determine the effect of various ways of regulation of the fuel system of the turbojet engine AŁ-21F3 in the shape of the phase portrait of the rotation speed.
- The proposed method, through careful observation of the phase portrait shape, allows an unambiguous defining of the optimal way of the adjustment of the engine fuel subunits and their components, and to determine its efficiency and potential further exploitation.
- Implementation of this method in operational procedures for turbojet engines will verify and optimize a set of diagnostic signals essential for smooth exploitation of the engines. This calls for a series of tests on a statistically reliable population of such engines.

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Odwzorowanie fazowe w diagnozowaniu silnika turboodrzutowego

Streszczenie

W referacie przedstawiono możliwości wykorzystania portretu fazowego do diagnozowania turbinowych silników odrzutowych typu AŁ-21F3. Opisano podstawy teoretyczne zastosowania tej metody do identyfikacji układu paliwowego silnika. Identyfikację układu realizowano dla każdego punktu regulacji eksploatacyjnej, zgodnie z planem monoselekcyjnym 3r, ze zmiennym okresem próbkowania danych, z częstotliwością równą stałej podwielokrotności częstotliwości obrotowej silnika. Wykazano wpływ nastawy regulacji eksploatacyjnej układu paliwowego silnika AŁ-21F3 na kształt charakterystyk fazowych prędkości obrotowej. Określono położenie charakterystycznych punktów portretu fazowego. Przedstawiono przykłady portretów fazowych dla wybranych zakresów pracy silnika. Jako przykład zastosowania odwzorowania fazowego pokazano możliwość kontroli parametrów automatycznego uruchamiania silnika przy pomocy wkręta korektora wysokości automatu uruchamiania oraz zmiany średnicy dyszy automatu uruchamiania. Wykazano także, że do analizy jakościowej regulacji poszczególnych zakresów pracy silnika wystarczającym jest określenie wpływu poszczególnych punktów regulacyjnych na te zakresy pracy.

Manuscript received September 23, 2011; accepted for print November 23, 2011