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ANALYSIS OF DIAGNOSTIC INFORMATIVENESS OF THE EXHAUST TEMPERATURE OF A NAVAL GAS TURBINE

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Summary. This article deals with diagnostic technology of naval gas turbine engines based on exhaust temperature measurements. It contains a detailed discussion devoted unsteady thermal-flow processes worked out within the considered two and three-shaft engine in terms of emergency overloads in passages that might lead to failures occurrence of the engine blading. An automatic control subsystem protecting the engine against an excessive growth of the exhaust stream temperature during start-up and acceleration processes has been described in order to explain the main aims of simulating examinations conducted on the engine in current operation: evaluation of the borders for the exhaust temperature's tolerances and early detection of the control subsystem's damages threatening the engine's reliability.

1 INTRODUCTION

The exhaust stream temperature behind a combustion chamber represents a basic control parameter of a naval gas turbine which is measured while the engine runs on steady load as well as during engine's start-up and transient processes from one steady state to another (rotor units' acceleration and deceleration). It results from the conducted operation (diagnostic) investigations that this parameter, which is usually the arithmetical average of indications of circumferentially placed thermocouples, enables the user to determine places in which the largest energy losses of the engine's working processes occur. The exit of measuring (static and dynamic) values of exhaust stream temperature beyond the settled operational borders signals an inadmissible disturbance of energetic processes worked out in the engine, threatening with its breakdown (e.g. a compressor's surging phenomenon) [2,4,5,8]. It is also possible carrying out an identification and localisation of the well-known and recogniseable failures of components and elements of the engine's passages as well as fuel fed system of the combustion chamber during current operation.

2 MEASUREMENTS OF EXHAUST STREAM TEMPERATURE

Measurements of the exhaust temperature in gas turbine operation, performed by means of thermocouples, are burdened with errors which result from the following factors:

- disorders in temperature field by the thermocouple,

- thermal inertia of the thermocouple's joint and cover,
- accelerated aging as well as the alterations of a chemical composition and physic-chemical properties of the thermocouple wire, under the influence of its usage in high temperatures (recrystallisation, oxygenation and diffusion in a superficial layer of wires in the vicinity of the thermocouple's measuring joint causes even several percent changes of thermoelectrical voltage after 1000 hours of the engine running) [9,10].

With regard to the significant nonstationarity of thermal-flow processes in the combustion chamber and resulting from that: pulsations of the flowing through exhaust stream as well as inequality of the circumferential distribution of the exhaust temperature in an outlet section of the combustion chamber, the averaged and selective exhaust temperature's measurements are carried out (it concerns serial engines) in the passage's control section situated in certain distance from the combustion chamber [9] - mostly, behind the gas generator (inlet section of the separate power turbine) – Figure 1. It goes without saying that a durability of the traditionally applied thermocouple is the most important operation feature and the higher the measured temperature is the bigger the thermocouple's durability gets [9,10].

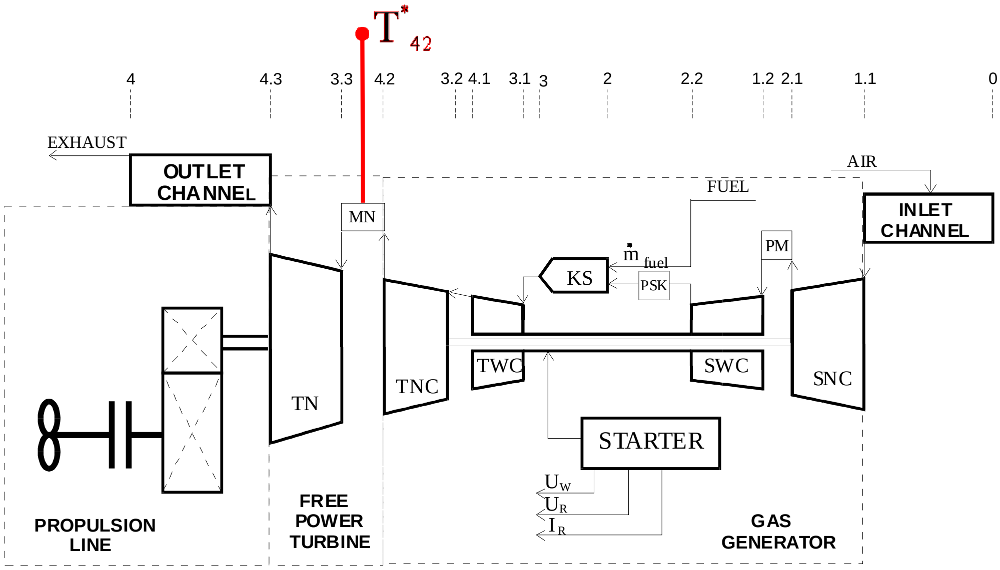

Figure 1: Schematic diagram of naval gas turbine along with marked control intersection where the exhaust temperature is measured - behind the gas generator T^*_{42}
SNC, SWC – respectively: low presssure and high pressure compressor, TNC, TWC, TN – respectively: low presssure and high pressure turbine and power turbine, KS – combustion chamber, MN – gas space between the gas generator and power turbine with a reverse device, PM – intercompressor space, PSK – gas space between the high pressure compressor and combustion chamber,

