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Method of diagnostic parameters determination applicable to dynamic processes of a naval gas turbine

SUMMARY

The paper presents a mathematical determination method of diagnostic parameters of the naval gas turbine configuration. The modelling of the unserviceability states and some results of the numerical simulation of the engine acceleration process are demonstrated as well. The number of selected diagnostic parameters was minimized by means of the entropy function according to information theory.

INTRODUCTION

One of the prospective ways to increase reliability and durability of contemporary naval gas turbines is permanently modernizing and developing the disassemble - free control methods of their technical state in service. Computer simulation techniques, being dynamically developed, are of increasing importance, when used as effective means for supporting the optimum choice of appropriate diagnostic parameters.

It is not possible to carry out direct assessment (measurements) of the parameters determining a structural state of separate engine subsystems inclusive of the regulation and control ones. Diagnostic information quantity contained for example in assembling tolerance values, active cross-section areas or surface roughness of flow passages, is directly determined by measuring the control parameters which characterize technical state of engine internal elements and adequacy of its functioning.

Operation conditions of a marine gas turbine and its low control dependability additionally impose limitations on measuring the necessary indirect parameters. In many cases application of the complicated and very costly measuring techniques applicable only for stand tests, is necessary.

In marine conditions it is also not possible to introduce defects and regulation deviations in order to experimentally confirm their influence on engine functioning quality and durability as well as to determine tolerances for dynamic parameters of diagnostic indirect control. The tolerances should account for manufacturing uniqueness, i.e. individual features of each engine, as well as its service conditions and time which usually lead to different ageing and wear-and-tear rates of elements in each case.

This is why it is necessary to support the experimental (traditional) diagnostic methods, consisting in the comparative analysis of courses of selected engine energy processes and their respective models, by means of computer modelling and simulation methods. By using them it is possible to determine the following:

- set of unserviceabilty states which should be distinguished during a diagnostic test
- necessary (minimum) number of the diagnostic parameters for identifying the states.

DIAGNOSTIC SIMULATION MODEL

The main aim of diagnostic investigations is the determination of the mutual relationship between the set of unserviceability states of engine functional modules and set of diagnostic parameters which unequivocally identify the states. One of the promising methods of the obtaining the so called „ defect-symptom " relationships applicable to the naval gas turbine, is the modelling method of unserviceability states of its elements by means of computer simulation [4, 5, 6]. The method is especially useful in designing a diagnostic system for naval engines, as it makes possible to determine, in a relatively simple way, the following:

- initial static and dynamic engine characteristics with their course deformations caused by influence of external conditions, manufacturing deviations and irreversible ageing and wear-and-tear processes accounted for
- a set of possible unserviceability states of selected engine functional modules
- a minimum set of the diagnostic parameters unequivocally identifying the modelled defects.

An example of the diagnostic simulation model of a naval gas turbine is shown in Fig.1. The system consists of two kinematically independent axial compressors: that of low (LPC) and of high (HPC) pressure, which coaxially cooperate with a triple-rotor gas turbine engine. The tapered flow passage of 0.2 m length and the volume V_{IP} = 12.4 dm^3 accumulating the mass and energy of the flowing air is the element which ensures their gasodynamic coupling (IP).

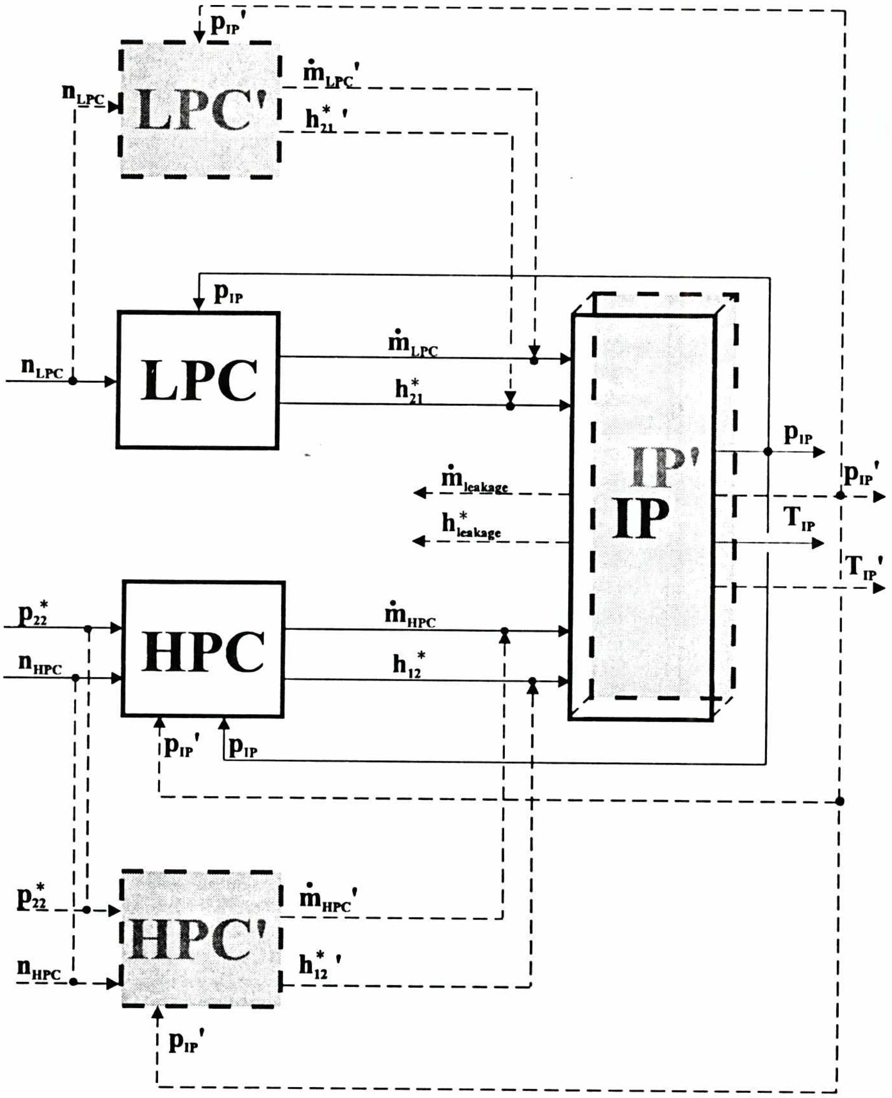

Fig. 1. Simulation model of a naval gas turbine compressor system
——— basic model ---------- defects containing model

The following was assumed to simplify the model the most:

- the considered system is modelled as a dynamic object of discrete parameters
- the working medium is considered as a semi-ideal gas
- values of thermogasodynamic parameters at inter-compressor space outlet are delayed relative to those of average parameters within the space, by a time interval of the working medium flow along the path between inlet and outlet sections
- quasi-stationary approach is applied to dynamic processes within compressors which are reduced only to mass and energy sources of the passage in question
- radial clearance changes of the rotors due to influence of centrifugal forces and thermal state changes of the system's structure are not accounted for.

