ZBIGNIEW KORCZEWSKI, D.Sc.,M.E.
Polish Naval Academy, Gdynia
Institute of Construction
and Propulsion of Vessels

Investigations of naval gas turbine dynamics in different thermal states

SUMMARY

The paper presents selected results of the research on acceleration process of a naval gas turbine in service. The investigations were carried out in view of preliminary evaluating the engine thermal state influence on its dynamic features. They present an important element of a diagnostic method under development. The method enables to diagnose the engine on the basis of testing of selected unsteady processes.

INTRODUCTION

During accelerating the naval gas turbine the unsteady heat exchange process takes place between the working medium and structural elements of engine's flow passage. It develops with rapidly in the hot part of the engine where heat capacity of the combustion gas flow is several times lower than total heat capacity of the entire engine metal structure. Therefore susceptibility to changing the average temperature of the combustion gas and that of the flow passage differ greatly. For instance, if the combustion gas temperature is changed within 10 to 15 s during engine's acceleration, the heating process of the engine elements will last even several minutes. The rotor rim blades and turbine body become heated the quickest, the rotor disc - much slower. In consequence the blade tip clearance of the rotor rim and gas flow temperature behind the turbine increases, and efficiency of the turbine stage drops [2,3].

Initial heat state of the engine a.o. is a decisive factor of the dynamic heat exchange process. The greater the difference of temperatures of the working medium and flow passage walls the greater the heat energy flux derived from fuel is utilized to heat engine's structural elements. Experience gained from experiments with aircraft engines showed that the increase of the turbine tip clearance is rather small in the preliminary phase of cold engine acceleration [3,7,8]. The accelerating rotor systems which obtain an assumed value of the rotational speed within 8 to 10 s, are exposed to high centrifugal forces. It leads to elastic radial displacements of the rotating elements and cancellation of the tip clearances, which partially compensates the thermal clearance component.

In the next acceleration phase, after about 20 to 30 s, a very high temperature increase of the turbine elements occurs. At that time the tip clearance may become two or even three times greater than its value characteristic of steady state operation. Efficiency of turbine energy processes drops. The engine load controller usually coupled with WC rotor unit intensifies fuel delivery to the combustion chamber, trying to maintain the rotational speed constant, n_{WC}= const.

Instantaneous values of the combustion gas temperature grow with respect to the values characteristic of engine's steady operation. Acceleration time grows even by several seconds. In an extreme case the limit temperature values of combustion gas can be exceeded and heat overload of the engine and even its spontaneous stopping can happen. The combustion gas temperature drops as heating the rotor disc elements develops and after 2 to 3 minutes the tip clearance achieves a steady value.

A relationship between the rotor tip clearance of WC turbine and its rotational speed during unsteady processes of DR77 gas turbine engine is presented in Fig.1. It was elaborated on the basis of results of the experimental investigations carried out in manufacturer's R&D laboratory.

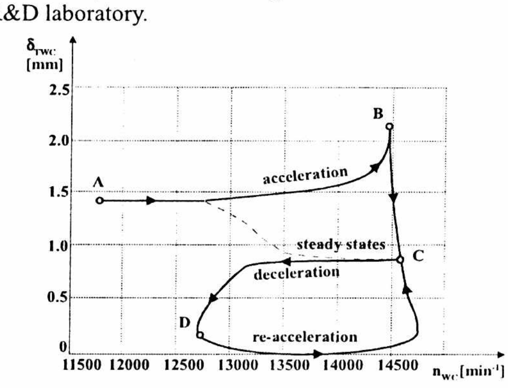


Fig.1. Tip clearance changes of WC turbine rotor versus turbine rotational speed, of DR77 turbine engine in various load states

The broken line in Fig.1 denotes δ_{TWC} tip clearance course in steady operation states of the engine. The point A denotes the starting point of the acceleration process. The tip clearance grows till it reaches the maximum value in the point B. In the point C the engine is re-manoeuvred towards lower load values (deceleration), after reaching a stable value of the tip clearance. The deceleration process is stopped at the point D by increasing the fuel flow delivered to the combustion chamber (re-acceleration). It results from the trajectory shown in Fig.1 that sudden re-accelerating the engine can cause cancelling the tip clearance at all and ramming the rotor in the turbine body.

The following relationship can be used to assess changes of the tip clearance between the rotor blades and turbine body [7] :

$$\delta = \delta_o(\Delta_k - \Delta_{tw} - \Delta_l - \Delta_{dyn}) \qquad (1)$$

where :

- δ_o - tip clearance value determined at the temperature of 288.15 K
- $\Delta_k, \Delta_{tw}, \Delta_l$ - relative tip clearance changes due to thermal expansion of the turbine body, rotor rim and blade, respectively
- Δ_{dyn} - relative tip clearance change due to interaction of centrifugal forces.

