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Entropy function application in the selection process of diagnostic parameters of marine diesel and gas turbine engines

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ABSTRACT

The article presents the method of analysing the diagnostic informativeness of the parameters characterizing gas dynamic processes observed inside the working spaces of marine diesel and gas turbine engines. The entropy function was used as the measure of indeterminacy of the identified set of engine unserviceability states. Based on numerical simulation experiments of the analysed gasodynamic processes, the amount of introduced diagnostic information was assessed and the most adequate parameters for the technical state of the engine were selected. These parameters compose the minimised set of diagnostic parameters which make it possible to assess unmistakably the technical state of the examined working spaces.

Keywords: marine diesel and gas turbine engines; diagnostics; diagnostic informativeness; entropy function

INTRODUCTION

Diagnostic investigation is a basic element of the diagnostic process of each technical device [1]. A diagnostician, expert in the given branch, collects so-called primary information on the examined object from organoleptic examination, or by measuring parameters of the signals generated by the object.

In the next step of the diagnostic activity the expert (diagnostician) performs a so-called measurement-based inference. He creates a set of symptoms, analyses it and formulates a preliminary diagnosis about the technical state of the machine based on his knowledge about past defects. Usually the created set of symptoms corresponds to a number of possible defects, therefore the diagnostician makes attempts to gain additional diagnostic information (symptoms), using more and more sophisticated (expensive and technically complicated) methods and means, to be able to eliminate less possible defects. An ideal situation is when only one possibility remains, being the final diagnosis characterised by a given probability [4].

The "bottleneck" of the diagnostic process organised in the above way, especially when it refers to technical objects of high complexity level, is the diagnostic knowledge resulting from the past experience of the diagnostician. This experience referring to the defect-symptom relations is gained from:

- experts' opinions,
- experimental investigations on a real object:
  - active experiments – with the introduction of real defects to the machine,
  - passive experiments – with many years' observation of a large number of examined machines of the same type, without interference into their technical state,
- simulation experiments on specially developed computer codes – with possible modelling of different types of machine defects.

Due to the dynamic development of the widely understood computer science and technology, in the next years to come the computer simulation methods can become very useful diagnostic tools. However, significant limitation in their practical application is the problem of experimental verification of the computer codes used for the simulation. The only way to confirm the credibility of the diagnostic simulation experiments is still the testing examination done on model rigs (or, if possible, on real objects), done with the aid of the traditional analogue technique.

DIAGNOSTIC PARAMETER TOLERANCE RANGE

Producers of marine internal combustion engines of both piston and turbine construction define a set of basic diagnostic parameters which can be determined by the user in sea conditions. They also give tolerance limits within which the values of these parameters should remain during engine operation. The parameters characterise the quality of engine operation and make it possible to assess its general technical state. When the value of any parameter goes beyond the given limits, it is a signal of inadmissible disturbance of the energy conversion processes taking place in the engine, and a threat of failure.

In this situation the user should begin to localise the defect by making attempt to collect detailed data on the technical state of particular functional modules. He has to analyse a large number of diagnostic parameters whose values, nearing the limits of the operating tolerance ranges, can be the symptoms of small technical state changes, characteristic for the "approaching" state of unserviceability. All this leads to a conclusion that precise assessment of the diagnostic tolerances determines the depth and quality of the formulated diagnosis [1].

The problem with selecting a set of adequate diagnostic parameters and limits of their operating tolerance is particularly complicated when analysing dynamic characteristics of the engine. An effective tool which can be used in searching an analytical solution to this problem is the concept of the distance between functions, known from the classical mathematical analysis [8] – Fig.1.

The distance between two continuous functions X(τ) and X'(τ) is defined as:

$$J = \sqrt{\int_{\tau=0}^{\tau=t} [X(\tau) - X'(\tau)]^2 d\tau} \qquad (1)$$

where:

X(τ) – known form of the function which maps the time-history of changes of the diagnostic parameter of the fully serviceable engine;

X'(τ) – known form of the function which maps the time-history of changes of the diagnostic parameter of the technically unserviceable engine.