The following input magnitudes of the modelled energy processes are assumed:

- the rotational speed of LP compressor: n_{LPC}
- the rotational speed of HP compressor: n_{HPC}
- the ram-effect pressure of the working medium at the HPC's outlet section (control intersection 2.2): p^*_{22}

The thermal magnitudes of the working medium within inter-compressor space: p_{IP}, T_{IP} and the temperature of passage structure elements: T_M considered as a measure of the accumulated internal energy, are the state magnitudes.

Mass and energy flow values to (at control intersection 2.1) and from (at control intersection 1.2) the inter-compressor space are determined on the basis of the universal compressor characteristics:

$$\begin{aligned} \dot m_{LPC} &= f(\pi^*_{LPC}, n_{LPC}, \alpha_{IGV}) \\ \eta^*_{eLPC} &= f(\dot m_{LPC}, n_{LPC}, \alpha_{IGV}) \end{aligned} \qquad (1)$$

$$\begin{aligned} \dot m_{HPC} &= f(\pi^*_{HPC}, n_{HPC}) \\ \eta^*_{eHPC} &= f(\dot m_{HPC}, n_{HPC}) \end{aligned} \qquad (2)$$

Therefore values of working parameters read out from the characteristics are the values referred to the so called normal conditions (standard atmosphere parameters) i.e. they are comparable, independent of changes of atmospheric conditions.

The standard atmosphere conditions: p_0, T_0 are the environment parameters of the passage: p_{ot}, T_{ot}, simultaneously.

It is possible to introduce, to the model shown in Fig.1, defects of both cooperating compressors, as well as of their connecting passage. The dash lines in the figure stand for the signal flow for the system with defects.

The following unserviceability states were modelled for analyzing the functioning quality of the gas turbines exploited on board Polish Navy vessels [3], with information on defects being recorded during their service accounted for:

- S_{m1} - fouling the LPC inter-compressor passage with the assumed 10% drop of efficiency and mass flow of the working medium forced through the compressor as well as 2% compression drop
- S_{m2} - fouling simultaneously the LPC and HPC inter-compressor passage with the assumed 10% drop of efficiency and mass flow rate of the working medium forced through the compressors as well as 2% LPC compression drop and 7% HPC compression drop
- S_{m3} - the inter-compressor passage leakage with the assumed mass flow rate of the „lost" working medium: $\dot m_{leakage} = 0.05\dot m_{HPCtr}$
- S_{m4} - the leakage of one out of two air bleeder valves behind the HP compressor with the assumed 10% HPC compression drop, 2.2% LPC compression drop, 4.9% mass flow rate increase of the working medium forced through the HP compressor and 2.8% mass flow rate increase of that forced through the LP compressor
- S_{m5} - the defect of the automatic fuel supply system of the engine, resulting in engine acceleration; it was assumed that the time of the working medium pressure increase behind the HP compressor, supplied in the same range, was shortened from 15 s to 10 s.

The „ typically " deformed stationary characteristics of the serially cooperating axial compressors, shown in Fig.2 and 3, were elaborated under the assumption that the engine control system keeps rotational speed of the rotor units constant, regardless of changes being introduced to the flow passage technical state.

It is revealed from the figures that in each of the considered cases a defect introduced to the system determines new working conditions of the gasodynamically coupled flow machines. The obtained stratification effect of the isodrome characteristics is, in the case of the uniform fouling of the inter-blade passages of the compressors, an intensity measure of the modelled defect whose character was verified by experiments [3,5,6].

The modelled leakages of the inter-compressor passage and of the air bleeder valve behind the HP compressor as well as the defect of the fuel supply system should be considered as a preliminary analysis of the problem, which still requires to be experimentally verified.

In order to mathematically model the analyzed unserviceability states, vectorial stratification procedures were applied to the calculated regression functions which analytically describe the co-working compressors [4,5].

