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RELIABILITY AND TYPES OF DIAGNOSIS IN THE PROCESS OF DIESEL ENGINE OPERATION

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Abstract: *The article presents complexity of the problem concerning development of diagnosis with defined reliability by a diagnosing system (SDG) on technical condition of marine combustion engines, especially main engines. It was shown that development of the final diagnosis, the so-called initial operation diagnosis, on the operational usability (fDG on PEx) of a main engine in particular, is not possible without prior development of reliable diagnoses such as: diagnosis on correctness of diagnostic signals, diagnosis on correctness of values of the measured diagnostic parameters of an engine (DG on pWM), diagnosis on technical condition of an engine (DG on ST) and initial diagnosis on operational usability of an engine (wDG on PEx), the so-called initial operation diagnosis. Difficulties in development of the diagnoses were emphasized herein due to the fact that the process of acquisition of information needed to develop diagnoses with certain reliability or accuracy is a two-dimensional stochastic process with components: B(t) – being considered during operation (use) of SDG (at so-called long time - quasistatic) and C(υ) – being considered while measuring diagnostic parameters and diagnostic inference (at so-called short time - dynamic). The need to determine reliability or accuracy rate of each diagnosis in the form of conditional probability P(S/**K**) was also indicated, where S – technical state of the engine and **K** – vector of values of diagnostic parameters reflecting state S. Diagnostic status of marine engine as a diagnosed system (SDN) was characterized in general, on the example of an engine operation process with regards to input (X), output (Y), constant (C) and interference (Z) values. Also there was explained how to understand the terms: diagnostic test, signal inference, measurement inference, structure inference and operation inference, and how inductive inference can be used to verify, for example, the hypothesis H on engine state S when vector **K** of values of engine diagnostic parameters is observed.*

Key words: diagnosis, marine engine, diesel engine, diagnosing system, diagnosed system, diagnosis reliability

1. Introduction

In the operation phase of marine combustion engines, the most important matter is rational control over the operation process of engines [8, 9, 14]. Such a process runs when the risk of occurrence of maritime accident at the time of performing a transportation task by a ship is negligible. In order to minimize the risk diagnosing systems (*SDG*) needs to be permanently improved by all producers.

Diagnosing systems (*SDG*) are currently produced by various companies in all highly industrialized countries, for specific sorts and types of engines as diagnosed systems (*SDN*) [4, 6]. The systems differ primarily in:

– reliability and lifetime,
– reliability (including accuracy) of the diagnoses developed,
– capability of recognizing states occurred during operation.

Knowledge of reliability and lifetime of diagnosing systems is of particular importance here. This is so because development of a diagnosis is based on the assumption that the diagnosing system (*SDG*) is in state of full ability. The lower the reliability and lifetime of the systems, the lower the probability that the diagnosing system will be in fully operation state at any time. This means that the probability of formulating an incorrect diagnosis is greater then. An equally important feature of *SDGs* is their adaptation to develop reliable diagnoses. No less important about the systems (*SDG*) is their ability of recognizing states occurring during operation of an engine as a diagnosed system (*SDN*).

Among the most well-known diagnosing systems for marine combustion (diesel) engines, the highest capability (possibilities) are presented by: MODIS- Geadit and CoCoS from MAN B&W, CBM from Wärtsila, Data Trend from Norcontrol, CC-10 from B&W, and SEDS from Sulzer. These systems as specified enable making diagnosis about fuel injection process, combustion process in cylinders, levels of thermal load, technical condition of turbocharger, filter and air cooler, piston rings and cylinder liners. Various possibilities, but less diagnostic capabilities are offered by such system as: MJ, NP and NK from Autronica, CYDELT from ASEA, DETS from Norcontrol, SIPWA from Sulzer, RED from SEMT-Pielstick. These systems are characterized by different capabilities of recognizing states occurring during operation of diagnosed engines, but also they are of different reliability and lifetime as well as different adaptation to develop reliable diagnoses. The greatest matter is to determine diagnosis reliability, or just its accuracy only. For this reason, it is necessary to undertake best efforts within this area, and this is why this issue was raised in this paper.