2.1 Engine’s start-up and acceleration processes

A gas turbine engine starting is viewed an unsteady process which aimed to drive the engine's rotor units from a standstill to the idle rotational speed. It mainly characterizes with largest alterations of the parameters' values of the worked out energetic processes. During only just several seconds the passages' constructional elements are subject to strong thermal loads, along with temporary increases of the inflowing exhaust temperature achieving 60-70 K/s – Figure 2. An excessive increase of the exhaust temperature might result from a deterioration of the passages technical shape or might be a consequence of the malfunctions within automatic control system of the engine's start-up (air and fuel fed stream controlling) [4,9].

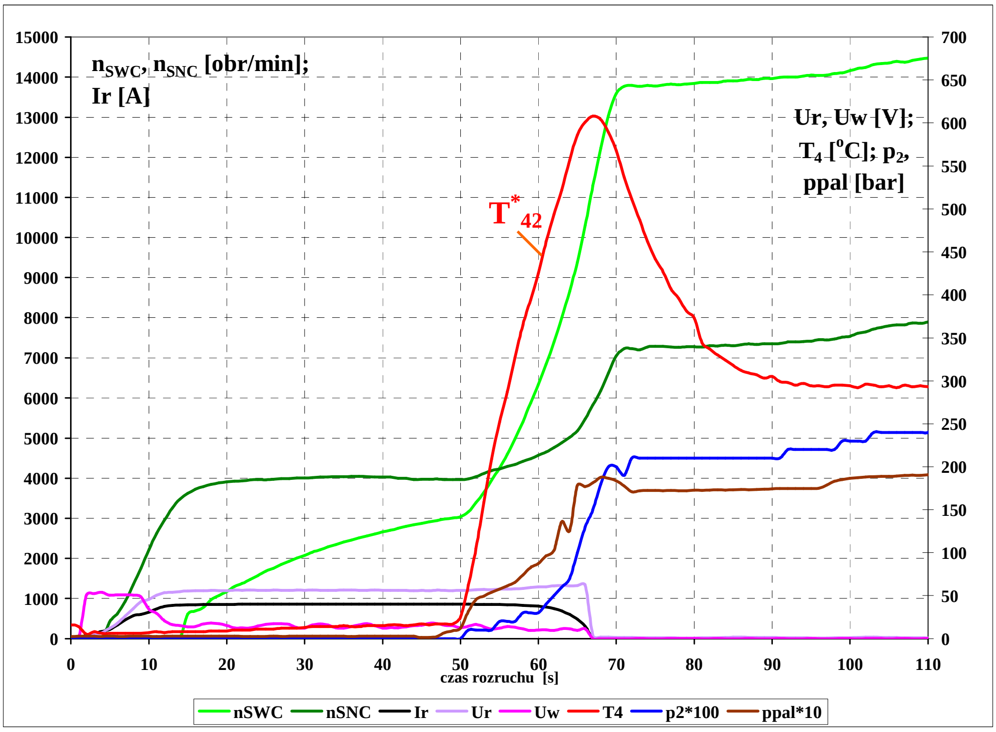

Figure 2: Time courses of the start-up control parameters of a three shaft engine with free power turbine in terms of duration of a start-up process
nSWC, nSNC - respectively: high pressure and low pressure compressor’s rotational speed, Ir, Ur, Uw – respectively: starting current and voltage as well as field voltage, T4 (T^*_{42}) – exhaust temperature behind the gas generator, p2 – pressure behind the high pressure compressor, ppal – fuel pressure.

Selective time courses of the exhaust temperature measured behind the low pressure turbine (behind the gas generator) in terms of duration of a start-up process are shown in Figure 3. The courses were registered for a five year operation period of the three shaft engine with free power turbine on the vessel. A characteristic trend of the continuous increase of a time derivative's value of the exhaust temperature in terms of flowing off the operation time was observed. Line courses in the figure show that because of deterioration of the passages technical state (it was confirmed by systematically executed endoscopic investigations [6]) an increase of the exhaust temperature reached the border value in which the automatic control system broke the start-up process, protecting the engine against the serious damage (point A on curve 4). The possibility of an excessive deviation of the co-operation line on the compressor's profile from the optimum line and the entry into a zone of the compressor's unstable work (surging phenomenon) represents the additional threat for the reliability of an engine being started-up [5].