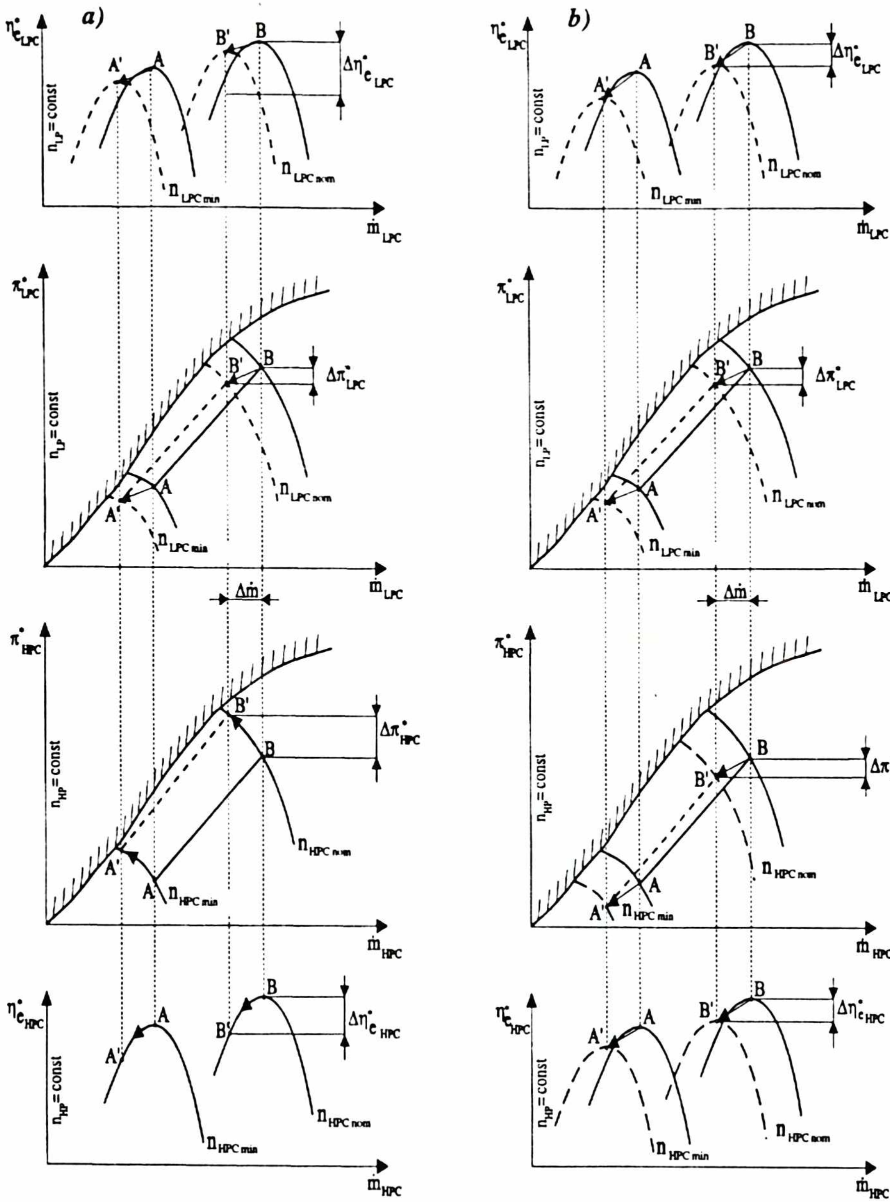

Fig.2. Course changes of the efficiency and compression characteristics of the LP and HP compressors versus working medium mass flow rate, caused by:
a) fouling the LPC inter-blade passages b) fouling the LPC and HPC inter-blade passages
A, B -operating points of the serviceable (clean) system A', B' - operating points at flow passage fouling

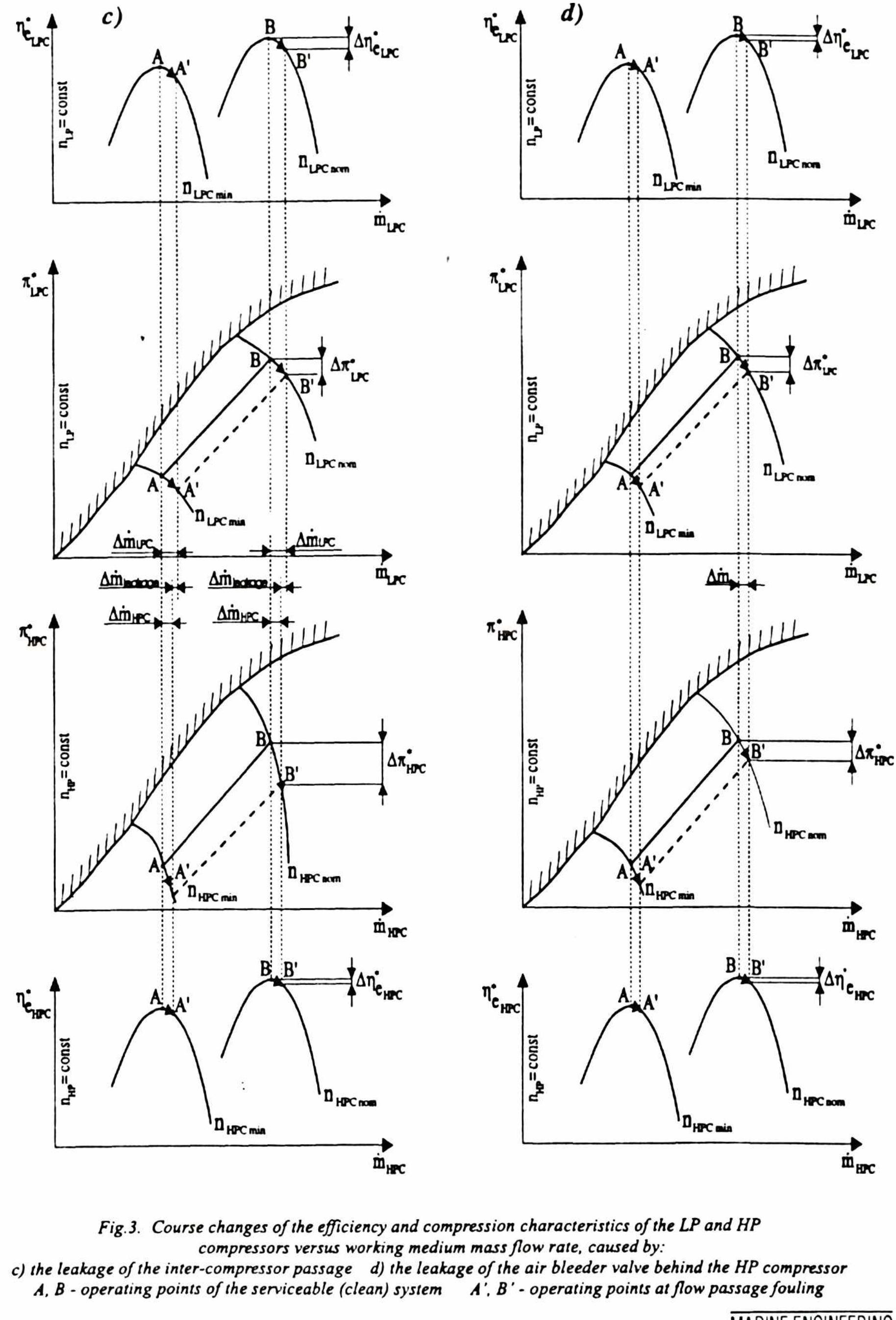

Fig.3. Course changes of the efficiency and compression characteristics of the LP and HP compressors versus working medium mass flow rate, caused by:
c) the leakage of the inter-compressor passage d) the leakage of the air bleeder valve behind the HP compressor
A, B - operating points of the serviceable (clean) system A', B' - operating points at flow passage fouling