Approximate values of the thermal components of the relative tip clearance changes can be determined from the relationship (2) under assumption that idealization of the turbine structural elements (body, rotor rim, blade) by the apparent bars of an appropriate length is acceptable [7] :

$$\Delta_e = \alpha_e T_e \qquad (2)$$

where :

- α_e - thermal, linear expansion coefficient (based on experiments)
- T_e - average temperature of the element e.

The dynamic component of the relative tip clearance change can be determined from the relationship (3), [7] :

$$\Delta_{dyn} = (n / n_o)^2 \qquad (3)$$

where :

- n - instantaneous value of turbine's rotor speed during engine acceleration
- n_o - stable, initial value of turbine's rotor speed.

It results from aeronautical experience that increasing the reference tip clearance value (defined by the ratio of the rotor tip clearance δ and average blade length) by 1% can cause efficiency of the turbine in dynamic operation states dropping even by 2.5% [8].

AIM OF THE INVESTIGATIONS AND APPLIED MEASURING EQUIPMENT

The experimental investigations were carried out on the existing gas turbine, DR76 [1,4], installed in COGAG system of a fast naval craft as the power engine. The engine designed as an co-axial rotor system, consists of a twin rotor gas generator and seperate power (propulsion) turbine not coupled with it kinematically. The turbine drives the kinematic system which transmits torque to the propellers. A scheme of the engine with marked control intersections within its gas flow part, is shown in Fig.2.

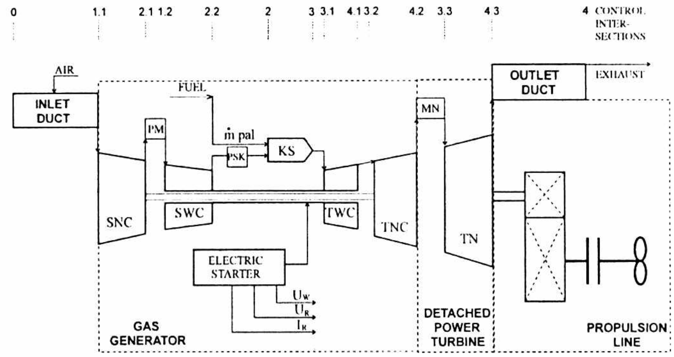
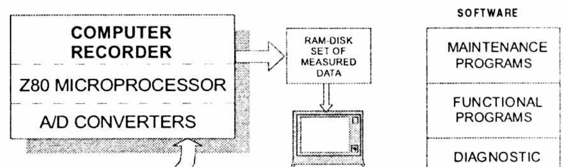


Fig.2. Scheme of the naval gas turbine engine with seperate, reversible power turbine

An aim of the research was to preliminarily assess the influence of engine's thermal state on its dynamic features. It makes necessary to apply the measuring equipment capable of simultaneously recording thermogasodynamic parameters of the working medium flow in a possible short sampling time. To this aim the Computerized Measuring System developed at the Institute of Construction and Propulsion of Vessels, Polish Naval Academy [1], was applied. A block diagram of the system is presented in Fig.3.



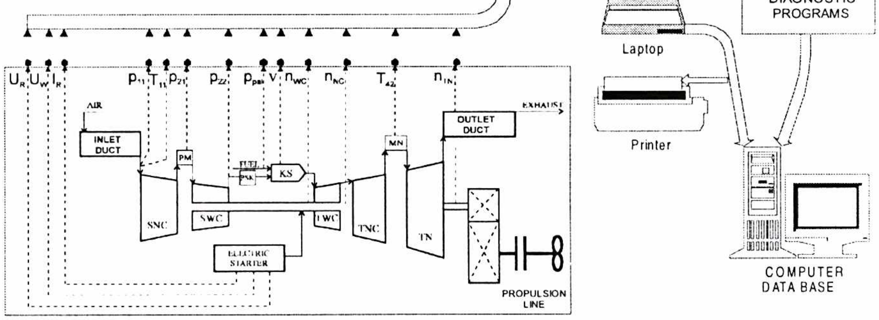


Fig.3. Block diagram of the Computerized Measuring System

The measuring system can be used in two variants :

- to measure parameters of the unsteady processes (acceleration, deceleration, starting, stopping and maneouvring the separate propulsion turbine)
- to measure parameters of engine's continuous operation at a determined load level.

The measuring system consists of the following elements :

- 13 measuring channels for determining values of the engine control parameters and recording them automatically at 1s sampling time
- a computerized recorder of the engine operation parameters, connected to a printer, and portable RAM-DISK,
- a laptop computer for pre-selecting and analyzing the measurment results on shipboard, and preparing them for sending to an on-shore data base
- IBM-PC computer which works as a data base for taking operational decisions.

The measured engine parameters are presented in Tab.1.

The measuring-recording part of the system is intended for carrying out experimental investigations of the engine during ship service. It was so designed as to make independent and safe operation of the standard, measuring-control system of the engine possible by applying opto-insulation systems in each measuring channel. Simultaneous measuring of all the operation parameters is made possible by application of A/D converters.