When the forms of the compared functions are not known, and the only information about them is given in the form of discrete values of the recorded dynamic time-histories, we can calculate the functional J(x, x'), bearing the name of metric, whose value for a given pair of elements {x, x'} of the compared time-histories is the distance between points x and x'. The metric defined in the above way can be used in two ways:

- for quantitative assessment of the time-histories – as the averaged value [8]:

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

- for qualitative assessment of the time-histories – ands the maximum value [8]:

$$J_{max}(x, x') = \max_{0 \le \tau \le t} |x_\tau - x'_\tau| \qquad (3)$$

where:

x(τ) – discrete value of the diagnostic parameter of the fully serviceable engine;

x'(τ) – discrete value of the diagnostic parameter of the technically unserviceable engine.

In both cases the value of the metric will be a number which expresses a certain dimension of the distance between the compared sets. The geometrical sense of the distance is explained in Fig. 1.

In order to perform a comparison analysis of a larger number of the recorded dynamic time-histories, given in different sets (units) of discrete function values, a concept of the referential metric is introduced, whose dimensionless value can be a general comparative factor for all analysed time-histories:

$$\delta J = \sqrt{\sum_{\tau=0}^{t} \left(\frac{x_\tau - x'_\tau}{x_\tau} \right)} 100\% \qquad (4)$$

If X_τ is the set of discrete values of the time-history of changes of the (reference) control parameter recorded during the acceleration of the analysed machine system without defects and X'_τ is the time-history of changes of the same parameter for the system with a defect, then the value of the metric defined by formula (4) will be the value of the diagnostic parameter which characterises certain state of unserviceability, in a quantitative aspect. This value can be considered the measure of diagnostic sensitivity of the parameter.

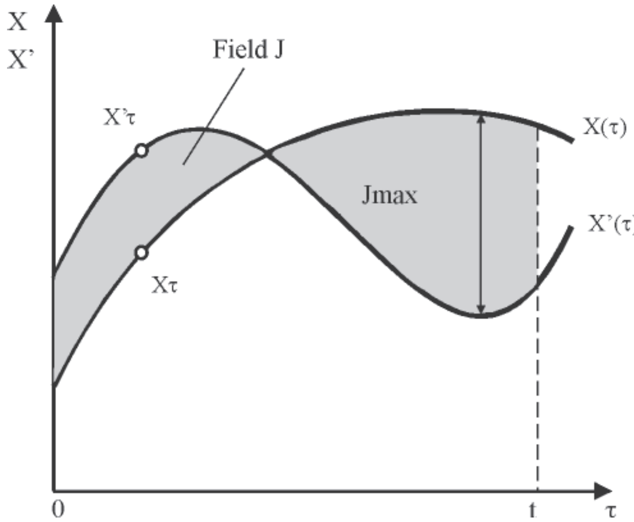

Fig. 1. Geometric interpretation of the distance between two functions recorded in the form of sets of discrete values

AMOUNT OF DIAGNOSTIC INFORMATION

The technical state of each module of the marine internal combustion engine is described by a relatively large set of diagnostic parameters (either directly measured or calculated), which could be initially determined after analysing its functional scheme. The analysis of all possible parameters in the diagnostic examination process is pointless and should be reduced to the optimal set of parameters which secures the control of the technical state of the engine and localisation of the identifiable (known and typical) engine defects. Therefore the hypothetical set of diagnostic parameters defined in the initial stage of the diagnostic process is to be minimised taking into account the following criteria:

- maximal amount of the introduced diagnostic information about the unserviceability states,
- diagnostic sensitivity of the examined engine type.

An attempt is to be made to reach a state in which the finally verified set of parameters provides opportunities for identification of each of operational unserviceability states of the analysed construction unit. The ideal situation is when one diagnostic parameter characterises unmistakably one certain fault. However, as results from the performed investigations [3, 7], in case of marine internal combustion engines one diagnostic parameter corresponds, as a rule, to a number of possible unserviceability states.