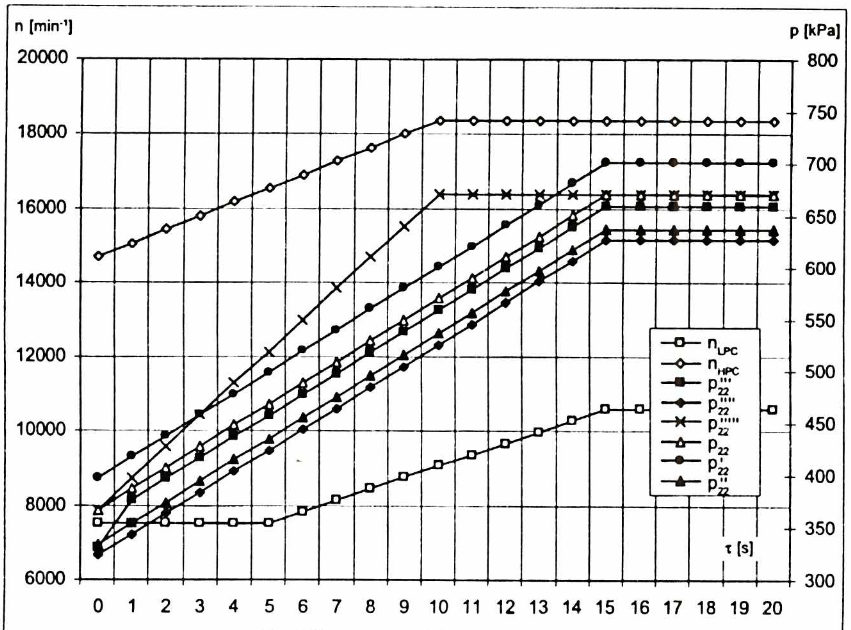

Fig.4. Time courses of the input magnitudes

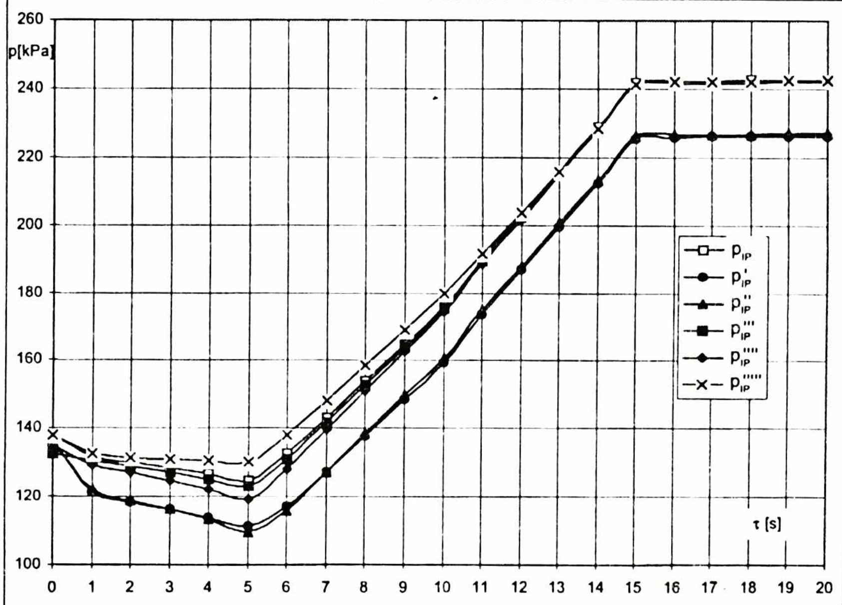

Fig.5. Time courses of the working medium pressure accumulated in the intercompressor space

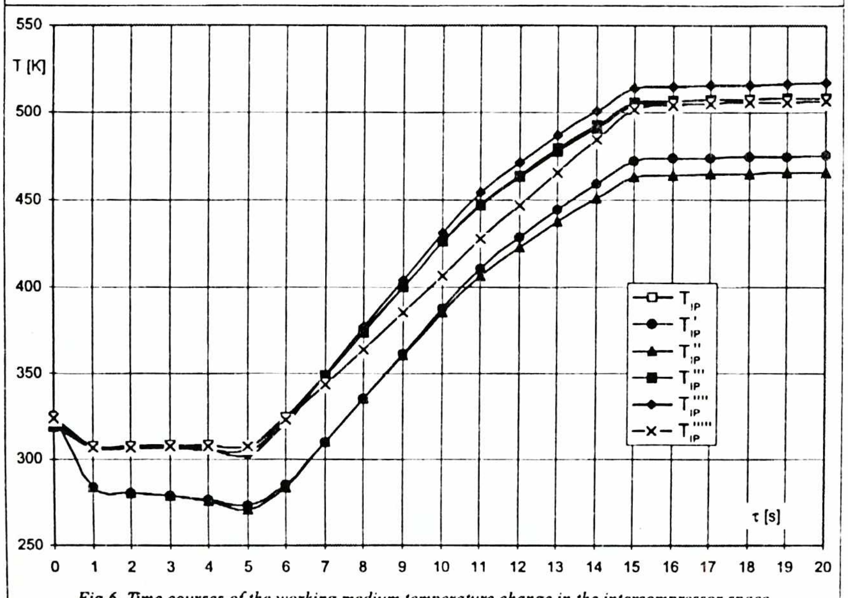

Fig.6. Time courses of the working medium temperature change in the intercompressor space

SIMULATION INVESTIGATIONS

The acceleration process of the compressor system rotor units having the modelled defects was investigated by means of simulation. Its aim was to determine influence of changes of the parameters which characterize mechanical structure of the analyzed machine, on its dynamic properties. In Fig.4 courses of the input signals versus time are illustrated.

The magnitudes marked by ('),.....,(''''') refer to the system with the introduced unserviceability states S_{m1}, S_{m2}, S_{m3}, S_{m4}, S_{m5}, respectively. The magnitudes without the indices refer to the standard courses of the serviceable system.

Four characteristic stages can be distinguished in the simulated acceleration process:

I stage - which lasts the first 5 seconds of simulation. HPC rotor starts accelerating at yet unchanged rotational speed of the LP compressor rotor. The ram-effect pressure of the working medium at the control intersection 2.2, which governs network characteristics of the system, grows. As the rotational speed of the LPC and HPC rotors was assumed unchanged regardless of the defects being introduced to the system, some changes of the pressure p'_{22} behind the system must appear to compensate the assumed stable state.