2. Diagnosis reliability

Knowledge of diagnosis reliability is necessary when making any operation decision about technical or energetic condition of each marine engine, especially main engine, i.e. engine designed to drive a ship. The reliability of the diagnosis should be as high as possible. The measure of the reliability is the most often the conditional probability $P(S/\mathbf{K})$ denoting that engine is in state S providing that vector $\mathbf{K}$ of diagnostic parameters values is observed.

The diagnosis reliability is determined differently [4, 6, 10, 11, 15].

Assuming that the important indicator characterizing the degree of recognition of the actual state of *SDN* by *SDG* is the probability of developing a correct diagnosis, the diagnosis reliability can be determined through the valuation approach as follows: diagnosis reliability is the probability of classification of the presumed and actual state of *SDN* to the class of reference diagnostic states which the actual state in fact belongs to, and which it should be so classified to by *SDG*.

It can be formulated by taking into account that any state of *SDN* can be recognized by *SDG* only when [4, 6]:

– event D occurs, denoting performance of diagnosis on *SDN* state by fully functional *SDG*;
– event $\mathbf{K}$ occurs, denoting appearance of a defined vector of diagnostic parameters values;
– occurrence of event $\mathbf{K}$ is a consequence of occurrence of event S denoting occurrence of SDN state considered for the diagnostic task, which should be classified to the corresponding class of reference diagnostic states.

In such a case, the diagnosis reliability may be determined by the probability of occurrence of events D, S, K simultaneously, according to the following formula [7]:

$$P(S/\mathbf{K}) = \frac{P(D)P(S/D)P(\mathbf{K}/D \cap S)}{P(\mathbf{K})P(D/\mathbf{K} \cap S)} \tag{1}$$

The occurrence of event D has no effect on the probability of occurrence of event S (which is obvious, since events S and D are independent), and this means that $P(S/D) = P(S)$. Assuming that *SDG* is reliable during diagnosis performance, the formula (2) should take into account the lack of the effect of event D on event $\mathbf{K}$, thus the dependence $P(\mathbf{K}/D \cap S) = P(\mathbf{K}/S)$. Moreover, having a reliable *SDG*, the event D can always be recorded on condition that $\mathbf{K} \cap S$ occurred. Therefore, provided that *SDG* is reliable at the time of diagnosis performance, the formula (2) should additionally consider that: $P(D) = 1$ and $P(D/\mathbf{K} \cap S) = 1$, as a result of which the formula (1) can take the following form:

$$P(S/\mathbf{K}) = \frac{P(S)P(\mathbf{K}/S)}{P(\mathbf{K})} \tag{2}$$

Formula (2) is therefore a measure of accuracy of the diagnosis [4, 7].

The reliability is decreased by:

- interference while measuring diagnostic parameters by *SDG*, that results mainly from the way the engines work and the properties of the measuring chain;
- inappropriate matching engines as *SDN* to *SDG*,
- use of *SDG* that do not enable recognition of all significant states of *SDN* during operation;
- low qualifications of *SDN* operators and *SDG* users, as well as recipients of diagnosis results.

The reliability depends not only on the features of *SDG*, but also on the diagnostic situation of marine engines.

3. Situation in diagnostics of marine combustion engines

In the operation phase of marine combustion engines, particularly main engines, the need is to make such operation decisions to avoid marine accidents [6, 9, 17]. When making such decisions, the operation specificity of the engines must be taken into account. It is the most complex in case of main engines due to significant changes in hydro-meteorological conditions while performing transportation tasks by ships, that include height, length and direction of wave, speed and direction of wind, speed and direction of sea currents, which constitute interference $Z = \{z_l\}$, $l = 1, 2, ..., k$ in the operation of this sort of engines (Fig. 1). Therefore, the characteristics of the operation of main engines change significantly. The values are presented in Fig. 1 that depicts the operation process for any diesel engine.