Tab.1. Measured engine parameters

Parameter		Measuring Range	Accuracy	Type of sensor
Start-up current	J_R	0 ÷ 999 A	± 0.1 A	ammeter
Start-up voltage	U_R	0 ÷ 100 V	± 0.1 V	voltmeter
Field voltage	U_W	0 ÷ 100 V	± 0.1 V	voltmeter
Air temperature at the engine inlet	T_{11}	-40 ÷ +40 °C	± 0.2 °C	resistive
Air pressure at the engine inlet	p_{11}	0 ÷ -0,03 MPa	± 1 kPa	strain gauge
Exhaust gas temperature	T_{42}	200 ÷ 990 °C	± 1 °C	thermocouple
Rotational speed of NC shaft	n_{NC}	0 ÷ 15 500 rev/min	± 10 rev/min	rate generator
Rotational speed of WC shaft	n_{WC}	0 ÷ 24 000 rev/min	± 10 rev/min	rate generator
Rotational speed of TN shaft	n_{TN}	0 ÷ 7 000 rev/min	± 10 rev/min	rate generator
NC compressor delivery gas pressure	p_{21}	0 ÷ 0.6 MPa	± 10 kPa	strain gauge
WC compressor delivery gas pressure	p_{22}	0 ÷ 2.0 MPa	± 10 kPa	strain gauge
Fuel pressure	p_{pal}	0 ÷ 10.0 MPa	± 10 kPa	strain gauge
Vibration velocity	v	0 ÷30 mm/s	± 2 %	piezoelectric

The external RAM-DISK with independent power supply makes it possible to pass the recorded measurement results from the engine room (of an elevated vibration level) to the portable computer memory and further to the main computer installed in the diagnostic laboratory.An organization scheme of the engine investigations on shipboard is presented in Fig.4.

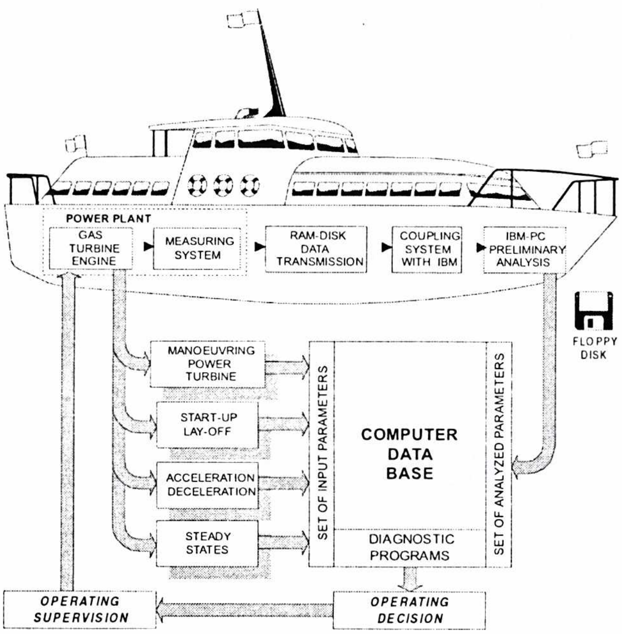


Fig.4. Organization scheme of shipboard investigations of the gas turbine engine

COURSE OF THE EXPERIMENTAL INVESTIGATIONS AND THEIR RESULTS

The investigations were performed at STOP position of the power turbine reversing gear, during the ship's lying at quay.

The experiment consisted in disturbing the steady, idle operation of the engine by increasing the flow rate of the fuel delivered to the combustion chamber up to the value which corresponded to the partial load of 0.3 p_{nom}. The limited range of load change resulted from the necessity of avoiding the disturbances connected with starting the controllable guide wheel of NC compressor to work. The change of fuel flow rate was forced by the change of fuel pressure in front of the injectors, realized by changing position of the fuel pump lever.

Maneouvring time of the engine towards greater load range is limited by features of the electronic-hydraulic, engine acceleration control unit. Growth of the fuel flow rate delivered to the combustion chamber is independent of the displacement velocity of the control lever. When the engine was passing from one value of steady rotational speed to another, values of the control parameters were recorded at one second sampling time.

The measurements were repeated two times. It made possible to distinguish two different, engine thermal states determined by lubricating oil parameters, exhaust gas temperature at the outlet duct and cooling air temperature under the thermal shield (Tab.2).

Tab.2. Parameters of engine thermal states

Engine therma state	$T_{ol(dol)}$ K	$P_{ol(dol)}$ MPa	$T_{p(os)}$ K	$T_{spal(wvl)}$ K
"1" cold state	292	3.6	281	313
"2" hot state	323	3.0	283	363

In result of the investigations, courses of the thermogasodynamic parameters versus time were obtained, which characterized an energy state of the engine which responded in that way to the applied excitations (Fig.6 to 11). Courses of the fuel pressure changes versus time are presented in Fig.5.