II stage - which begins at 5th second with increasing the LPC's rotor rotational speed and terminates at 10th second when the HPC rotor rotational speed is stabilized.

III stage - which is contained between 10th and 15th seconds. The LPC rotor accelerates, ram-effect pressure of the working medium behind the system grows, at the stabilized rotational speed of the HPC rotor.

IV stage - which starts at 15th second and is characterized by stable values of all the input magnitudes.

In result of the simulation, courses of the parameters which characterize the energy state of the flow path of the engine compressor system, being a response of the system to the assumed input, were obtained. Courses of the state parameters of the process versus time for the intercompressor passage, are presented in Fig.5, 6 and 7.

Comparative analysis of the working medium pressure accumulated in the intercompressor space reveals that a small increase of the instantaneous values of p_{IP} appears only while forcing the acceleration of the engine (Fig.5). The maximum deviation of the instantaneous pressure values does not exceed 6 kPa and appears at the end of I stage of the simulated process. The remaining defects being introduced to the system cause the following drops of the instantaneous values of p_{IP}:

- due to the flow passage leakage - small (of only 5 kPa) and transient drop
- due to the inter-blade passage fouling of the compressors - intensive (of 16 kPa) and permanent drop.

The courses of changes of the working medium temperature in the inter-compresor space, shown in Fig.6, confirm that the system is most sensitive to fouling the flow passages of the compressors. The deviation of the instantaneous values of T_{IP} due to fouling simultaneously the LP and HP compressors reaches 41 K during the last stage of the simulated process. Changes of the instantaneous values of T_{IP} due to introduction of

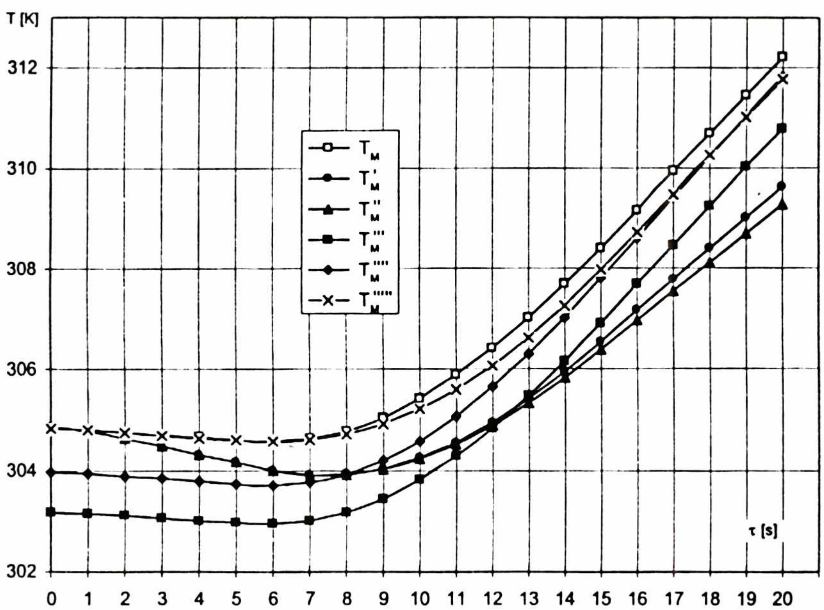

Fig.7. Time courses of the average temperature of the intercompressor passage structural components

the remaining defects to the system do not exceed, respectively, in the case of:

- forcing the engine to accelerate: - 19 K
- leakage of the air bleeder valve behind the HPC: 10 K
- leakage of the inter-compressor passage: 2 K.

The simulation results demonstrate that all the modelled defects, regardless of a phase of the acceleration process, cause dropping the instantaneous values of the average temperature of the inter-compressor passage structural elements, relative to those characterizing the standard (of no defects) system (Fig.7). The highest changing intensity of T_M, especially during I and II stage of the process, is revealed by the system with the leaking inter-compressor passage. The fouling of the inter-blade passages, especially in the case of the simultaneous fouling of both cooperating compressors, lead to the highest drop of the instantaneous values of T_M during the last stage of the simulated process. Forcing the engine to accelerate as well as the leakage of the air bleeder valve, which shape the network characteristics behind the HP compressor, do not substantially influence changing the T_M course. Deviations of the instantaneous values of the temperature do not exceed - 0.4 K and - 0.8 K, respectively.

DIAGNOSTIC PARAMETER FIELD OF TOLERANCE

Marine gas turbine producers define a set of the basic diagnostic parameters possible to be determined by a gas turbine user during its operation at sea. They establish also the tolerance limits within which values of the parameters should be kept during the exploitation process. The values characterize functioning quality of an engine and make determining the general technical state of it possible. Exceedance of the established limits by anyone of the diagnostic parameters is a signal of an inadmissible disturbance of energy processes of the engine, which can lead to its failure.

In the situation its operator should start localizing the defect and make efforts to gain detail information about the technical state of each its functional module. Therefore analyzing much greater number of diagnostic parameters is required, whose values, when approaching to limits of the operation field of tolerance, would signal symptoms of slight changes of technical state, which are characteristic of „oncoming" unserviceability state. Therefore it can be concluded that the exactness of determination of the diagnostic tolerances determines thoroughness and quality of a diagnosis [1].

The problem of selection of a set of appropriate diagnostic parameters and of their exploitation tolerances is particularly complex while analyzing the engine dynamic properties. One of the very effective means, possible to be used in searching for an analytical solution of the problem, is application of the notion of **the distance between functions**, known from the classic mathematical analysis [7].

The distance between two continuous functions $X(\tau)$ and $X'(\tau)$ can be determined from the following formula:

$$J = \sqrt{\int_{\tau=0}^{\tau=t} [X(\tau) - X'(\tau)]^2 d\tau} \tag{3}$$

If forms of the compared functions are unknown, but a set of discrete values of recorded dynamic processes are available, the functional J(x, x'), called **the metric**, can be determined, the value of which, calculated for the selected pair of elements { x, x' } of the compared process courses, stands for the distance between the points x and x'. The so defined metric can be used in two ways:

- to quantitatively assess the process courses - by calculating its average value:

$$J(x,x') = \sqrt{\sum_{\tau=1}^{t} (x_\tau - x'_\tau)^2} \tag{4}$$

- to qualitatively assess the process courses - by calculating its maximum value:

$$J_{\max}(x,x') = \max_{0 \le \tau \le t} |x_\tau - x'_\tau| \tag{5}$$

In both cases the number which expresses the definite distance between the compared sets is the metric value. The geometric meaning of the distance is highlighted in Fig.8.