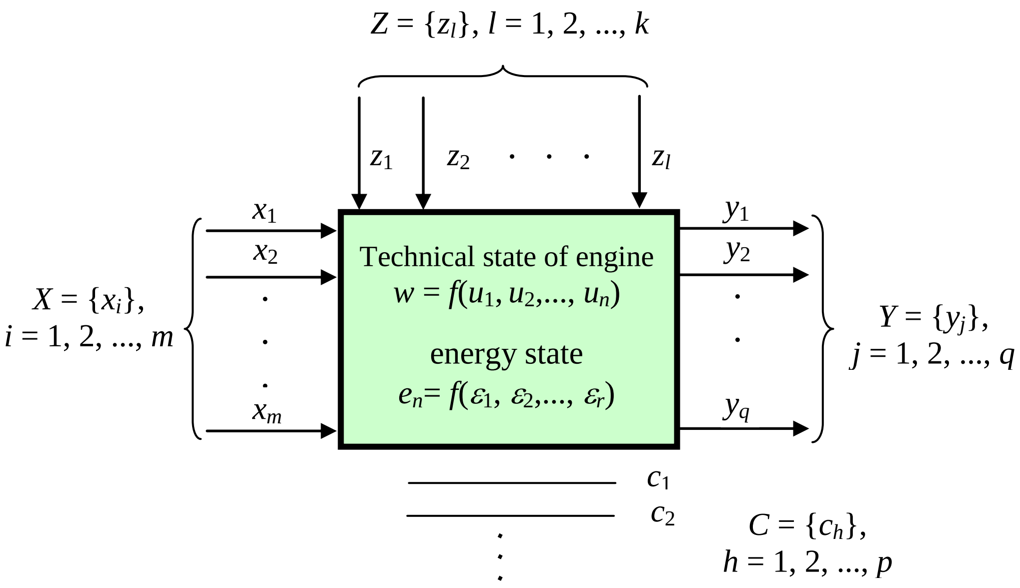

Fig. 1. Operation process for a marine main engine driving an adjustable-pitch propeller: X - set of input values, w - technical state (characterized by parameters of state u_i, $i = 1, 2, ..., n$), e_n– energy state (characterized by parameters of state ε_j, $j = 1, 2, ..., r$), Y - set of output values, Y - set of output variables (diagnostic parameters), C - set of constant values, Z - set of interference values (deterministic and random).

The input values $x_i \in X$ are of the following interpretation:

- x_1 – injection pump adjustment (or fuel dose),
- x_2 – engine rotational speed (n),
- x_3 – fuel injection timing (α_{ww}),
- x_4 – adjustable screw pitch adjustment (H/D),
- x_5 – control time of electronic fuel injection (τ_{wp}),

  .
  .
  .
- x_m – cylinder switching off from operation upon occurrence of seizure process in a piston

The output values $y_i \in Y$ are of the following interpretation:

- y_1 – propeller thrust force (thrust) (T),
- y_2 – average engine torque (M_o),
- y_3 – useful power of engine (N_e),
- y_4 – maximum cylinder pressure ($p_{\max}$),
- y_5 – maximum temperature in cylinder ($T_{\max}$),

  .
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  .
- y_q– amplitude vibration measurement (RMS value, peak value, mean value), dimensionless vibration discriminants (crest factor, shape ratio, pulse rate), and other

The constant values $c_h \in C$ are of the following interpretation:

- c_1 – ambient temperature in engine room (T_o),
- c_2 – ambient pressure in engine room (p_o),
- c_3 – air humidity in engine room (φ),
- c_4 – timing of opening and closing the inlet and outlet valves, or of uncovering and covering the inlet and outlet slots,
- c_5 – injector opening pressure (p_{ow})
  .
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  .
- c_p – fuel cetane number (LC).

The interference values $z_l \in Z$ are of the following interpretation:

- z_1 – sea state (wave height and direction),
- z_2 – wind condition (speed and direction of air movement),
- z_3 – geometric parameters of the waterbody (depth and width),
- z_4 – properties of water currents (speed and direction),
- z_k – processes interfering the correct operation of the propeller ..

Each marine engine under operation can be found in various technical states. Taking usability of a given marine engine for task performance as a criterion to recognize the states, the following states can be distinguished [6, 8, 17]:

$$S = \{s_i\ ;\ i = 1, 2, 3\} \tag{3}$$

with interpretation as below:

- s_1 – state of full (total) ability,
- s_2 – state of partial (not full, not total) ability,
- s_3 – state of inability.