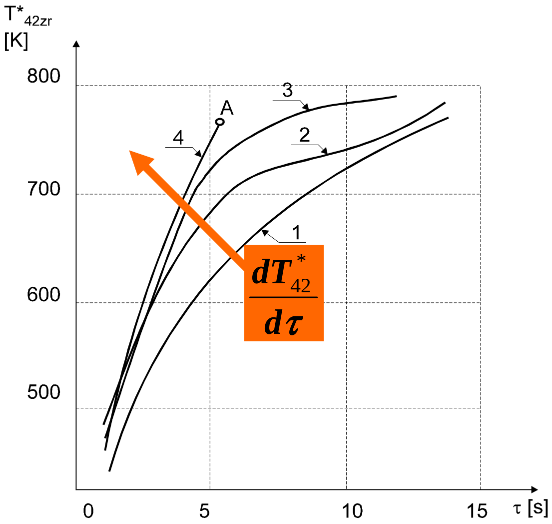

Figure 3: Time courses of the exhaust stream temperature behind TNC of a three shaft engine with free power turbine in terms of duration of a start-up process: 1 – brand new engine; 2 – engine in the fourth year of operation; 3 - engine after five years of operation; 4 – unsuccessful engine’s start-up after five years of operation; A – the engine’s self-acting lay-off process.

An associated profile of the compressor-combustion chamber-turbine arrangement presented in Figure 4 reflects graphic interpretation of both the undesirable phenomena. Hypothetic courses of the co-operation lines during performing the engine's start-up process were plotted on the profile. In such a situation a displacement of the arrangement co-operation points from the optimum line in steady states towards the surging line occurs. It represents lines 2 and 2' in Figure 4. A surge margin of the compressor gets lower, and it is defined as:

$$\Delta Z_s = (Z_s - 1)100\% \qquad (1)$$

where:

$$Z_s = \frac{(\pi_S / \dot{m})_{gr}}{(\pi_S / \dot{m})_p} \qquad (2)$$

where: Z_s – coefficient of the compressor’s surge margin;

$(\pi_S / \dot{m})_{gr}$ - relation of the compression ratio to the mass flow rate of the working medium on the border of the compressor's surge line;

$(\pi_S / \dot{m})_p$ - relation of the compression ratio to the mass flow rate of the working medium during crossing the engine from the settled rotational speed of the electric turning to the steady idle rotational speed.

Decreasing the coefficient of the compressor’s surge margin below the value of 5% causes a tearing the boundary layer off on the convex profiles of the rotor blades as well as a pulsation of flowing through air stream [2]. Similar gasdynamic phenomena occur during the acceleration process the engine's rotor units from one steady load to another.

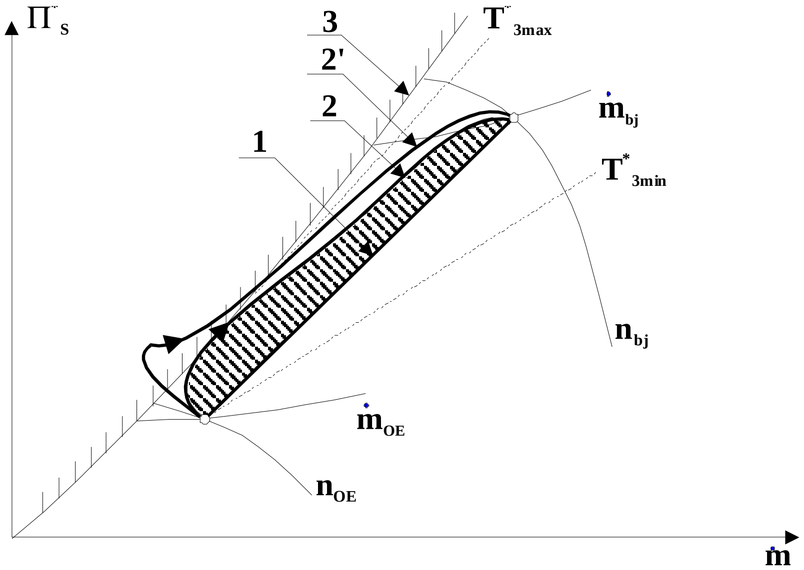

Figure 4: An alteration of the co-operation range on the associated profile of the compressor-combustion chamber-turbine arrangement during start-up process
1 – a co-operation line in steady states; 2 – an alteration of the co-operation range at $dT_3^* / d\tau = dop$; 2' - an alteration of the co-operation range at $dT_3^* / d\tau = kryt$; 3 – a surging border; $n_{bj} > n_{OE}$ – isodroms of an idle and electric rotation of the compressor-turbine arrangement, $\dot{m}_{bj} > \dot{m}_{OE}$ - lines of constant values of the fuel for an idle and electric rotation (the combustion's beginning); $T^*_{3\max}, T^*_{3\min}$ - isotherms of the exhaust temperature stream from the combustion chamber.

