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CREATING A RANKING OF DIAGNOSTIC PARAMETERS FOR THE DYNAMIC PROCESS OF A MARINE COMBUSTION ENGINE IN THE ASPECT OF MULTI-CRITERIA EVALUATIONS

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Abstract

The change of some of the engine's structural parameters affects the change of toxic compound emission in exhaust gases. It mainly applies to the damage sustained by the charge exchange system as well as the fuel system and the engine supercharging system. These changes are definitely higher during dynamic states and the related transient states. As such, it is possible to speak of a diverse sensitivity of the diagnostic parameters on the exact same excitations which come from the structure of the engine but are realized in other states of load. Presented in the paper is the diagnostic model of an engine, based on the theory of multi-equation models, in which the diagnostic symptoms are the indices and characteristics of exhaust gas compound emissions. For the sake of this paper, the modal value of the structure parameters was assumed to be the change in the angle of the fuel injection advancement. The diagnostic model of the engine was supplemented with the results of research conducted on a station equipped with a single cylinder CI test engine. In previous works of the author, the information capacity index method (the Hellwig method) was suggested for the measurement of sensitivity of a diagnostic parameter. Based on this method, a ranking of diagnostic parameters can be created, which divides the set of diagnostic transients into stimulators, destimulators and nominants. This normalization of the set seems to be helpful while making a diagnostic decision.

Keywords: diagnostic, marine diesel engine, exhaust gas toxicity, multi-equation models

1. Introduction

Nonstationary states are particular states of the combustion engine operation. It should be explained by stating that the nonstationary states disrupt the thermodynamic equilibrium of the cylinder which is present during the stationary loads. It disrupts the flow of the combustion process through momentary changes of the stream of fresh load delivered to the cylinder, as well as the amount of delivered fuel. As such, the ratio of fuel-air is temporarily changed, resulting in the shift of the combustion air factor, which leads to the increased emission of combustion products created through the local deficiency of oxygen. Further consequence of the increased amount of carbon oxide CO and unburned hydrocarbons HC is the decrease in the combustion temperature, which dictates the lowered emission of nitric oxide NO_x.

As such, the deciding factor for the value of toxic compound emissions originating from the nonstationary states is, above all else, the value of excitations which trigger these states. It is not, however, the only factor. Another factor shaping the value of toxic compound emissions originating from the nonstationary states which should be taken into consideration is the technical state of the engine. This state, described using the structure parameters, undergoes constant changes throughout the operation of the engine, which changes are responsible for the wear process. This intensifies the changes in the development of the toxic compounds during the nonstationary states because the processes, while momentary, are dynamic enough to result in the CI concentrations by far exceed the values of the stationary states. Thus it should be expected that the engine with its structural parameters changed through wear will be more sensitive to the influence of nonstationary states and determining its technical state will be easier. At the same time, a problem of unique identification arises, not for the diagnostic parameters, but for their sensitivity. It is especially vital in the cases with large quantities of the tested material as well as with large variations in the operation of the nonstationary states. The aforementioned sensitivity of the diagnostic parameter can be defined as an information capacity and used further to specify the parameters that best describe the given phenomenon [2].

The basic parameter deciding the correctness of the course of combustion inside of the CI engines is the angle of advance of fuel injection. Even a small deviation of this angle results in substantial changes in the main indices of the engine operation, including the indices of exhaust emission. In the case of classic engine design, the “spontaneous” change in the angle of advance of fuel injection is unlikely. On the other hand, in the modern engine design, where the majority of the regulatory parameters is electronically controlled, it is possible for a situation to occur where it results in damage being done to the control system and the change of the angle of advance of fuel injection.

This paper is a continuation of the problem published by the author in [6]. Currently, the author concentrates on defining and researching of the information capacity of the diagnostic parameter, which, as mentioned before, are the indices and characteristics of the exhaust gas compound emissions.