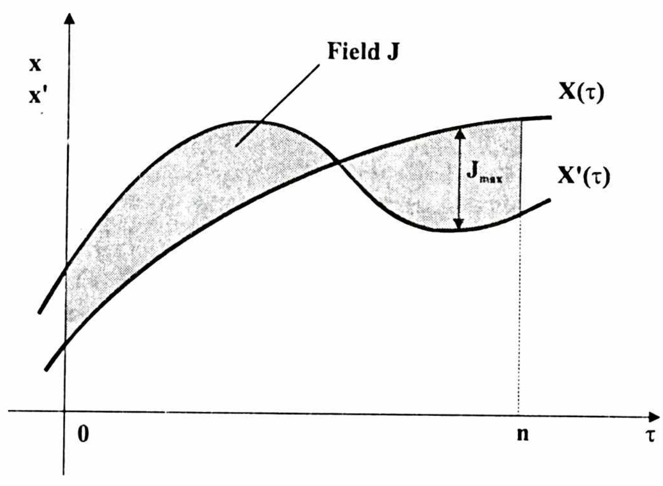

Fig.8. Geometric interpretation of function distance

The notion of **the reference metric** whose dimensionless value can serve as an universal comparative index for all the analyzed processes is introduced in order to make possible a comparative analysis of a greater number of the dynamic processes recorded in the form of different sets of function discrete values.

$$\delta J = \sqrt{\sum_{\tau=0}^{t} \frac{(x_\tau - x'_\tau)^2}{x_\tau}} 100\% \tag{6}$$

The metric value defined by (6) is the value of the diagnostic parameter which quantitatively characterizes a given unserviceability state, if X_τ is a discrete value set of control parameter course changes during acceleration of a considered defect-free engine system (standard one) and X'_τ is a course of changes of the same parameter for the system with a defect. The metric value is used as a diagnostic sensitivity measure of the control parameter against the occurred defect. The values of metrics (of diagnostic parameters) δx_j shown in percentages in table, were determined by comparing the standard time courses of the thermogasodynamic parameters, recorded during simulation of the acceleration process of the serviceable engine compressor system, with the relevant time courses of the system containing the modelled unserviceability states S_{m1}, S_{m2}, S_{m3}, S_{m4}, S_{m5}.

The metric values δx_j for the modelled unserviceability states of the compressor system of DR76 naval gas turbine

		S_{mi} unserviceability state				
		S_{m1}	S_{m2}	S_{m3}	S_{m4}	S_{m5}
δx_j diagnostic parameter	δT_{IP}	38.3	41.7	2.1	6.9	9.2
	δT_M	2.1	2.3	2.3	1.1	0.4
	δp_{IP}	38.9	38.3	5.4	8.7	9.2
	δm_{IP}	3.2	6.4	4.1	10.2	16.6
	$\delta \tau_p$	16.3	22.8	7.8	17.0	24.9
	δn_{HPCzr}	20.5	22.4	1.0	3.4	4.8
	$\delta \dot{\pi}_{LPC}$	38.7	38.1	5.1	8.0	8.3
	$\delta \dot{\pi}_{HPC}$	70.6	14.7	9.1	32.7	34.6
	$\delta \dot{m}_{LPC}$	17.5	18.5	6.1	8.0	8.5
	$\delta \dot{m}_{HPC}$	10.7	11.5	6.8	16.4	19.1
	$\delta \dot{m}_{HPCo}$	17.5	18.4	2.9	8.0	8.5
	$\delta \dot{\eta}_{LPC}$	66.9	66.9	5.2	10.9	8.4
	$\delta \dot{\eta}_{HPC}$	44.6	45.1	3.7	7.7	62.9
	$\delta \dot{p}_{21}$	38.7	38.1	5.0	8.0	8.3
	$\delta \dot{p}_{12}$	38.3	37.7	5.1	7.9	8.3
	$\delta \dot{p}_{22}$	26.8	29.3	13.5	38.6	42.3
	$\delta \dot{T}_{21}$	38.2	41.7	2.1	6.9	9.3
	$\delta \dot{T}_{12}$	38.1	41.6	2.1	6.8	9.3
	$\delta \dot{T}_{22}$	9.1	24.3	4.1	7.1	31.0

QUANTITY OF DIAGNOSTIC INFORMATION

The technical state of each module of the naval gas turbine may be described even by quite a large set of diagnostic parameters (directly measurable and computational ones), preliminarily determined by analyzing its functional scheme. It is not reasonable to perform the analysis of all possible parameters during diagnostic investigations and it should be reduced to searching for an optimum set of them by the use of which it is possible to control the state and localize the identifiable (known and typical) defects of the engine. Therefore it is necessary to minimize the elaborated set of hypothetical diagnostic parameters in compliance with the following criteria:

- criterion of the maximum quantity of gained information about unserviceability states
- criterion of diagnostic dependability of an investigated type of engine.

Such situation should be aimed at that a finally verified set of parameters would make identification of each unserviceability state of an analyzed structural component possible. An ideal situation would be if a single diagnostic parameter unequivocally characterized a given defect. However in the case of gas turbines several possible unserviceability states can be related to a single diagnostic parameter as it resulted from the performed investigations [2, 3].

An uncertainty level analysis of the determined set of unserviceability states is usually performed in order to rationally select diagnostic parameters. The quantity of the diagnostic information on engine's technical state contained in each of the analyzed parameters can be determined (according to Shannon) by means of:

- **unconditional entropy** - being an uncertainty measure of a set of unserviceability states:

$$E(S_n) = -\sum_{i=1}^{k} p_{bi} \log_2 p_{bi} \qquad (7)$$

where:

S_n - finite set of engine unserviceability states

k - number of possible unserviceability states forming the set S_n

p_{bi} - occurence probability of one of possible unserviceability states

- **average conditional entropy** - which makes it possible to calculate an uncertainty drop of a set of unserviceability states provided that δx_j value of one (consecutive) diagnostic parameter is determined:

$$E(S_n / \delta x_j) = p_{bj}(\delta x_j) E_{\delta x_j}(S_n) + p_{bj}(\overline{\delta x_j}) E_{\overline{\delta x_j}}(S_n) \qquad (8)$$

where:

δx_j - diagnostic parameter value

$\overline{\delta x_j}$ - value opposite to δx_j ($\overline{\delta x_j} = 1 - \delta x_j$)

$p_{bj}(\delta x_j)$, $p_{bj}(\overline{\delta x_j})$ - probability of reaction of the parameter δx_j to engine's unserviceability states, and that of no $\overline{\delta x_j}$ reaction of to these states, respectively

$E_{\delta x_j}(S_n)$, $E_{\overline{\delta x_j}}(S_n)$ - conditional entropy values of the set of unserviceability states after determination of δx_j diagnostic parameter value, respectively for the sub-set of the states to which the parameter δx_j reacts and the sub-set of the states to which the parameter $\overline{\delta x_j}$ does not react.