The acceleration time τ_p depends on the mass polar moment of inertia J of the whirling arrangement as well as on the rotational speed alterations from n_1 to n_2. It results from a motions' equation of each engine's rotor units which is given by [2,5]:

$$\tau_p = \frac{\pi}{30} J \int_{n_1}^{n_2} \frac{dn}{M_p} \tag{3}$$

The larger value of the accelerating torque M_p on a rotor's shaft is and the smaller value of the mass polar moment of inertia of the whirling masses is as well as the smaller range of the rotational speed alterations is the shorter a time of its driving on the enlarged load's level is. Therefore, in order to increase the engine's power, a stream of the fuel delivered to the combustion chamber has to be greater than the one related the unit's running with the same rotational speed at the settled steady range, for every transient rotational speed of the rotor unit.

The maximally intensive course of the engine's fuel feeding process during acceleration $\dot{m}_{pal} = f(n)$ is limited with a maximum value of the exhaust temperature in front of the high pressure. It results from the constructional materials' creep-resistance of the turbine blades (especially guide vanes) and the working efficiency of the turbine's cooling installation as well as the border of the compressor's surge. Utilization of the maximally admissible fuel excesses is determined by the engine's acceleration time.

A gasdynamic surge margin of the compressor ΔZ_{sa} utilized within an acceleration process is evaluated, for every temporary value of the rotational speed, by the product of two coefficients: ΔZ_{su} - the compressor's surge margin conditioned with exhaust temperature's value in front of the turbine during engine's work on settled steady loads, ΔZ_{sp} - the compressor's surge margin characterizing the admissible value excess of the exhaust temperature's value in front of the turbine during engine's acceleration [2,5]:

$$\Delta \boldsymbol{Z}_{sa} = \Delta \boldsymbol{Z}_{sp} \cdot \Delta \boldsymbol{Z}_{su} = \sqrt{\frac{\boldsymbol{T}^*_{spala}}{\boldsymbol{T}^*_{spal\,\max}} \cdot \frac{\boldsymbol{T}^*_{spal\,\max}}{\boldsymbol{T}^*_{spalu}}} = \sqrt{\frac{\boldsymbol{T}^*_{spala}}{\boldsymbol{T}^*_{spalu}}} \tag{4}$$

where:

$T^*_{spalmax}$ – exhaust temperature in front of the turbine on the engine’s maximum steady load,
T^*_{spala} – exhaust temperature in front of the turbine during engine’s acceleration,
T^*_{spalu} – exhaust temperature in front of the turbine on a range of the engine’s steady load.

3 SIMULATING EXPERIMENTS

In order to protect the engine against failures in similar situations a large number of limitations concerning the engine's usage is foreseen an also the automatically worked control system of the start-up and load alterations process. The main aim of the system is to affect the energy stream delivered to the engine (with the fuel fed system as well as the electric starter) and to steer the elements of the passages' geometry control system (controlled inlet guide vanes, air bleed valves behind SWC, valves of the air feeding the second channel of injectors, a reverse mechanism of the free power turbine and the like), in such a way that the excessive thermal and mechanic overloads of the engine constructional elements are eliminated. The marked area between lines 1 and 2 in the Figure 4 illustrates the accessible loads range.

Figure 5 presents a block diagram of the engine's control system. The average temperature of the exhaust stream measured behind the gas generator represents the system's input signal. Excessive increases of this temperature can cause a functioning "only" the fuel overflow valve or can immediately lay the engine off by the simultaneous effect on the fuel master valve and fuel emergency (drainage) valve. There should be paid special attention on a fact that a measurement of the exhaust temperature during the engine's start-up process of fumes in process (and other unsteady processes) is burdened with a determined, sufficiently considerable inertia, which might be electronically can in the engine's control system - Figura 6. [9]. Because the productive (processing) uniqueness reaches even several percent and decides about so-called the engine's thermal starting sensitivity (vulnerability) the correction of thermocouples' measurement inertia is individually adjusted for every one of the engine's copy. However, an interference into the manufacturing control system's adjustments during engine operation is strictly forbidden, especially while the engine's start-up process is made difficult by the worsened passages' technical state or fuel fed system [3,4].