In order to perform a rational selection of diagnostic parameters, the degree of indeterminacy of the selected set of unserviceability states is analysed. According to Shannon, the amount of diagnostic information about the technical state of the engine which is carried by each analysed parameter can be assessed using:

- unconditional entropy – as the measure of indeterminacy of the set of unserviceability states:

$$E(S_n) = -\sum_{i=1}^{k} p_{bi} \log_2 p_{bi} \tag{5}$$

where:

S_n – finite set of engine unserviceability states,

k – number of possible unserviceability states composing the set S_n,

p_{bi} – probability of appearance of one of possible unserviceability states.

- averaged conditional entropy – which makes it possible to calculate the decrease of the indeterminacy of the set of unserviceability states after one (successive) diagnostic parameter δx_j is determined:

$$E(S_n/\delta x_j) = p_{bj}(\delta x_j)E_{\delta x_j}(S_n) + p_{bj}(\overline{\delta x_j})E_{\overline{\delta x_j}}(S_n) \tag{6}$$

where:

δx_j – diagnostic parameter value

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

$p_{bj}(\delta x_j)$, $p_{bj}(\overline{\delta x_j})$ – probability with which the parameter δx_j reacts to engine unserviceability states, and the probability at which $\overline{\delta x_j}$ does not react,

$E_{\delta x_j}(S_n)$, $E_{\overline{\delta x_j}}(S_n)$ – conditional entropies of the unserviceability set after determining the diagnostic parameter δx_j for the subset of states to which the parameter δx_j reacts and the subset of state to which $\overline{\delta x_j}$ does not react, respectively.

The amount of diagnostic information about the engine unserviceability states S_n which is carried by the parameter δx_j can be calculated using the formula:

$$I_{\delta x_j \to S_N} = E(S_n) - E(S_n/\delta x_j) \tag{7}$$

SAMPLE RESULTS OF EMPIRICAL INVESTIGATIONS

The applicability of the proposed method to the process of selection of diagnostic parameters with the aid of the entropy function was verified using the results of past numerical experiments simulating gasodynamic processes realised in the working spaces of the selected marine engines: a medium speed diesel engine with pulsating turbo pressure charging system, and a three-shaft gas turbine engine with a separate power turbine [5, 6]. The mathematical models of processes, developed for this purpose, made it possible to simulate selected known and recognisable defects of the constructional structure of the examined engines, which are most frequently observed in the engine operation process.

The marine diesel engine

The states of engine unserviceability and the state of its full serviceability, which are used in the analysis, were obtained as a result of mathematical modelling of gasodynamic processes taking place in the working spaces of the marine engine. The analysed time-histories of gasodynamic parameters (temperature T, pressure p, and the speed v of the exhaust gas pressure peak amplitude displacement) were calculated for the selected control section of the exhaust gas outlet channel (the channel which connects engine cylinders with the turbo compressor turbine). Percent values of the referential metrics (diagnostic parameters) δx_j which are given in Tab. 1, were assessed by comparing the standard time-histories of gasodynamic parameters recorded during the simulation of engine processes in full serviceability conditions, and corresponding curves recorded for the engine with the modelled operational unserviceability states S_{n1}, S_{n2}, S_{n3}, S_{n4}, S_{n5}, S_{n6}, S_{n7}, S_{n8}, S_{n9}, S_{n10}, S_{n11}, S_{n12}, S_{n13} and S_{n14}.

Mutual relations between the finite set of engine working space unserviceability states S_{ni} and diagnostic parameters δx_j, identifying those states can be clearly presented using so called diagnostic matrices – Tab. 2. It was assumed that if the diagnostic parameter value δx_j exceeds the tolerance range limits by 10 percent or more ($\delta x_j \geq 10\%$) while reacting to the unserviceability state S_{ni}, then "1" is placed in the diagnostic matrix entry situated at the crossing of the j-th row and the i-th column. If the parameter does not react to the unserviceability state – "0" is placed. The last matrix column contains the amounts of diagnostic information calculated using formula (7).