2. Tests of toxic compound concentration sensitivity as the diagnostic parameter during the dynamic processes

The tests were conducted on an engine fuel supply system (angle of advance of fuel injection) of a single cylinder test engine 1-SB, installed inside of the Laboratory of Marine Plant Exploitation of Polish Maritime Academy [3]. The experimental material was gathered using a developed trivalent complete plan. The realization of separate measurement systems (measurement points) of the aforementioned plan of experiment was achieved by using a programmable controller which allowed for getting a high repeatability of the dynamic processes. The duration of the dynamic process was assumed as the period between the introduction of the new injection system setting and the recurring stabilization of the output quantities. This time was chosen through experimentation and it amounts to about 106 seconds.

In order to identify the impact of the technical state of the fuel system on the power parameters of the engine during the dynamic processes, determined were ranges of input quantities (preset parameters) and output quantities (observed parameters).

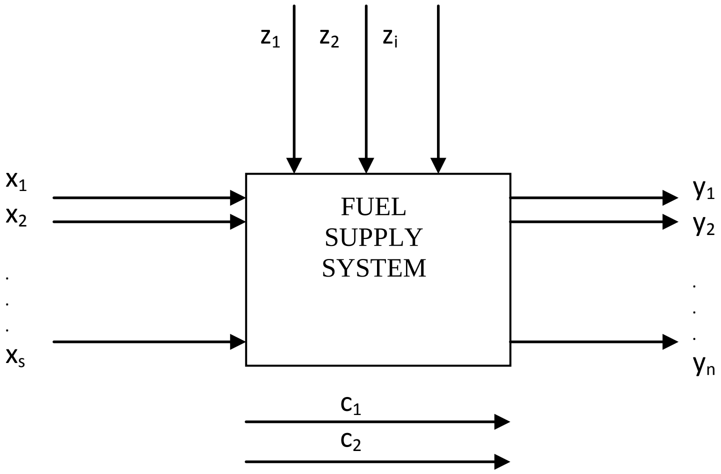

Fig. 1. Quantities characterizing the test subject
x – input quantities, y – output quantities, z – disturbances,
c – constant quantities

To the needs of this paper, the size of the input quantities X was limited to three elements, i.e.: x_1 – engine speed n [r/min]; x_2 – engine torque T_{tq} [N·m]; x_3 – angle of advance of fuel injection α_{ww} [ºOWK]. The research was conducted according to the adopted complete plan for the three engine speed values, i.e.: 850, 950, 1100 [r/min]. For each of the engine speed values the torque T_{tq} was increased, resulting in nonstationary states for the following loads: 10, 20, 30, 50, 70 [Nm]. In the case of the rotational speed of 850 r/min, out of concern for overworking the engine, loads of 50 and 70 Nm were omitted. Similarly treated was the speed of 950 r/min with the load of 70 Nm. The angle of advancement of fuel injection was changed by ±5ºOWK, resulting in three values, i.e.: nominal value – N, accelerated angle – W, delayed angle – P. Using this method resulted in 36 repeated nonstationary states. The model scheme of the functional test subject was represented in fig. 1.

Similarly treated was the range of output values Y, the number of its elements reduced to only the basic toxic compounds in the exhaust manifold: y_1 – condensation of carbon dioxide in the exhaust manifold C_{CO} [ppm]; y_2 – condensation of hydrocarbons in the exhaust manifold $C_{HC(k)}$ [ppm]; y_3 – condensation of nitric oxides in the exhaust manifold C_{NOx} [ppm]; y_4 – temperature of the exhaust gases t_{sp} [°C]; y_5 – excess air number λ.

As mentioned before, the observed data gathered during the active experiment, as well as the multiequation model [3, 4, 5, 6] based off of it, were used for the detailed analysis of the dynamic processes.

The statistical identification of both the empiric data and the model data was conducted using the GRETL software [1]. The estimation of the equation factors of the specific output variables was conducted with the help of the least squares method, and its purpose was the verification of the significance of its parameters and, in effect, the discarding of insubstantial values, which, consequently, helped to greatly simplify the models. As a measure of the strength and the direction of the correlation between the observed variables (Y, X), the linear correlation coefficient of Pearson was adopted.