Recognition of states s_i (i = 1, 2, 3) of marine engines proceeds as a result of conduction of a diagnostic process. In the case when it can be stated that during diagnostic test of engine and development of a diagnosis on its technical condition the diagnosing system (*SDG*) was in full ability (thus it worked reliably), accuracy of the diagnosis should be taken into account (2) [6, 7]. Otherwise, diagnosis reliability (1) has to be determined. This requires identification of the diagnosis process in order to obtain information defining specificity of the process. This information is important because the run of this process has a significant impact on reliability, formula 1 (or accuracy, formula 2), of the diagnosis on technical state of internal combustion engines. This process can be perceived differently. On the basis of the so far considerations concerning diesel engines as diagnosed systems (*SDN*) [1, 2, 6, 11, 12] it can be assumed that the process of diagnosing the crank-piston systems as *SDN* is a two-dimensional stochastic process that consists of the process $\{B(t): t \geq 0\}$ of operating (using) *SDG* and the process $\{C(\vartheta): \vartheta \geq 0\}$ of acquiring information about *SDN* state. This process can therefore be defined as follows:

$$D(t, \vartheta) = [B(t), C(\vartheta)];\ t, \vartheta \in R_+ \tag{4}$$

where:

• $B(t)$, a component of the process, which is considered during operation (use) of *SDG*, i.e. the component being considered in long time (during *SDG* operation, within which the instant diagnoses are not required to be generated),

• $C(\vartheta)$, a component of the process, which is considered during performance of measuring and diagnostic inferring, i.e. the component being considered in short time (during *SDG* operation, within which the diagnosis is obtained),

• R, a set of non-negative real numbers.

The process $\{C(\vartheta): \vartheta \geq 0\}$ is always formed by the following realizations:

• diagnostic test,

• diagnostic inference.

Diagnostic inference is generally made up by: signal, measurement, symptom, structure and operation inferences [1, 17]. The diagram of such inference is presented in Fig. 3