Tab. 1. *Metric values δx_j for the modelled operational unserviceability states of the working spaces of SULZER engine 6AL20/24 type*

		Operational unserviceability states														
		S_{n1}	S_{n2}	S_{n3}	S_{n4}	S_{n5}	S_{n6}	S_{n7}	S_{n8}	S_{n9}	S_{n10}	S_{n11}	S_{n12}	S_{n13}	S_{n14}	S_{n15}
		[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]
Diagnostic parameter	δT	6.28	12.7	15.7	6.1	12.4	15.4	20.5	20.5	13.5	14	6.96	9.57	5.31	7.75	0
	δp	6.81	13.9	17.2	6.35	13	16.1	20.7	20.7	13.9	14.5	6.96	10	5.6	8.22	0
	δv	20.3	50.6	49.8	15.2	30.4	37.4	31.9	31.9	22	25	14.4	20	10.8	15.3	0

S_{n1} – decreasing outlet valve active cross-section areas in cylinders 1, 2 and 3 by 5 %,
S_{n2} – decreasing outlet valve active cross-section areas in cylinders 1, 2 and 3 by 20 %,
S_{n3} – decreasing outlet valve active cross-section areas in cylinders 1, 2 and 3 by 30 %,
S_{n4} – decreasing outlet valve active cross-section areas in cylinder 1 by 5 %,
S_{n5} – decreasing outlet valve active cross-section areas in cylinder 1 by 20 %,
S_{n6} – decreasing outlet valve active cross-section areas in cylinder 1 by 30 %,
S_{n7} – changing outlet valve opening and closing angles in cylinders 1, 2 and 3 by +5° OWK,
S_{n8} – changing outlet valve opening and closing angles in cylinders 1, 2 and 3 by -5° OWK,
S_{n9} – changing outlet valve opening and closing angles in cylinder 1 by +5° OWK,
S_{n10} – changing outlet valve opening and closing angles in cylinder 1 by -5° OWK,
S_{n11} – decreasing combustion chamber volumes in cylinder sections 1, 2 and 3 by 25%,
S_{n12} – decreasing combustion chamber volumes in cylinder sections 1, 2 and 3 by 50%,
S_{n13} – decreasing combustion chamber volumes in cylinder section 1 by 25%,
S_{n14} – decreasing combustion chamber volumes in cylinder section 1 by 50%,
S_{n15} – state of full operational serviceability of engine working spaces.

Tab. 2. Diagnostic matrix of the SULZER engine working spaces 6AL20/24 type

		Operational unserviceability states															
		S_{n1}	S_{n2}	S_{n3}	S_{n4}	S_{n5}	S_{n6}	S_{n7}	S_{n8}	S_{n9}	S_{n10}	S_{n11}	S_{n12}	S_{n13}	S_{n14}	S_{n15}	I
Diagnostic parameter	δT	0	1	1	0	1	1	1	1	1	1	0	0	0	0	0	1.000
	δp	0	1	1	0	1	1	1	1	1	1	0	1	0	0	0	0.970
	δv	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0.355

As results from the numerical data collected in the diagnostic matrix (Tab. 2), the diagnostic information maximum criterion, I = max, leads to the selection of the exhaust gas temperature as the best diagnostic parameter ($I_{\delta T}$ = 1.0). This makes it possible to reduce the diagnostic inference analysis to eight states, to which this parameter reacts, or seven remaining states, depending on the value which it reaches in the control process.

The diagnostic parameter of similar applicability is the exhaust gas pressure in the outlet channel, for which the amount of the introduced diagnostic information about the analysed technical states of the engine working spaces is equal to $I_{\delta p}$ = 0.970.

At the same time we can neglect the exhaust gas velocity which introduces the smallest amount of diagnostic information, $I_{\delta v}$ = 0.355. This parameter reacts to all analysed unserviceability states by exceeding the assumed operating tolerance limits.