Correlation coefficients r_{yx_k} between the variable Y and the variables X_k make up a vector of correlation coefficients $\mathbf{R_0}$, while, between individual illustrative variables, correlation coefficients $r_{y_k x_s}$ make up a matrix of correlation coefficients **R** (1) of the following form:

$$\boldsymbol{R_0} = \begin{bmatrix} r_{yx_1} \\ r_{yx_2} \\ \vdots \\ r_{yx_K} \end{bmatrix}_{K\times 1} \quad , \quad \boldsymbol{R} = \begin{bmatrix} r_{x_1x_1} & r_{x_1x_2} & \cdots & r_{x_1x_K} \\ r_{x_2x_1} & r_{x_1x_2} & \cdots & r_{x_2x_K} \\ \vdots & \vdots & \ddots & \vdots \\ r_{x_Kx_1} & r_{x_Kx_2} & \cdots & r_{x_Kx_K} \end{bmatrix}_{K\times K} \tag{1}$$

In the presented analysis of the test results, a substantial merit of the multiequation models comes into view – that is the possibility of a multi-criteria evaluation of the output quantities in the case where these quantities remain in a mutual correlation. Despite their unquestionable advantages, multiequation models do not directly provide the information on the quality of changes, which, in the given situation, are the changes in condensation of individual toxic compounds based on the shifts of the angle of fuel injection advance. Only after compiling the courses of the experiment, or analyzing the produced models, does the image of the phenomenon come into view. Individual correlations along with the fitting of the model to the values received from the experiments held on the engine are presented in further detail in works [5, 6].

As mentioned before, the values of condensations of individual condensations of toxic compounds derived from the nonstationary states are characterized by a particular regularity and repeatability. In no way does it make the analysis easier, considering the notable similarity, independent from the values of the excitations of nonstationary state courses. As such, a tool had to be found, which would be able to describe with relative accuracy and objectivity the character of the changes in the toxic compound concentrations. Using this method allows to describe the correlation of the researched nonstationary state with the nonstationary state adopted as the standard describing the given phenomenon. The analysis of the correlation function makes it possible to define the level of correlation as well as its character. Analyzing the components of a function lets us deduce the aforementioned character of the nonstationary state, i.e. the involvement and intensity of its individual phases.

One of the selection methods for illustrative variables (input quantities of the plan of the experiment) for the model, based on the values of the correlation coefficients, is the information capacity index method of Hellwig [6]. This method relies on the choice of a combination of illustrative variables for which the information capacity is the biggest, and all of the potential illustrative variables are considered as information carriers. The experiment scheme itself imposes a suitable number of available combinations, which, in the given case, with the three input values being $K = 3$ (x_1 – engine speed n [r/min]; x_2 – engine torque T_{tq} [N·m]; x_3 – angle of fuel injection advance α_{ww} [ºOWK]), is as follows:

$$L(K) = 2^K - 1 \tag{2}$$

Thus created are (for each of the illustrated – output – variables) the following combinations:

- one-element: $C_1 = \{X_1\}$, $C_2 = \{X_2\}$, $C_3 = \{X_3\}$,
- two-element: $C_4 = \{X_1, X_2\}$, $C_5 = \{X_1, X_3\}$, $C_6 = \{X_2, X_3\}$,
- three-element: $C_7 = \{X_1, X_2, X_3\}$.

For each of the combinations mentioned above, an individual information capacity index h_{mx_k} for the variable X_k in the m^th^ variable combination must be defined:

$$h_{mx_k} = \frac{r_{yx_k}^2}{1 + \sum_{\substack{k,s\epsilon K_m \\ k\neq s}} \left| r_{x_k\,x_s} \right|} \tag{3}$$

where:

r_{yx_k} – correlation coefficient between the illustrated variable Y and the illustrative variable X_k (correlation coefficient matrix $\mathbf{R_0}$),
$r_{x_k x_s}$ – correlation coefficient between the illustrative variables (correlation coefficient matrix $\mathbf{R}$),
m – number of combinations,
k – number of illustrative variable X_k, for which the individual information capacity index h_{mx_k} is being calculated.

The next step in the Hellwig analysis is calculating for each of the combinations the integral information capacity index H_m

$$H_m = \sum_{k \epsilon K} h_{mx_k} \tag{4}$$

The highest value for this index makes up for the criterion for the choice of the suitable combination between the illustrative variables. Of course, taking into consideration the goal of this analysis, i.e.: the identification of the sensitivity of diagnostic parameters, which are the concentrations of the individual gas components of exhausts on the changes of parameters of the structure that was the angle of fuel injection advance, particular care was taken during the analysis of the input parameter combinations. These systems were C_3, C_5, C_6 and C_7.