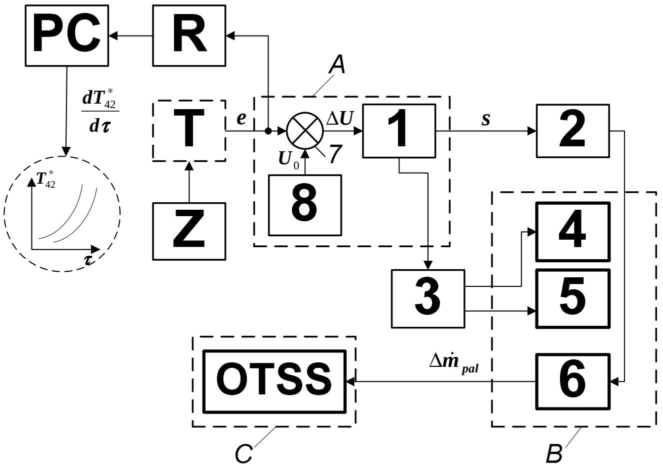

Figure 5: Block diagram of the control system limiting the exhaust stream temperature of a gas turbine engine A – unit of the impulse thermoregulator, B – unit of the execute mechanisms, C – naval gas turbine (OTSS), T – thermocouples' unit (TXA-1368), Z – temperature assignment, R – computer processing program for measurements, registration and analysis of the engine's start-up parameters, 1 – signal's amplifier and modulator, 2 – circuit controlling the electromagnetic overflow valve (by-pass), 3 – circuit controlling the fuel master valve and emergency valve (drainage), 4 – fuel master valve (ZGP), 5 – fuel emergency valve (ZAP), 6 – fuel overflow valve (ZPP), 7 – comparing element, 8 – standard voltage generator, e – averaged value of the thermoelectric voltage, s – impulse control signal.

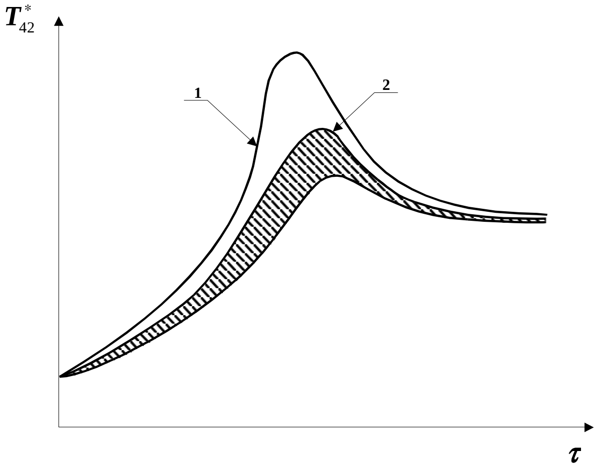

Figure 6: Hypothetical time courses of the exhaust temperature during gas turbine engine's start-up process (acceleration) – shading area stands for a range of the correction of thermocouples' measurement inertia 1– real temperature, 2 – measured temperature.

A lack or disturbances of a functioning the automatic control system of the exhaust temperature causes usually extensive, irreversible damages of the passages. In such a situation the engine's technical state reproduction might be carried out by the emergency repair at the engine's manufacturer only. Figure 7 shows overburnt rotor blades of the high pressure turbine as a result of unsteady work of the combustion chamber during an acceleration process of a two-shaft engine with a free power turbine. Because of the accidental choking of the air inlet channel, while the air bleed valve was being closed along with accelerated a rotational speed of the gas generator's shaft, the violent growth of underpressure at the inlet compressor's section and drop of compressor's delivery took place. It consequently led to the significant, excessive growth of the exhaust stream temperature behind the combustion chamber - Figure 8. A maximally admissible value of the exhaust temperature in steady states has been limited to 970 ^{0}C and numerical data represented by the courses introduced in Figure 8b,c and Figure 9 confirm that this value was considerably exceeded (an upper range of the measuring channel was exceeded). Moreover, the exhaust stream temperature in front of the engine's low pressure turbine was also considerably exceeded - Figure 8d.