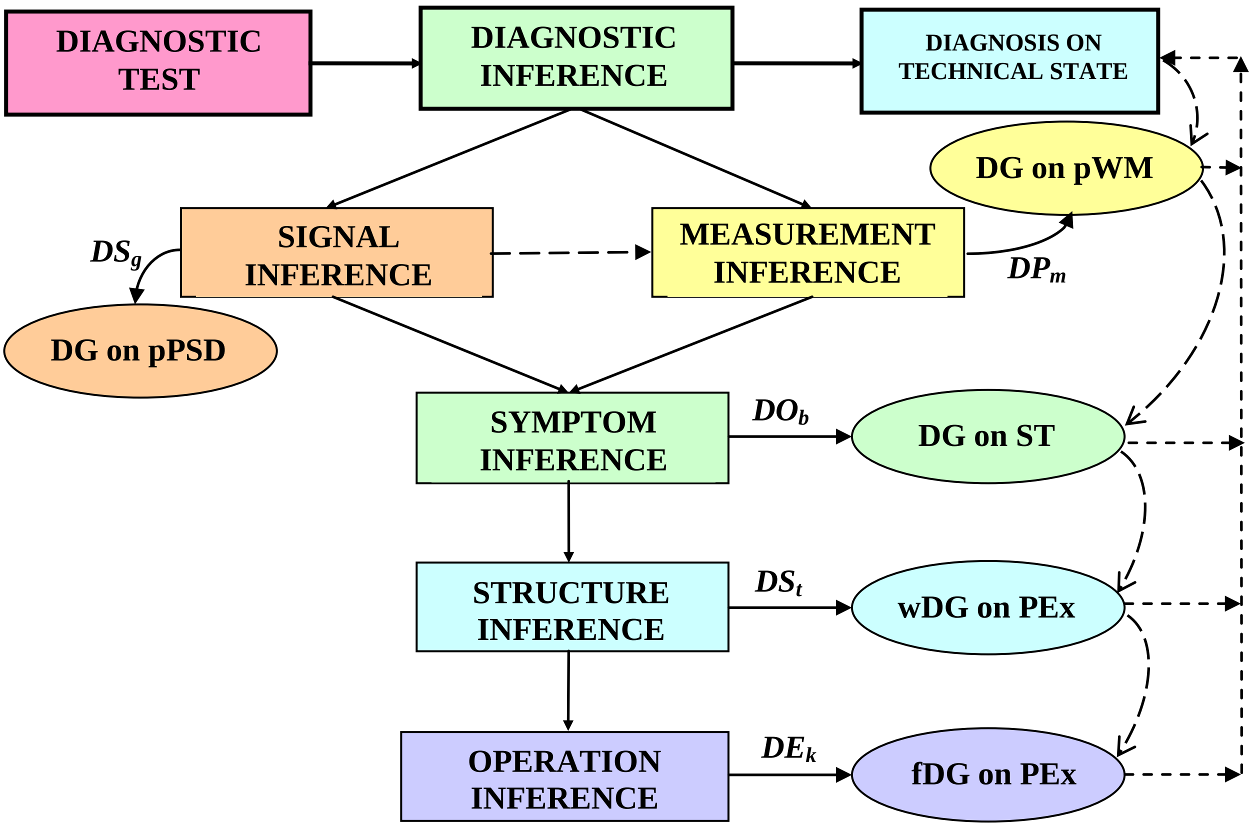

Fig. 3. Diagram of diagnostic inference allowing to develop a diagnosis on technical state of any UKT_S (*SDN*) and thus to make an operation decision about the engine: "able", "partly able" or "unable" for use as intended: UKT_S – crank-piston system of engine, DS_g – signal diagnosis, DP_m – measurement diagnosis, DO_b – symptom diagnosis, DS_t – structure diagnosis, DE_k – operation diagnosis, DG on pPSD – diagnosis on correctness of diagnostic signal flow, DG on pWM – diagnosis on correctness of diagnostic parameters measured, DG on ST - diagnosis on technical state, wDG on PEx – initial diagnosis on operational usability (initial operation diagnosis), fDG on PEx – final diagnosis on operational usability (final operation diagnosis) [17]

Diagnostic test consists in observing and organoleptic recognition of diagnostic signals (thermodynamic, vibroacoustic, radiographic, ultrasonic and other) and, if necessary, – in measuring (by using measuring devices *SDG*) the values of diagnostic parameters of the said signals generated by *SDN*. This test allows to form the sets of results from organoleptic recognition and the values of measurements performed (e.g. by means of auditory or visual perception). The sets contain original information about the (technical and energetic) state of *SDN*.

Signal inference enables development of information on whether the diagnostic signal is correct or deviates from the accepted pattern and thus makes it possible to determine whether the SDN works correctly (whether it is in the required condition) or not, but without the need to perform measurements. Signal inference results from sensory cognition of the person who performs diagnosis. Thus, it allows to determine symptoms in quality terms as a result of analysis and evaluation of signal properties by means of senses of the person performing a diagnosis (organoleptic recognition). A set of the symptoms formed in consequence of applying this inference is diagnostic information, which can be called **a measurement diagnosis**.

Measurement inference enables (*by performing empirical diagnostic tests*) development of information on whether the *SDN* works properly and what state it is in as a result of the analysis and evaluation of the results of diagnostic tests where relevant measurements were taken. The results of measurements performed with measuring devices *SDG* are the basis (input values) for this inference. This inference consists in analyzing the set of measurement results and isolating the symptoms from them. The result of this inference is therefore a diagnostic information, which can be called a **symptom diagnosis**.

Symptom inference enables development of information about *SDN* state, and thus recognition (identification) of this state by revealing the properties of the system structure (e.g. technical, energetic, functional, etc.). It consists in separating from the set of symptoms the information mostly about properties of structural (technical) construction of *SDN*. The result of this inference is **a structure diagnosis**.

Structure inference enables development of information on operational properties of *SDN*. Based on a symptom diagnosis, the inference allows to determine only the mentioned properties *of SDN*, and thus to determine potential possibilities of its functioning, e.g. in the form of estimates of the expected value of time of the correct operation till getting damaged, maximum power (maximum torque at a given rotational speed or maximum rotational speed at a given torque), range of engine performance (maximum and minimum adjustment of the fuel rail, and the maximum and minimum adjustment of the rotational speed controller), etc. Therefore, this inference consists among other in determining the set of energetic (operation) states which the *SDN* can be found in. The result of this inference is an **initial operation diagnosis**.