Considering that the majority of the gathered empirical material and the limited form of this paper, the analysis of the information capacity index's variability was limited to one engine speed only, i.e.: n = 1100 [r/min] as well as only one toxic compound, i.e.: hydrocarbon concentration HC [ppm]. The choice of unburned hydrocarbons was made due to the highest values of the H_m index were observed for the excess air number λ and the unburned hydrocarbons HC [x]. The lowest values of H_m were present for nitric oxides NO_x.

The highest values of the H_m index are present mainly in the C_5 combination, which binds together the rotation speed (x_1) and the structure parameter of the engine, which was the changed angle of fuel injection advance (x_3), for both the accelerated and the delayed fuel injection. The insignificantly lower values of the H_m index are present in the C_7 combination, which binds together three input quantities of the experiment scheme (fig. 2).

The analysis of the integral information capacity index value H_m gives us not only the possibility of an accurate estimation of the model (which is its intended use) but also, thanks to this analysis, it is possible to define, from a vast pool of data, the conditions in which the impact on the researched subject is the greatest. Nevertheless, the values of the H_m index, relatively close to each other in numbers, are making difficult the deduction of which of the experiment plans wields the maximum information value, especially when they are only referring to one parameter or one combination of said parameters.

In the above mentioned situation, using a parameter ranking seems to be a helpful option, as a ranking reflecting the multi-criteria evaluations (which includes all of the parameters and their combinations) is one of the main premises of making accurate diagnostic decisions.

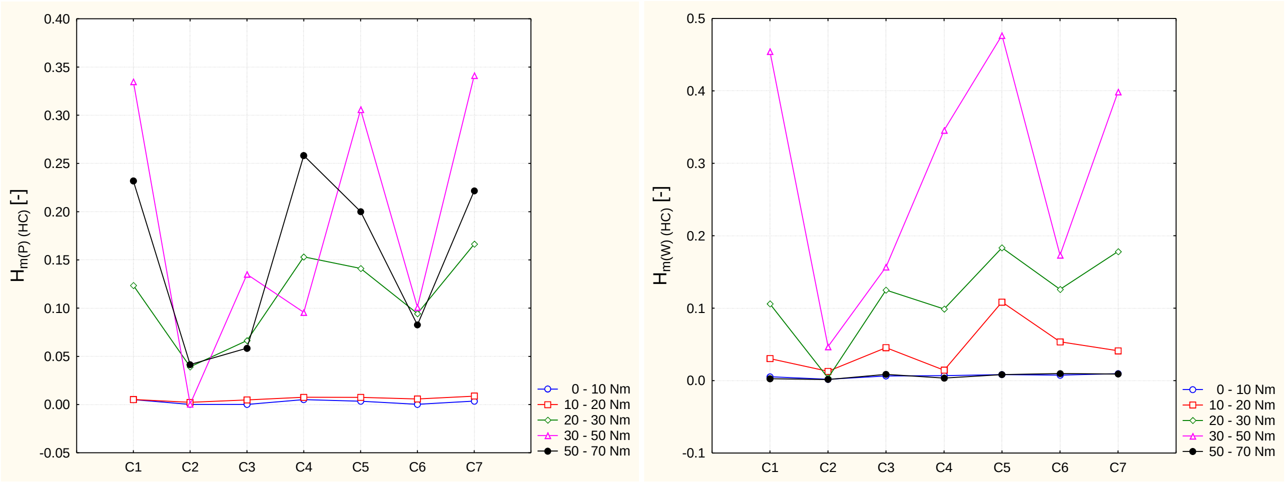

Fig.2. Values of the information capacity index H_m for HC and the nonstationary state at n = 1100 r/min and a change of load from T_{tq} = 0 Nm to T_{tq} = 70 Nm: P – delayed angle of injection advance; W – accelerated angle of injection advance; C1 – C7 – combinations of illustrative variables

3. Building a ranking

Taking into account the large quantities of the research material as well as the need of an objective indication of the most favorable diagnostic parameter, considering its sensitivity, a ranking was built on the basis of the zero unitization method. Because earlier each of the illustrative variables for the experiment scheme was run through the Hellwig's information capacity index method analysis, in the early stages of the creation of the ranking it was assumed that the diagnostic variables of the individual illustrative variables will be taken from the Hellwig's index values. These values, for the individual systems and input parameter combinations, are shown in table 1.