The quantity of diagnostic information on S_n unserviceability states, which is contained in δx_j, can be obtained by using the following expression:

$$I_{\delta x_j \to S_n} = E(S_n) - E(S_n / \delta x_j) \qquad (9)$$

Mutual relationships between the finite set of the unservice ability states S_{ni} of the compressor system and the δx_j diagnostic parameters identifiying the states, can be presented by means of the so called **diagnostic matrices** shown in Fig.9. It was assumed that „1" has to be put into the cell at the j-th matrix row and i-th column crossing, if the δx_j diagnostic parameter reacts to the unserviceability state S_{ni} by 10% exceedance of the tolerance field limits ($\delta x_j > 10\%$). If a parameter does not react to the unserviceability state, „0" has to be put in. In the last column of matrix 1 (Fig.9) the quantity of diagnostic information obtained from (9) has to be put in. By applying the criterion of $I_1 = max$ fourteen diagnostic parameters can be selected which contain the identical information quantity $I_1 = 0.971$. However that parameter is selected first which is most easily measurable for structural reasons.

In the considered case δp_{IP} pressure of the working medium accumulated in the inter-compressor space was selected. It should be observed that a diagnostic parameter which reacts (or does not react) to all unserviceability states bears no diagnostic information, e.g. in the case of δT_M and $\delta \dot{p}_{22}$ the information quantity $I_1(\delta T_M) = 0$ and $I_1(\delta \dot{p}_{22}) = 0$ respectively is obtained.

In the consecutive selection stages (see matrices 2 and 3 in Fig.9), by transforming the diagnostic matrices and using some available generalized calculation procedures [2] , the next parameters can be determined in a relatively simple way, which contain the maximum information quantity provided that the first, second and consecutive diagnostic parameter were earlier selected.

The diagnostic dependability of the system is also analyzed in each case. The selection is carried out until full diagnostic information about the system state is obtained.

If it is assumed that „k" unserviceability states of the compressor system, S_{ni} , i = 1, 2, ...k, form a set of equally probable events of $p_{bi} = 1/k$, which is practically confirmed [2, 3] in the case of gas turbines, the following expression can be obtained:

Matrix 1

δx_j diagnostic parameter			S_{ni} unserviceability S_{n1}	S_{n2}	S_{n3}	S_{n4}	S_{n5}	I_1
	1	δT_{IP}	1	1	0	0	0	0.971
	2	δT_M	0	0	0	0	0	0
	3	δp_{IP}	1	1	0	0	0	0.971
	4	δm_{IP}	0	0	0	1	1	0.971
	5	$\delta \tau_p$	1	1	0	1	1	0.722
	6	δn_{LPCzr}	1	1	0	0	0	0.971
	7	$\delta \pi^*_{LPC}$	1	1	0	0	0	0.971
	8	$\delta \pi^*_{HPC}$	1	1	0	1	1	0.722
	9	$\delta \dot{m}_{LPC}$	1	1	0	0	0	0.971
	10	$\delta \dot{m}_{HPC}$	1	1	0	1	1	0.722
	11	$\delta \dot{m}_{HPCo}$	1	1	0	0	0	0.971
	12	$\delta \eta^*_{LPC}$	1	1	0	1	0	0.971
	13	$\delta \eta^*_{HPC}$	1	1	0	0	1	0.971
	14	δp^*_{21}	1	1	0	0	0	0.971
	15	δp^*_{12}	1	1	0	0	0	0.971
	16	δp^*_{22}	1	1	1	1	1	0
	17	δT^*_{21}	1	1	0	0	0	0.971
	18	δT^*_{12}	1	1	0	0	0	0.971
	19	δT^*_{22}	0	1	0	0	1	0.971

Matrix 4

δx_j diagnostic parameter			S_{ni} unserviceability S_{n1}	S_{n2}	S_{n3}	S_{n4}	S_{n5}
	3	δp_{IP}	1	1	0	0	0
	19	δT^*_{22}	0	1	0	0	1
	4	δm_{IP}	0	0	0	1	1

Fig. 9. Determination scheme of the minimum number of diagnostic parameters

Matrix 2

			d_1		d_2			I_2
			S_{n1}	S_{n2}	S_{n3}	S_{n4}	S_{n5}	
δx_j diagnostic parameter	3	δp_{IP}	1	1	0	0	0	0
	1	δT_{IP}	1	1	0	0	0	0
	4	δm_{IP}	0	0	0	1	1	0.551
	5	$\delta \tau_p$	1	1	0	1	1	0.551
	6	δn_{HPCzr}	1	1	0	0	0	0
	7	$\delta \pi^*_{LPC}$	1	1	0	0	0	0
	8	$\delta \pi^*_{HPC}$	1	1	0	1	1	0.551
	9	$\delta \dot{m}_{LPC}$	1	1	0	0	0	0
	10	$\delta \dot{m}_{HPC}$	1	1	0	1	1	0.551
	11	$\delta \dot{m}_{HPCo}$	1	1	0	0	0	0
	12	$\delta \eta^*_{LPC}$	1	1	0	1	0	0.551
	13	$\delta \eta^*_{HPC}$	1	1	0	0	1	0.551
	14	δp^*_{21}	1	1	0	0	0	0
	15	δp^*_{12}	1	1	0	0	0	0
	17	δT^*_{21}	1	1	0	0	0	0
	18	δT^*_{12}	1	1	0	0	0	0
	19	δT^*_{22}	0	1	0	0	1	0.951