In this case the selection of the adequate diagnostic parameters should be done using the criterion of control sensitivity of the examined engine type and ability to perform necessary measurements. Since the measurements of the working medium temperature reveal remarkable inertia, which forces the use of thermo-elements of an order of several tens of micrometers in diameter [9], it is the exhaust gas pressure in the outlet channel which should be selected for further analysis, as the measurement of this parameter seem to be most reasonable taking into account the marine engine diagnosing technology.

Based on the results of the diagnostic investigations of the diesel engines used in the RP Navy, it was assumed that "k" engine working space unserviceability states S_{ni}, where i = 1, ... k, compose a finite set of equally probable events p_{bi} = 1/k [3, 7]. Therefore the formula which defines the unconditional entropy takes the form:

$$E(S_n) = -\sum_{i=1}^{k} \log_2 \frac{1}{k} = \log_2 k \tag{8}$$

For the analysed system k = 15, hence the unconditional entropy:

$$E(S_n) = \log_2 15 = 3.908 \tag{9}$$

The selected diagnostic parameters δT, δp and δv, collected in the diagnostic matrix 2, include only part of the diagnostic information about the technical state of the engine working spaces. Despite the fact that the condition which unmistakably determines the initial measure of indeterminacy of the analysed states is not met:

$$E(S_n) = I(\delta T) + I(\delta p) + I(\delta v) \tag{10}$$

We can name four groups of equally probable unserviceability states. For instance, when we analyse a set of diagnostic parameters (tab. 2) we can conclude that if the result: {δT, δp, δv} = {0, 0, 1}, appears in the diagnostic examination process, this may testify to the appearance of the following unserviceability states: S_{n1}, S_{n4}, S_{n11}, S_{n13} and S_{n14}, respectively. Any identical configuration of the results of the examination does not appear anywhere except these five cases.

At the same time, equally probable appearance of the unserviceability states S_{n2}, S_{n3}, S_{n5}, S_{n6}, S_{n7}, S_{n8}, S_{n9} and S_{n10} is fully defined by the result: {δT, δp, δv } = {1, 1, 1}. In a similar way the unserviceability state S_{n12} – {δT, δp, δv } = {0, 0, 1} can be identified. When the result {δT, δp, δv } = {0, 0, 0} is obtained in the diagnostic examination process, this may signal full serviceability of the engine working spaces, provided that relation (10) is met. But this is not true, as the sum of the amounts of diagnostic information on the technical state of the engine working spaces introduced by parameters δT, δp, δv is equal to 2.325, and the unconditional entropy is equal to 3.908. To reduce the level of indeterminacy of the analysed unserviceability states (missing 1.583 of the amount of diagnostic information) we have to complete the set of diagnostic parameters in such a way that the condition (10) of the ability to make unmistakable distinction between these states is met.

The missing amount of the diagnostic information about the technical state of the engine working spaces (additional diagnostic parameters) can be obtained from the harmonic analysis of the time-histories of pressure pulsations in the exhaust gas channel recorded experimentally on real objects (with real introduction of defects to laboratory engines) and systematic observations of the thermal and flow processes on a large number of examined objects of the same type, without interference into their technical state (such observations of the engines in operation on RP Navy vessels have been conducted for three years now).

Marine gas turbine engine

Operational conditions and small control sensitivity of a gas turbine engine installed in the marine power plant impose certain limits on the possible measurements of engine operation parameters. In numerous cases, complicated and extremely expensive measuring methods, only applicable in the engine test bed, are to be used. The sea conditions do not provide opportunities for introducing defects and changes in control procedures to confirm experimentally their impact on the quality of engine functioning and lifetime, and to assess diagnostic tolerances for indirect control parameters, which define a permissible course of the realised dynamic processes. The diagnostic tolerances should take into account uniqueness of engine production, i.e. individual characteristics of each engine unit, as well as different operating conditions and times of operation which result in different rates of aging and wear of elements.