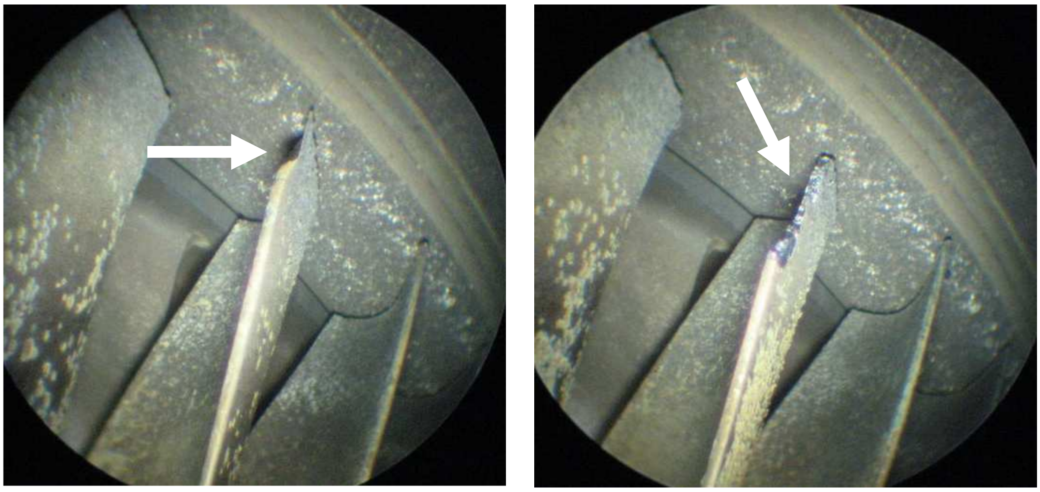

Figure 7: Overburnt rotor blades of the high pressure turbine

Although, a short-duration excess of the maximum exhaust temperature in front of the high pressure turbine is permissible during unsteady processes, however in any cases this temperature should not grow up 20% over its maximum value corresponding the engine's steady work on a nominal load (depending on applied constructional materials and the manner of cooling the turbine) [1,2,3]. Because of fuel delivery excess in the combustion an enrichment of the fuel-air mixture occurred. A value of the excess air number λ got decreased - fig. 10. After reaching the critical value ($\lambda << \lambda$min) for the particular rotational speed of the gas generator's rotor unit, so called "rich" stall of the combustion chamber (flame's break) and the engine's self-acting lay-off took place. Despite this, a temperature growth of the passages' elements (the high pressure turbine's blading) was so large, that the happened damages of the constructional material (overburnings, cracks mainly) eliminated the engine from further operation.

According what was mentioned above the engine's maximum reliability during operation process represents one of the basic requirements made the engine's protection system. It is systematically inspected during diagnostic investigations. Simulating investigations worked out by means of testers, especially designed to this aim, create a vital important diagnostic tool for identification of the selected, most typical operation failures of the engine's automatic control system [12].