Operation inference allows to determine usability or serviceability of *SDN*, and therefore information on its operation usability (ability) with regards to costs of use and maintenance. Thus, tis diagnosis contains information on what tasks the *SDN* can be applied to. This inference therefore consists in comparing the potential possibilities (operation potential) of the *SDN* to the needs resulting from the tasks reported for execution. The result of the operation inference is a **final operation diagnosis**.

Operation inference allows to decide about operational usability of a diagnosed system *SDN*, in this case marine main engines. A diagnosis obtained as a result of this inference contains information whether the engine is ready for use and performance of tasks for which it was adapted during the designing and manufacturing phases, or whether it should undergo appropriate service in order to restore its technical condition, e.g. by replacing an element or component, or adjustment, or refurbishment of the engine.

This results from the fact that when developing a diagnosis (inference) about state of a given engine, as *SDN*, the sentence **K** (i.e. the sentence that there is just this and no other vector of values of diagnostic parameters that characterize the technical condition of crank-piston systems) is considered to be a completely certain premise. On the other hand, the sentence S (i.e. the sentence that there is such and no other technical state of the engine as *SDN*) is an inference being developed on the basis of sentence **K**, in the process of non-deductive reasoning. This inference proceeds according to the following scheme [13]:

$$(\mathbf{K}, S \Rightarrow \mathbf{K}) \vdash S$$

where:

K – completely certain premise,

S – inference developed basing on sentence *K*.

The output of such inference is therefore the following hypothesis: *engine as SDN is in state S, because vector* **K** *of values of diagnostic parameters is observed.* Of course, this hypothesis (on *SDN* state) can also be formulated through a different (equivalent) approach, i.e.: *The vector* **K** *of values of diagnostic parameters is observed, because the engine, as SDN, is in state S.*

This inference is a reduction inference that does not allow formulation of certain inferences (in this case the sentence S), but only probable ones. Probability of diagnosis reliability can be obtained by applying the formula 1.

4. Remarks and conclusions

The considerations provided in the paper have been made with regards to the knowledge of technical diagnostics for marine combustion engines, but the results of these considerations may also be useful for other (different than marine) diesel engines.

It has been shown that despite the complexity of diagnostic inference that should lead to development of a diagnosis, additionally it is necessary to make the effort of determining its reliability. For determination of diagnosis reliability about engine state the conditional probability $P(S/\mathbf{K})$ was proposed, being the probability of occurrence of state *S* under the condition that vector **K** of values of the diagnostic parameters is observed.

The described situation in diagnostics of marine combustion engines has been limited only to specification of reasons and effects of operation of any marine engine as an energy converter, with consideration of: a set of input values (X), a set of output values (Y), a set of inference values (Z) and a set of constant values (C).

In the presented concept of diagnostics to apply for identification of states $s_i \in S(i = 1, 2, 3)$ for marine combustion engines, two processes are reflected:

- process of diagnosing $\{C(\vartheta): \vartheta \geq 0\}$, which is the course of succeeding and cause-related in time activities forming the following diagnostic chain: diagnostic test $\rightarrow$ diagnostic inference that may consist of consecutive inferences: signal, measurement, symptom, structure and operation,
- process $\{B(t): t \geq 0\}$ of using *SDG*, the states of which can be interpreted as follows:

d_1 – state denoting its use when being in full ability,

d_2 – state denoting its use when being in state other than full ability (i.e. in state of partial ability or inability)

d_3 – state denoting its use when being in full ability, however such a state of an engine crank-piston system occurred that was unconsidered in the diagnostic task.

For this process, basing on publication [4], there were distinguished such types of inference as: measurement, symptom, structure and operation. However, diagnostic practice shows the need to specify additionally the signal inference, which was not provided in the publication. This results from the fact that sensory experience of the user of the combustion engine, who is an important element of *SDG* since controls the process of diagnosing with the help of his/her senses, cannot be ignored.

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