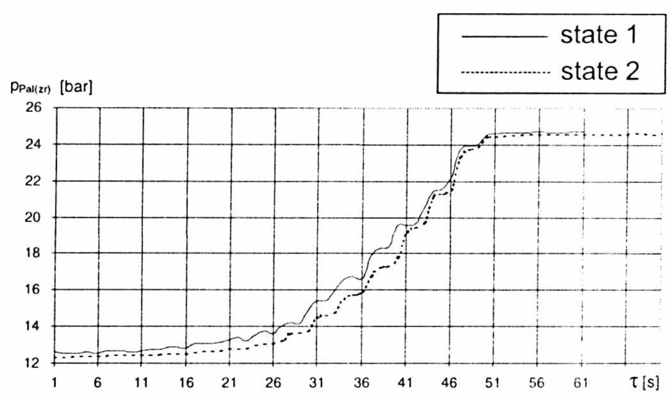


Fig.5. Fuel pressure changes in function of time during accelerating the engine

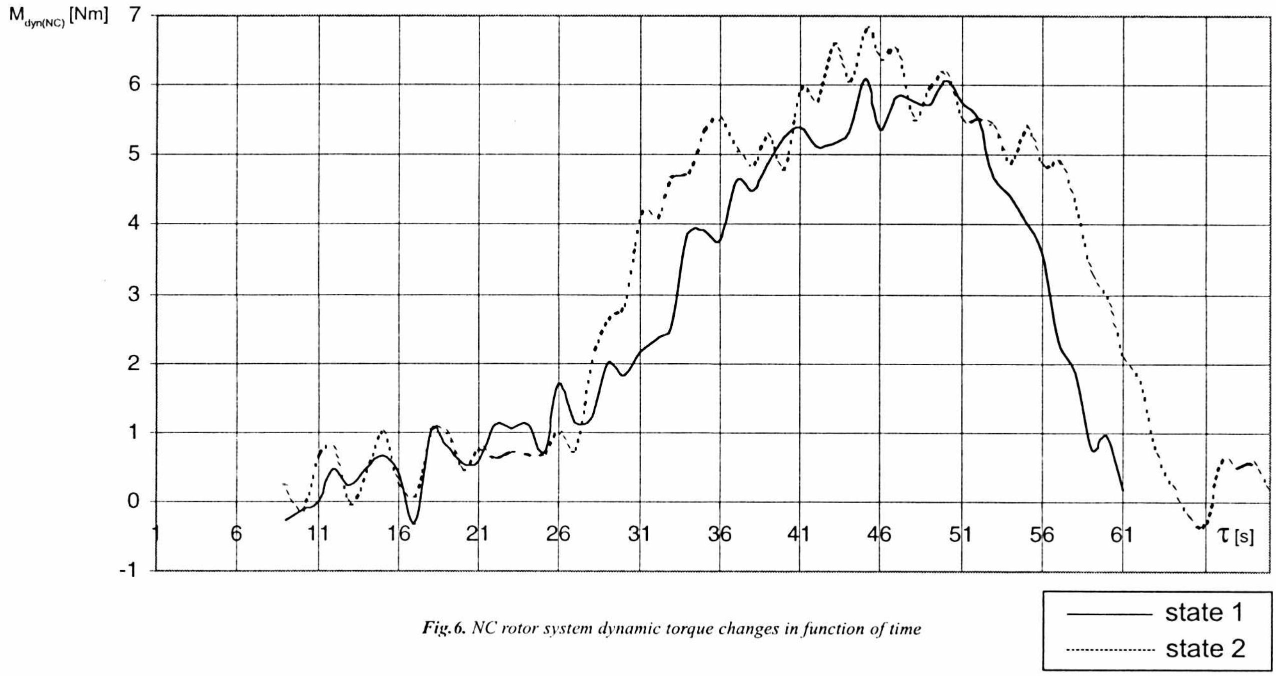


Fig.6. NC rotor system dynamic torque changes in function of time

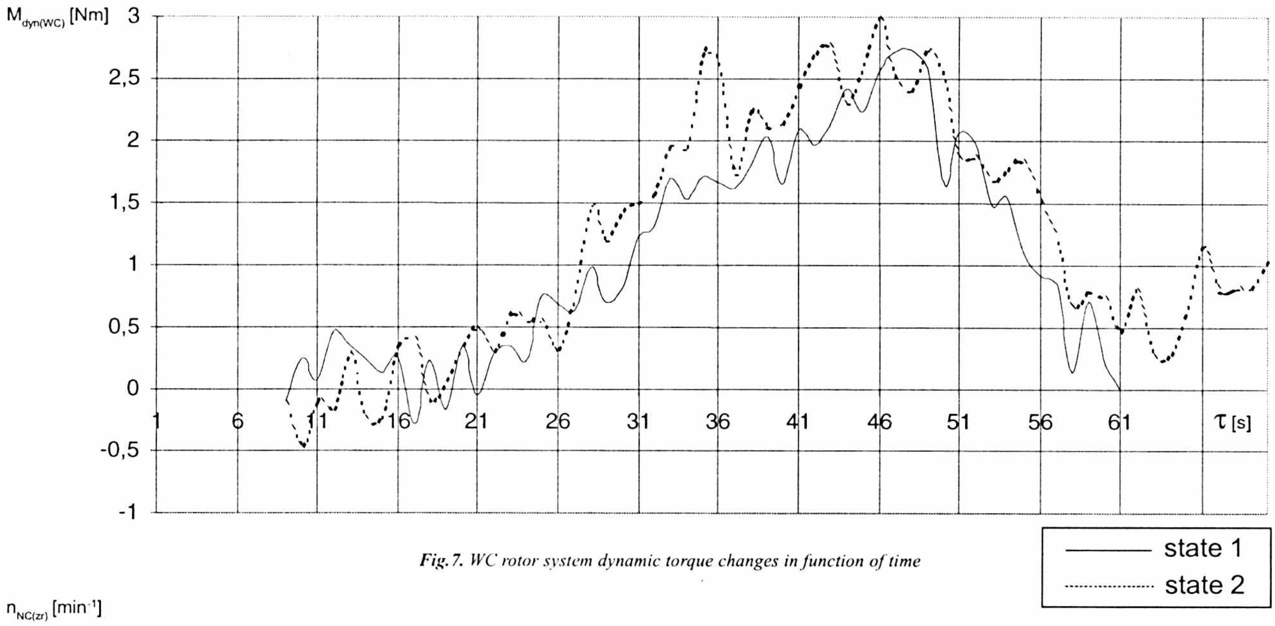


Fig.7. WC rotor system dynamic torque changes in function of time

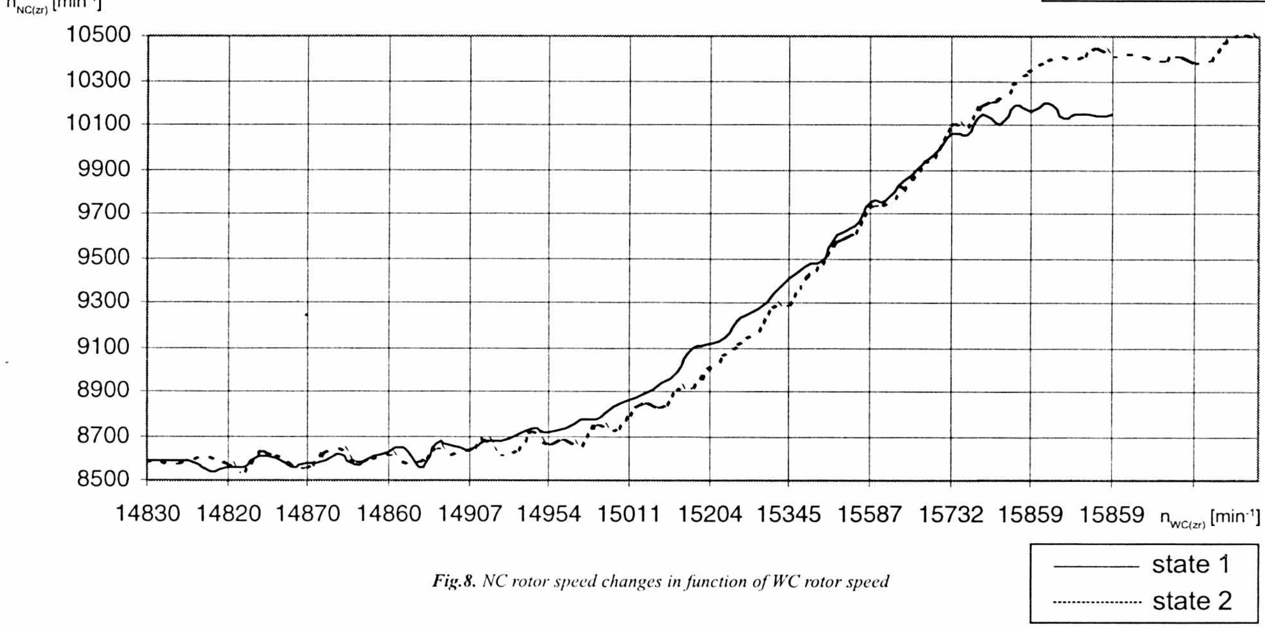


Fig.8. NC rotor speed changes in function of WC rotor speed

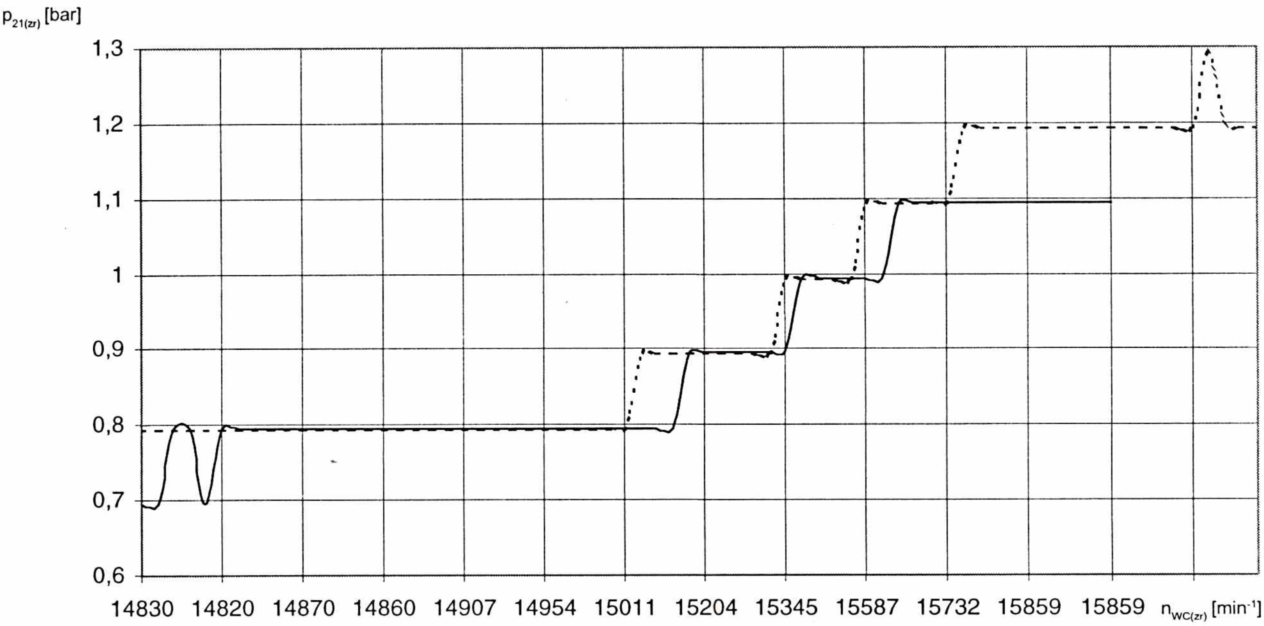


Fig.9. Air pressure changes behind NC compressor in function of WC rotor speed

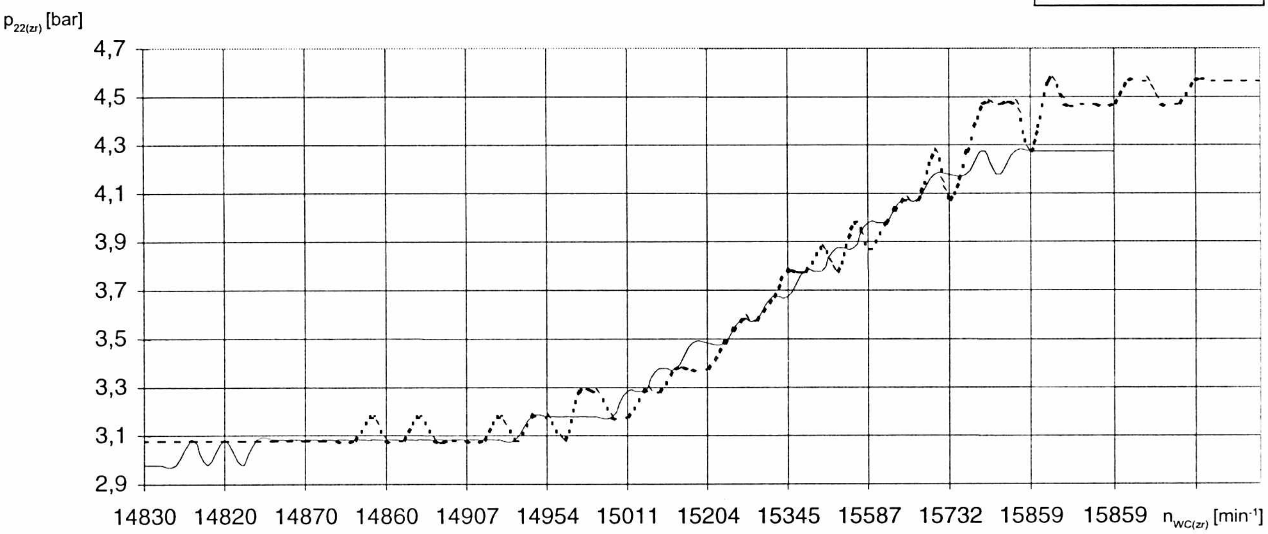


Fig.10. Air pressure changes behind WC compressor in function of WC rotor speed

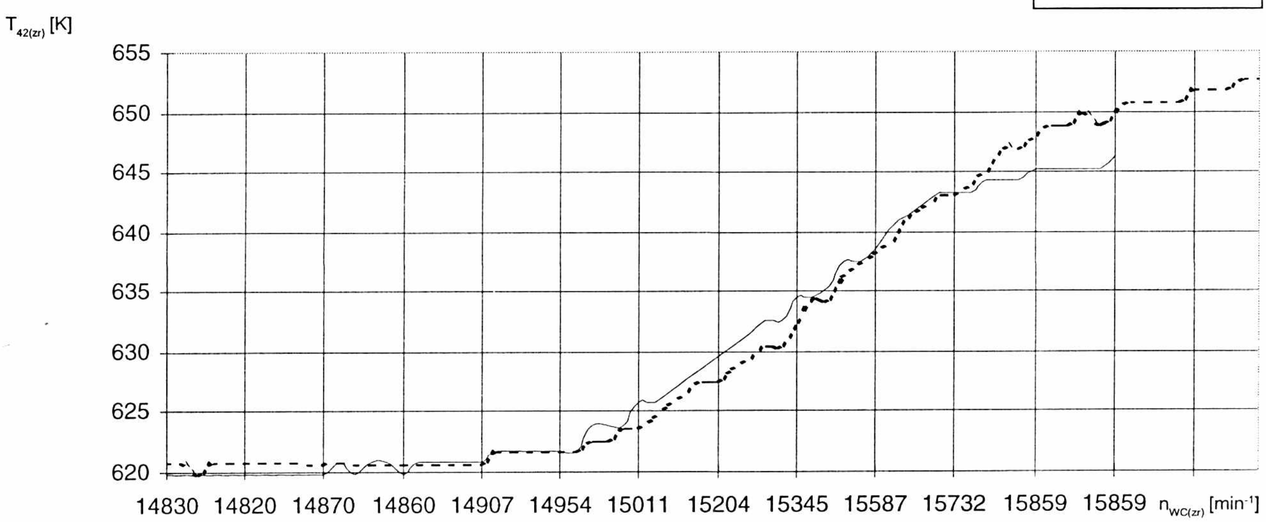


Fig.11. Exhaust gas temperature changes at the control intersection behind NC turbine in function of WC rotor speed