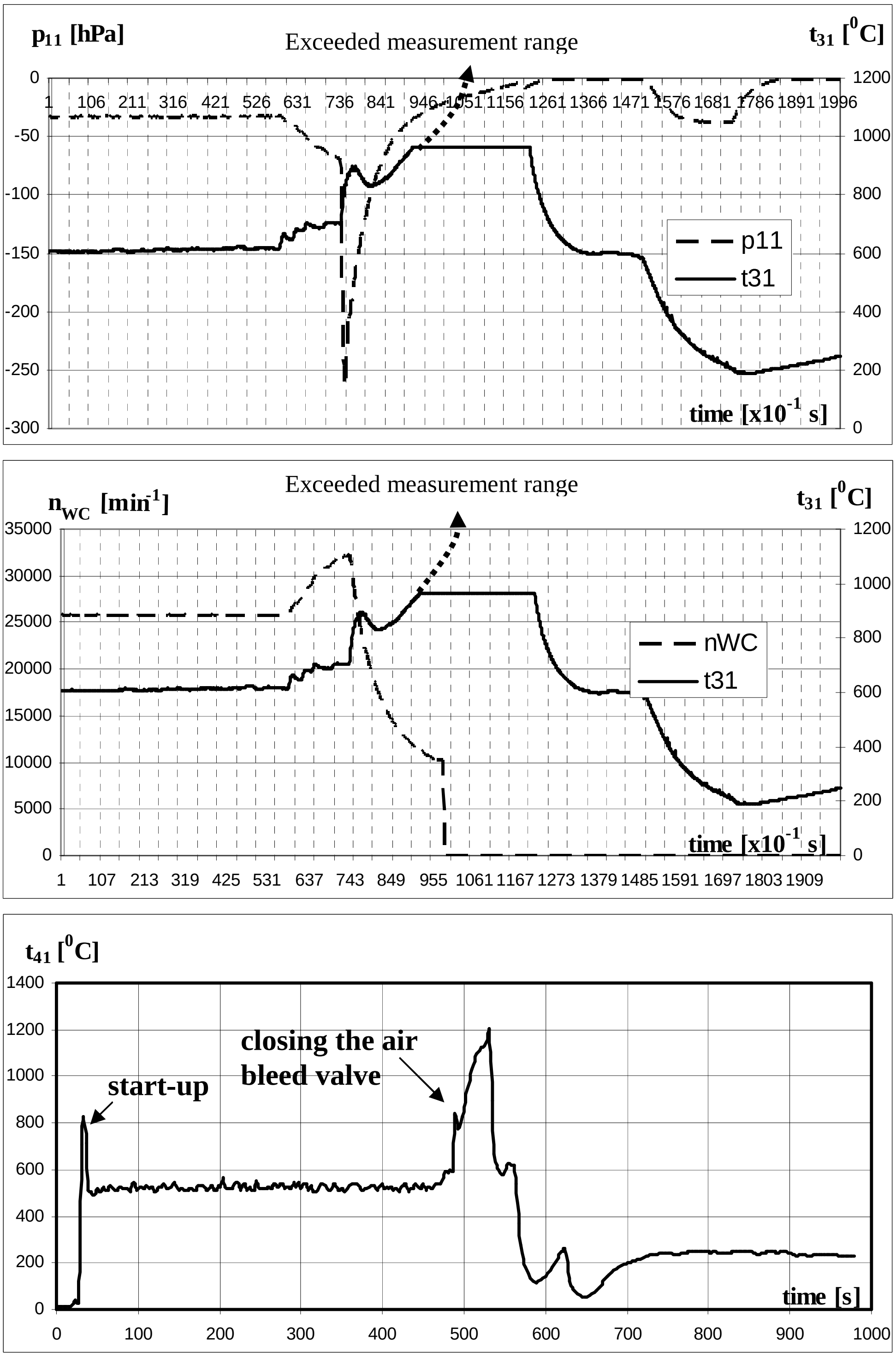

Figure 8: Time courses of the high pressure rotor's rotational speed, vacuum in the compressor's inlet section as well as the exhaust temperature in the inlet section of high pressure turbine and power turbine during two-shaft engine's acceleration process.

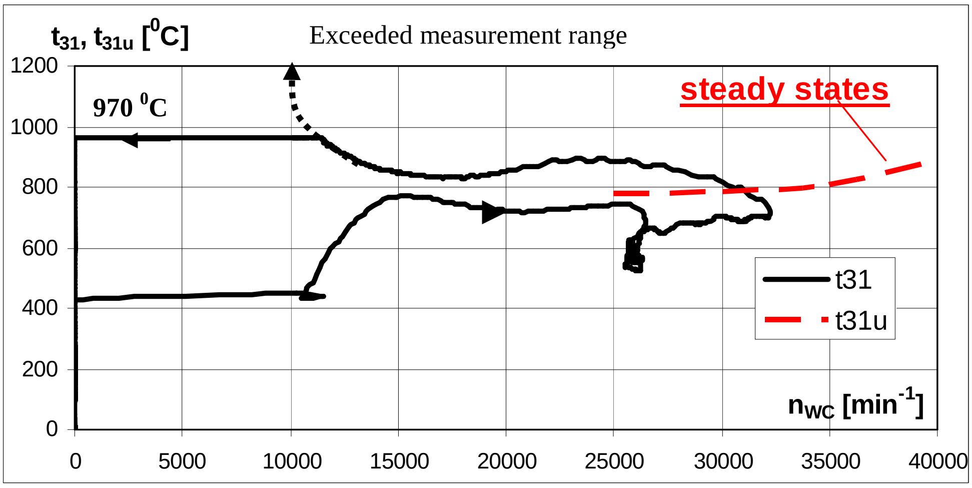

Figure 9: Courses of the exhaust temperature in front of high pressure turbine during start-up process, acceleration process and steady state running of a two-shaft engine with free power turbine in terms of high pressure rotor's rotational speed

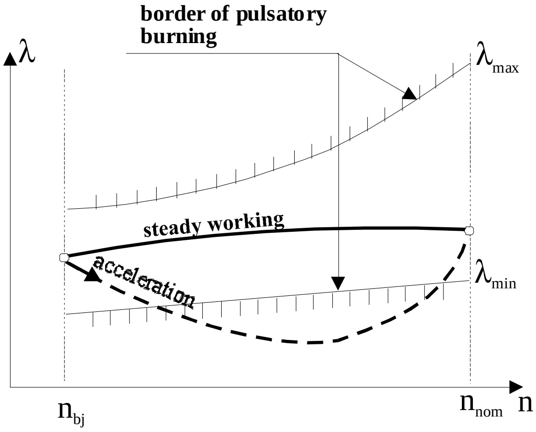

Figure 10: An excess air number in the combustion chamber in terms of a rotational speed of the gas generator's rotor unit

Simulation diagnostic examinations, checking the correctness of a functioning the protection subsystem against the excessive exhaust temperature's increase, are carried out on a stopped engine. The main aim of the examinations is to determine a correctness of threshold (maximum) adjustment of the exhaust stream temperature's values as well as such the temperature's time increases, in which the executive elements of the automatic control system switch on:

⇒ fuel overflow valve (ZPP),
⇒ fuel master valve (ZGP),
⇒ valve of emergency engines' lay-off (ZA).

The values evaluated in this way represent the borders of an operation tolerances' field of the permissible alterations of the foregoing parameters in a start-up process. The selective investigation results in form of simulated dynamic courses of the exhaust temperature are shown in Figure 11. In order to accomplish an evaluation of the examined engine's serviceability (operation readiness) the courses acquired during simulations should be compared with the real courses, registered during earlier startings.