Matrix 3

			d_1	d_2	d_3	d_4		I_3
			S_{n2}	S_{n1}	S_{n5}	S_{n3}	S_{n4}	
δx_j diagnostic parameter	19	δT^*_{22}	1	0	1	0	0	0
	4	δm_{IP}	0	0	1	0	1	0.4
	5	$\delta \tau_p$	1	1	1	0	1	0.4
	8	$\delta \pi^*_{HPC}$	1	1	1	0	1	0.4
	10	$\delta \dot{m}_{HPC}$	1	1	1	0	1	0.4
	12	$\delta \eta^*_{LPC}$	1	1	0	0	1	0.4
	13	$\delta \eta^*_{HPC}$	1	1	1	0	0	0

$$E(S_n) = -\sum_{i=1}^{k} \frac{1}{k}\log_2\frac{1}{k} = \log_2 k \tag{10}$$

As k = 5 for the considered system, the unconditional entropy is:

$$E(S_n) = \log_2 5 = 2.322 \tag{11}$$

The selected diagnostic parameters δp_{IP}, $\delta T^{\bullet}_{22}$ and δm_{IP} presented in matrix 4 of Fig.9, contain full diagnostic information about the technical state of the compressor system. The condition which unequivocally determines the preliminary uncertainty measure of the considered states:

$$E(S_n) = I_1(\delta p_{IP}) + I_2(\delta T^{\bullet}_{22}) + I_3(\delta m_{IP}) \tag{12}$$

It can be concluded, when analyzing the minimized set of the diagnostic parameters, that an intensive fouling of the LPC inter-blade passages (S_{n1} unserviceability state) happens, if the result of $\{\delta p_{IP}, \delta T^{\bullet}_{22}, \delta m_{IP}\} = \{1,0,0\}$ appears during the diagnostic investigation. No identical result appears elsewhere.

The simultaneous intensive fouling of the inter-blade passages of both cooperating compressors (S_{n2} unserviceability state) is unequivocally defined by the result of $\{\delta p_{IP}, \delta T^{\bullet}_{22}, \delta m_{IP}\} = \{1,1,0\}$. The leakage of air bleeder valve (S_{n4} unserviceability state) can be identified in a similar way: $\{\delta p_{IP}, \delta T^{\bullet}_{22}, \delta m_{IP}\} = \{0,0,1\}$, as well as the defect of the engine fuel supply system (S_{n5} unserviceability state): $\{\delta p_{IP}, \delta T^{\bullet}_{22}, \delta m_{IP}\} = \{0,1,1\}$. The obtained result of $\{\delta p_{IP}, \delta T^{\bullet}_{22}, \delta m_{IP}\} = \{0,0,0\}$ signalizes that the engine compressor system is serviceable. The modelled defect of S_{n3} type did not cause any substantial disturbance in functioning of the engine, which could lead to exceeding the tolerance field limits of the selected set of the diagnostic parameters.

CONCLUSIONS

- The proposed method of application of the computer simulation to naval gas turbine diagnostics can be an important complement to the basic experimental diagnostic methods. The presented methodic way of rational selection of appropriate diagnostic parameters of the compressor system can be extended to similar analyses of mutual „defect- symptom" relationships of the remaining engine structural components. In result it would make it possible to obtain the finite and complete set of the exploitation unserviceability states as well as the minimized set of the diagnostic parameters which allow for identifying the states.
- The presented simulation method of the unserviceability states of the engine compressor system subject to diagnosis as well as the performed qualitative and quantitative assessment of the allowable deviations of dynamic processes need to be verified during multi-year exploitation of real objects. Experimental methods of establishing the diagnostic tolerances should be deemed basic and final ones in this case.

NOMENCLATURE

d	-	partition group
E(S)	-	entropy of the set of states
h	-	specific enthalpy
HP, HPC	-	respectively: high pressure system shaft and high pressure compressor #
I	-	diagnostic information quantity
IGV	-	inlet guide vanes #
IP	-	intercompressor passage #
J	-	functional, distance between two functions
L	-	length
LP, LPC	-	respectively: low pressure system shaft and low pressure compressor #
m	-	mass
$\dot{m}$	-	mass flow rate
n	-	rotational speed
p	-	pressure
p_h	-	probability
S	-	state
S_m	-	modelled unserviceability state
S_n	-	finite set of unserviceability states
t	-	duration time of transient process
T	-	absolute temperature
V	-	volume
α	-	vane angle
δ	-	relative value, change
η	-	efficiency
π	-	compression ratio
τ	-	time

Note: *the above specified notations marked "#" are also used as indices*

Other indices

c	-	constant
e	-	effective
f	-	flow
i	-	i-th state number or i-th finite set of states number
j	-	j-th parameter number
max	-	maximum
min	-	minimum
M	-	composite material
nom	-	nominal
o	-	standard, design state
ot	-	surrounding
zr	-	reffered to ambient ISA (standard atmosphere)
1.1, *2.1*, *1.2*, *2.2*	-	control intersection numbers: the first figure denotes an intersection behind or in front of a compressor, the second figure - the next compressor within the series configuration, e.g.: 1.2 - control intersection in front of the second compressor.
•	-	total value of a parameter

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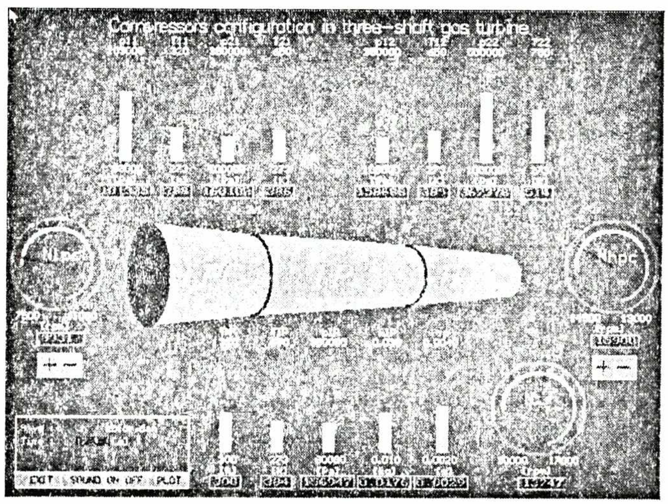

View of the computer simulator of the axial compressors that operate within marine gas turbine configuration applicable to training purposes