ANALYSIS OF THE INVESTIGATION RESULTS

It can be generally stated on the basis of the investigation results that all the analyzed parameters demonstrated more dynamic changes in result of increased temperature of the engine construction. This important phenomenon happened at much lower instantaneous values of the fuel pressure in front of the injectors (Fig.5). It may be also concluded, if the slight deviations of instantaneous values of the air pressure behind WC compressor (Fig.10) are taken into consideration, that the flow rate of the fuel delivered to the combustion chamber during engine's acceleration process was increasing much slower in the thermal state 2.

Dynamic properties of the turbine engine can be described in the most suitable way by means of the dynamic energy equations of its rotor units :

$$I_{NC}\frac{d\omega_{NC}}{d\tau} = M_{iTNC} - M_{iSNC} - M_{mNC} \qquad (4)$$

$$I_{WC}\frac{d\omega_{WC}}{d\tau} = M_{iTWC} - M_{iSWC} - M_{mWC} \qquad (5)$$

$$I_{TN}\frac{d\omega_{TN}}{d\tau} = M_{iTN} - M_{obcTN} \qquad (6)$$

The dynamic torques which appear on the left hand side of the equations characterize the engine ability to accumulate kinetic energy.

Comparative analysis of the dynamic torques (Fig.6 and 7) calculated on the basis of the recorded courses allows to conclude that the amount of the kinetic energy accumulated in the rotors (represented by the areas under the course curves) distinctly grows in the heat state 2. The phenomenon is caused first of all by a drop of the mechanical drag in the bearings and drives of the mechanisms coupled to the rotors, as well as an efficiency improvement of the working medium compression and decompression processes in particular flow machines.

In Fig.8 courses of NC rotor speed changes recorded during the experiments are shown in function of WC rotor speed. The instantaneous, rotational speed slip values calculated on their basis form an important diagnostic information about the engine structure state :

$$\Delta n(\tau) = n_{WC}(\tau) - n_{NC}(\tau) \qquad (7)$$

It can be observed that the slips which occur in the „hot" engine are distinctly greater in the initial phase of accelerating the engine. The phenomenon favourably lowers occurrence probability of the unstable engine operation. The slip of the „hot" engine clearly drops relative to that of the „cold" engine in the end phase of the process when speeds of the rotors are asymptotically approaching the state of equilibrium. Greater mechanical losses of the „cold" rotor units are supposed to cause the observed phenomenon.