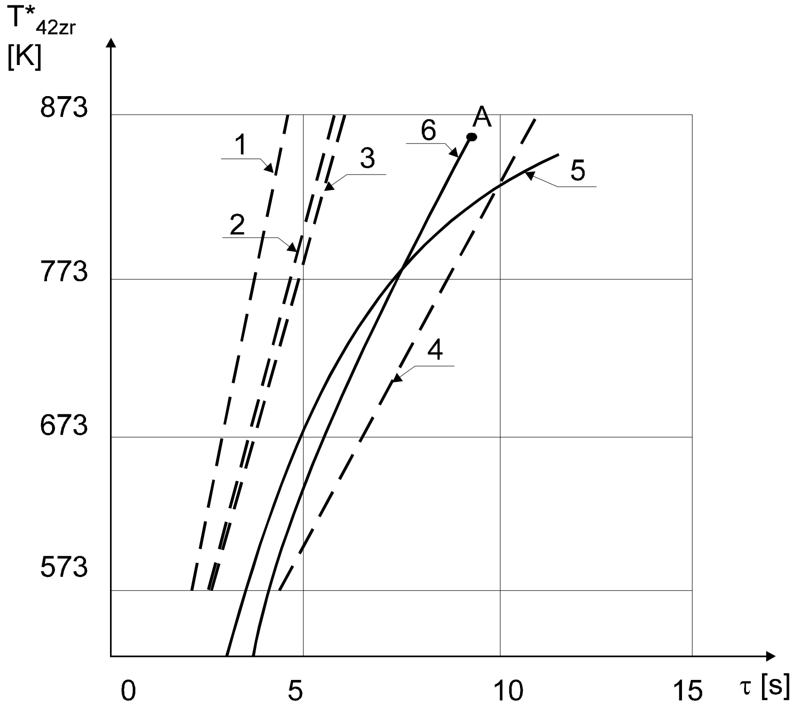

Figure 11: Simulated and real courses of the exhaust stream temperature behind low pressure turbine in terms of start-up duration registered during diagnostic investigations on UGT3000 engine

1 – input (function) $dT_{42}^{*}/d\tau$ = 112 K/s - ZPP(-), ZGP(+), ZA(+) ; 2 – input $dT_{42}^{*}/d\tau$ =88 K/s - ZPP(-), ZGP(+), ZA(+); 3 - input $dT_{42}^{*}/d\tau$ =84 K/s - ZPP(+), ZGP(+), ZA(+); 4 - input $dT_{42}^{*}/d\tau$ = 48 K/s - ZPP(-), ZGP(-), ZA(-); 5 – successful engine's start-up $dT_{42}^{*}/d\tau$ = 64 K/s ; 6 – failure engine's start-up $dT_{42}^{*}/d\tau$ = 82 K/s; A - the engine's self-acting lay-off .

A comparative analysis of the results of many years' investigations of ZORYA naval engines UGT type, which have been involved with diagnostic supervision [12], enabled the Author to follow and settle the characteristic thresholds of the protection subsystem. They stand for borders of the operation tolerance's field in relation to the time derivative of the averaged exhaust stream temperature measured behind the gas generator:

- $dT_{42}^{*}/d\tau \rangle$ 80 K/s – the engine's self-acting lay-off - ZPP(+), ZGP(+), ZA(+);
- $dT_{42}^{*}/d\tau = 50 \div 80$ K/s – the engine' start-up along with an automatic fuel dosage - ZPP(+), ZGP(-), ZA(-);
- $dT_{42}^{*}/d\tau \langle 50$ K/s – the engine is started-up automatically without any protection subsystem's interferences - ZPP(-), ZGP(-), ZA(-).

The data presented in Figure 11 lead to the conclusion that the engines' thermal protection subsystem does not operate properly. The conducted studies confirmed that the fuel overflow valve (ZPP) was not functioning with any regard to growth of the exhaust temperature (courses 1 and 2). After detailed analyses of the unserviceable state's symptoms the damaged elements of the engine's control system were localized and exchanged. Repeated simulating investigations confirmed diagnosis' accuracy which illustrates line 3 in Figure 18, registered after the defect's removal.

The next important feature of the examined thermal protection subsystem results from the conducted investigations: there is the acting insensibility zone within the range 273-593 K, without regard on a dynamics of the exhaust temperature's growth.

4 CONCLUSIONS

Systematically performed diagnostic investigations of the automatic control subsystem by means special testers protect the engine passages against thermal overloads and blading failures.

Presented simulating experiments additionally enable the operator to evaluate and check a correctness of the exhaust temperature thresholds individual for each engine.

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