Determining the nature of mutual relations between the set of unserviceability states of functional engine modules and the set of diagnostic parameters which unmistakably identify those states is a basic goal of the diagnostic activity. A promising method of collecting so-called defect-symptom relations to be used in marine diagnostics of the gas turbine engines is modelling unserviceability states of turbine subunits with the aid of computer simulation [2, 5]. This method is extremely useful at the stage of designing the diagnostic system for engines used in marine conditions, as it makes it possible, in a relatively simple way, to:

- determine initial static and dynamic characteristics of the engine, taking into account the deformation of their time-histories resulting from the action of external conditions, production differences, and irreversible aging and wear processes,
- determine the set of possible unserviceability states for selected functional modules,
- determine a minimal set of diagnostic parameters which unmistakably identify the modelled defects.

When analysing the quality of functioning of the selected gas turbine engines, used on RP Navy vessels [4], the following unserviceability states were modelled based on the information about the defects recorded during their operation:

S_{m1} – pollution of compressor passages in SNC – assuming 10% decrease in the efficiency and mass flow rate of the working medium compressed in the compressor and 2% compression decrease,

S_{m2} – simultaneous pollution of the compressor passages in SNC and SWC – assuming 10% decrease in efficiency and mass flow rate of the working medium compressed in the compressors, along with 2% compression decrease for SNC and 7% compression decrease for SWC,

S_{m3} – leakage in the compressor passages – assuming that the mass flow rate of the "lost" working medium is equal to: $\dot{m}_{nieszczel.} = 0.05\dot{m}_{SWCzr}$,

S_{m4} – leakage in one of two air release valves behind SWC – assuming 10% decrease in SWC compression, 2.2% decrease in SNC compression, 4.9% increase of the mass flow rate of the working medium compressed in SWC and 2,8% increase of the mass flow rate of the working medium compressed in SNC,

S_{m5} – defect of the automatic engine fuel supply system which results in forcing the engine acceleration process – the time of the working medium pressure increase, set at the same range behind SWC, was assumed to be reduced from 15 to 10 seconds.

The object of simulation investigations was the process of acceleration of a three-shaft engine after introducing the modelled defects. The simulation aimed at determining the effect of changes of parameters that characterise the constructional structure of the analysed machine system on its dynamic characteristics.

Tab. 3 collects per cent values of the metrics (diagnostic parameters), which were assessed by comparing the referential time-histories of the gasodynamic parameters recorded during the simulation of the process of acceleration of the fully serviceable engine, with corresponding time-histories for the engine with the modelled unserviceability states S_{n1}, S_{n2}, S_{n3}, S_{n4} and S_{n5}. These values were calculated using the referential metric (4) in the same way as for the diesel engine, as was described in Section 4.1.

This way a set of nineteen diagnostic parameters was obtained. This set is to be minimised using the entropy function:

δT_{IP}, δp_{IP}, δm_{IP} – temperature, pressure and mass of the air accumulated in the inter-compressor space, respectively

δT_M – averaged temperature of the flow passage constructional material,

$\delta \tau_p$ – time of the air flow in the compressor space,

δn_{HPCzr} – rotational speed of the high pressure rotor (reduced to the normal atmospheric conditions at SWC inlet),

$\delta \pi^*_{LPC}$, $\delta \pi^*_{HPC}$ – compression of the low and high pressure compressor, respectively

$\delta \dot{m}_{LPC}$, $\delta \dot{m}_{HPC}$, $\delta \dot{m}_{HPCo}$ – is the mass flow rate through SNC and SWC, respectively

$\delta \eta^*_{LPC}$, $\delta \eta^*_{HPC}$ – is the SNC and SWC efficiency, respectively

δT^*_{21}, δp^*_{21} – is, respectively, the air temperature and pressure behind SNC,

δT^*_{12}, δp^*_{12} – is, respectively, the air temperature and pressure at SWC inlet,

δT^*_{22}, δp^*_{22} – is, respectively, the air temperature and pressure behind SWC.