The air pressure accumulated in the engine inter-compressor space is an important diagnostic parameter of the engine. It results from the recorded dynamic courses of the pressure behind NC compressor (Fig.9) that the air pressure in the „hot" engine increases more intensively as WC rotor transient speed increases. That is an efficiency measure of the gasodynamic processes which occur in the flow passages of the co-operating compressors.

The character of the experimentally recorded changes of the average exhaust gas temperature measured behind NC turbine (Fig.11) indicates that the fuel-air mixture of the „cold" engine is of a higher enrichement. It is caused on the one hand by a quicker increase of the fuel pressure in front of the injectors (fuel rate in the combustion chamber), and on the other by a lower efficiency of the compressors. For this reason the engine manufacturer requires to heat the idle running engine for several minutes before increasing its load. Not complying with the limitation can lead to a violent buildup of the exhaust gas temperature and stopping the running engine as it results from the service experience.

CONCLUSIONS

- The investigation results demonstrate that the gas turbine engine is very sensitive to changes of its structure heat state. It can be concluded from the recorded courses of the control parameters that engine dynamic properties improve along with the growing temperature.
- The dynamic torque characteristics of particular rotor units are very useful for qualitative and quantitative assessing of the energy states of a running engine. Their further application is expected in diagnosing the kinematic system elements.

NOMENCLATURE

Parameters

I	-	polar moment of inertia
J	-	current
M	-	torque
$\dot{m}$	-	mass flow rate
n	-	rotational speed
p	-	pressure
T	-	absolute temperature
U	-	voltage
v	-	vibration velocity
α	-	coefficient of thermal expansion
δ	-	tip clearance
Δ	-	increment
τ	-	time
ω	-	angular velocity

Abbreviations

COGAG	-	Combined Gas turbine and Gas turbine propulsion system
KS	-	combustion chamber
MN	-	gas space between the gas generator and power turbine with a reverse device
NC, WC	-	low pressure and high pressure system shaft , respectively
PM	-	inter-compressor space
PSK	-	gas space between the high pressure compressor and combustion chamber
SNC, SWC	-	low pressure and high pressure compressor, respectively
TNC, TWC, TN	-	low pressure, high pressure and power turbine, respectively

Lower indices

dol	-	of inlet	ol	-	of lubricating oil
dyn	-	dynamic	p	-	of air
e	-	of element	pal	-	of fuel
i	-	internal	pom	-	measured
k	-	of casing	R	-	at start-up
l	-	of blade	spal	-	of exhaust gas
m	-	of mechanical losses	tw	-	of rotor disc
nom	-	nominal	w	-	of rotor
o	-	steady, of design state	W	-	of excitation
obc	-	of load	wyl	-	of outlet
os	-	of thermal shield	zr	-	reduced (reffered to ambient ISA-standard atmosphere)

0,1.1, 2.1, 1.2, 2.2, 2, 3, 3.1, 4.1, 3.2, 4.2, 3.3, 4.3, 4 - control intersection numbers : the first figure denotes an intersection behind or in front of : compressor (1or 2) or turbine (3 or 4) respectively, the second figure - the next compressor or turbine within the series configuration, e.g.: 1.2 - control intersection in front of the second compressor.

BIBLIOGRAPHY

1. Charchalis A. Korczewski Z.: „Naval gas turbine diagnostics". The Second International Conference on Marine Technology ODRA'97. Szczecin 1997
2. Cohen H., Rogers G.F.C., Saravanamuttor H.I.H.: „Gas turbine theory". Longman Scientific & Technical. New York 1987
3. Dobrankij G.W., Martinowa T.S.: „Dinamika awiacionnych gazoturbinnych dwigatieliej". Maszinostrojenje. Moskwa 1989
4. Korczewski Z.: „ Badanie procesu przyspieszania w konstrukcjach wielowirnikowych okrętowego turbinowego silnika". XVII Międzynarodowe Sympozjum Siłowni Okrętowych. Szczecin 1995
5. Korczewski Z.: „Badanie procesu hamowania w konstrukcjach wielowirnikowych okrętowego turbinowego silnika spalinowego". III Krajowa Konferencja Diagnostyki Technicznej. Szczyrk 1995
6. Korczewski Z.: „Badanie procesu zwrotnego przyspieszania wielowirnikowego okrętowego turbinowego silnika spalinowego". Zeszyty Naukowe AMW nr 3. Gdynia 1995
7. Sosunow W.A., Litwinow J.A.: „Nieustanowiwsziesja riżimy roboty awiacjonnych gazoturbinnych dwigatieliej". Maszinostrojenje. Moskwa 1975
8. Szczeciński Z.: „Studium o luzach wierzchołkowych zespołów wirnikowych lotniczych silników turbinowych jako parametrze konstrukcyjnym i eksploatacyjnym". Dodatek do biuletynu WAT nr 4 (248)/1973

Appraised by Adam Charchalis, Prof.,D.Sc.,M.E.