Tab. 3. *Metric values δx_j for the modelled unserviceability states of the three shaft ZORYA marine gas turbine engine UGT3000 type*

		Operational unserviceability states				
		S_{n1}	S_{n2}	S_{n3}	S_{n4}	S_{n5}
Diagnostic parameter δx_j	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
	$\delta \pi^*_{LPC}$	38.7	38.1	5.1	8.0	8.3
	$\delta \pi^*_{HPC}$	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
	$\delta \eta^*_{LPC}$	66.9	66.9	5.2	10.9	8.4
	$\delta \eta^*_{HPC}$	44.6	45.1	3.7	7.7	62.9
	δp^*_{21}	38.7	38.1	5.0	8.0	8.3
	δp^*_{12}	38.3	37.7	5.1	7.9	8.3
	δp^*_{22}	26.8	29.3	13.5	38.6	42.3
	δT^*_{21}	38.2	41.7	2.1	6.9	9.3
	δT^*_{12}	38.1	41.6	2.1	6.8	9.3
	δT^*_{22}	9.1	24.3	4.1	7.1	31.0

Firstly, the diagnostic matrix was created, at the same assumptions as for the earlier analysed diesel engine – matrix 1 in Fig. 2. The last column in matrix 1 contains the amounts of diagnostic information carried by particular parameters and calculated using formula (7). Applying the criterion $I_1 = \max$ we can select fourteen diagnostic parameters which carry identical amount of information $I_1 = 0.971$. But as the first step, a parameter is to be selected whose measurement is the simplest from the constructional point of view. In this case the selected parameter was the pressure of the working medium accumulated in the compressor space, δp_{PM}. It is noteworthy that the diagnostic parameter which reacts (or not) to all unserviceability states carries no diagnostic information - for δT_M and δp^*_{22} we get, respectively: $I_1(\delta T_M) = 0$ and $I_1(\delta p^*_{22}) = 0$.

In the next selection steps, by proper restructuring of the diagnostic matrices and using available generalised calculation procedures [8], we can relatively easily select next parameters which carry the maximal amount of diagnostic information, provided that the first, second and next diagnostic parameter

Matrix 1

Diagnostic Parameter δx_j		S_{n1}	S_{n2}	S_{n3}	S_{n4}	S_{n5}	I_1
		Unserviceable states					
1	δT_{PM}	1	1	0	0	0	0.971
2	δT_M	0	0	0	0	0	0
3	δp_{PM}	1	1	0	0	0	0.971
4	δm_{PM}	0	0	0	1	1	0.971
5	$\delta \tau_p$	1	1	0	1	1	0.722
6	δn_{SWCzr}	1	1	0	0	0	0.971
7	$\delta \pi^*_{SNC}$	1	1	0	0	0	0.971
8	$\delta \pi^*_{SWC}$	1	1	0	1	1	0.722
9	$\delta \dot{m}_{SNC}$	1	1	0	0	0	0.971
10	$\delta \dot{m}_{SWC}$	1	1	0	1	1	0.722
11	$\delta \dot{m}_{SWCo}$	1	1	0	0	0	0.971
12	$\delta \eta^*_{SNC}$	1	1	0	1	0	0.971
13	$\delta \eta^*_{SWC}$	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 2

Diagnostic Parameter δx_j		d1 S_{n1}	d1 S_{n2}	d2 S_{n3}	d2 S_{n4}	d2 S_{n5}	I_2
3	δp_{PM}	1	1	0	0	0	0
1	δT_{PM}	1	1	0	0	0	0
4	δm_{PM}	0	0	0	1	1	0.551
5	$\delta \tau_p$	1	1	0	1	1	0.551
6	δn_{SWCzr}	1	1	0	0	0	0
7	$\delta \pi^*_{SNC}$	1	1	0	0	0	0
8	$\delta \pi^*_{SWC}$	1	1	0	1	1	0.551
9	$\delta \dot{m}_{SNC}$	1	1	0	0	0	0
10	$\delta \dot{m}_{SWC}$	1	1	0	1	1	0.551
11	$\delta \dot{m}_{SWCo}$	1	1	0	0	0	0
12	$\delta \eta^*_{SNC}$	1	1	0	1	0	0.551
13	$\delta \eta^*_{SWC}$	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 4

Diagnostic Parameter δx_j		S_{n1}	S_{n2}	S_{n3}	S_{n4}	S_{n5}
		Unserviceable states				
3	δp_{PM}	1	1	0	0	0
19	δT^*_{22}	0	1	0	0	1
4	δm_{PM}	0	0	0	1	1

Matrix 3

Diagnostic Parameter δx_j		d1 S_{n2}	d2 S_{n1}	d3 S_{n5}	d4 S_{n3}	d4 S_{n4}	I_3
19	δT^*_{22}	1	0	1	0	0	0
4	δm_{PM}	0	0	1	0	1	0.4
5	$\delta \tau_p$	1	1	1	0	1	0.4
8	$\delta \pi^*_{SWC}$	1	1	1	0	1	0.4
10	$\delta \dot{m}_{SWC}$	1	1	1	0	1	0.4
12	$\delta \eta^*_{SNC}$	1	1	0	0	1	0.4
13	$\delta \eta^*_{SWC}$	1	1	1	0	0	0

Fig. 2. Scheme for determining the minimum number of diagnostic parameters

were selected - matrices 2 and 3. In each case the diagnostic sensitivity is also analysed.

The selection is continued until full diagnostic information about the technical state of the examined engine is obtained.

Assuming that "k" engine compressor system unserviceability states, S_{ni}, i = 1, ... k, compose a finite set of equally probable events p_{bi} = 1/k, which in cases of gas turbine engines is confirmed in practice [3,4], we get k = 5 for the analysed system, hence the unconditional entropy is:

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

The selected diagnostic parameters δp_{PM}, δT^*_{22} and δm_{PM}, collected in matrix 4, carry, in total, full diagnostic information on the technical state of the compressor system. Then the condition is met which unmistakably defines the initial measure of indeterminacy of the analysed states:

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

Analysing the minimised set of diagnostic parameters we can conclude that if the result: $\{\delta p_{PM}, \delta T^*_{22}, \delta m_{PM}\} = \{1, 0, 0\}$, appears in the diagnostic investigation process, then we can conclude about intensive pollution of blade passages in SNC (S_{n1}). Any identical arrangement of the results of investigations does not exist anywhere except this only case.

Simultaneous intensive pollution of blade passages in the two cooperating compressors (S_{n2}) is completely defined by the result: $\{\delta p_{PM}, \delta T^*_{22}, \delta m_{PM}\} = \{1, 1, 0\}$. In a similar way we can identify the leakage in the air release valve (S_{n4}) – (δp_{PM}, δT^*_{22}, $\delta m_{PM}\} = \{0, 0, 1\}$, and the defect of the engine fuel supply system (S_{n5}) – $\{\delta p_{PM}, \delta T^*_{22}, \delta m_{PM}\} = \{0, 1, 1\}$. When the result $\{\delta p_{PM}, \delta T^*_{22}, \delta m_{PM}\} = \{0, 0, 0\}$ is obtained in the diagnostic investigation process, it signals full serviceability of the engine. The modelled defect consisting in the leakage in the compressor passage (S_{n3}) did not bring any substantial disturbance to engine operation which would result in exceeding tolerance range limits for the selected set of diagnostic parameters.

CONCLUSIONS

The method presented in the article consists in assessing the diagnostic informativeness of the measureable gasodynamic parameters of marine engines of both piston and turbine constructions. This assessment makes it possible to select a set of diagnostic parameters which precisely defines the technical state of constructional elements of the marine engine working spaces. The method provides opportunities for calculating the amount of diagnostic information of the selected parameters with the aid of the entropy function. As a consequence, it eliminates those diagnostic parameters which do not introduce valuable information on the technical state of the engine working spaces.

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