The first step to building the ranking was the division of the diagnostic variable set into three subsets: *S*, *D* i *N*, i.e.:

$$X = S \cup D \cup N \tag{5}$$

where: *S* – subset of diagnostic variables called the stimulators,

D – subset of diagnostic variables called the destimulators,

N – subset of diagnostic variables called the nominants.

Tab. 1. Numerical values of the diagnostic variables

Plan system	C_1	C_2	C_3	C_4	C_5	C_6	C_7
1	2	3	4	5	6	7	8
1100P(50-70)	0,2318	0,0416	0,0586	0,2583	0,2001	0,0826	0,2217
1100P(30-50)	0,3350	0,0004	0,1351	0,0956	0,3060	0,1009	0,3412
1100P(20-30)	0,1236	0,0392	0,0665	0,1532	0,1412	0,0944	0,1664
1100P(10-20)	0,0053	0,0024	0,0049	0,0076	0,0075	0,0058	0,0087
1100W(50-70)	0,0027	0,0015	0,0087	0,0036	0,0084	0,0098	0,0092
1100W(30-50)	0,4545	0,0471	0,1570	0,3458	0,4768	0,1734	0,3988
1100W(20-30)	0,1059	0,0037	0,1252	0,0989	0,1835	0,1261	0,1784
1100W(10-20)	0,0304	0,0130	0,0456	0,0144	0,1086	0,0536	0,0414

The transformation of stimulants into the normalized form was calculated using the correlation:

$$z_{ij} = \frac{x_{ij} - \min_i x_{ij}}{\max_i x_{ij} - \min_i x_{ij}}, \qquad \begin{pmatrix} i = 1,2,\dots,r \\ j = 1,2,\dots,s \end{pmatrix},\ X_i \in S, \tag{6}$$

respectively, the correlation used for destimulants:

$$z_{ij} = \frac{\max_i x_{ij} - x_{ij}}{\max_i x_{ij} - \min_i x_{ij}}, \qquad \begin{pmatrix} i = 1,2,\dots,r \\ j = 1,2,\dots,s \end{pmatrix}, \qquad X_i \in D \tag{7}$$

Chosen as the stimulants, that is, the diagnostic variables whose growth should be associated with an increase, while the drop with a decrease of the evaluation of a complex phenomenon, were the combinations of illustrated variables C_1, C_3, C_4, C_5, C_7. While the chosen destimulants, that is, the diagnostic variables whose growth is associated with a decrease, while the drop with an increase of the complex phenomenon, were the combinations C_2 i C_6.

In the case of building a ranking which reflects the mutual interactions of individual exhaust components (which is the case presented in this paper) as well as a ranking which reflects the changes of the structure parameters (changed angle of fuel injection advance), the parameter should be added to the subset of nominants, whose normalization should proceed as follows:

$$z_{ij} = \begin{cases} \frac{x_{ij} - \min_i x_{ij}}{c_{0j} - \min_i x_{ij}}, & \text{when } x_{ij} < c_{0j}, \\ 1, & \text{when } x_{ij} = c_{0j},\ X_i \in N, \\ \frac{x_{ij} - \max_i x_{ij}}{c_{0j} - \max_i x_{ij}}, & \text{when } x_{ij} > c_{0j} \end{cases} \tag{8}$$

The following step was the creation of the diagnostic characteristic normalization. This step is essential as it allows for receiving a linked multi-criteria evaluation of the analyzed subject. The linked evaluation is reached through aggregation, i.e., setting an aggregate (synthetic) variable Q_i.

$$Q_i = \frac{1}{s} \sum_{j=1}^{s} z_{ij} \qquad (i = 1, 2, \dots, r) \tag{9}$$

Knowledge of the variable Q allows building a ranking relative to the non-increasing Q_i values. As expected, the order of the ranking will be determined by the value of the synthetic variable Q_i, which is presented in table 2.

Tab. 2.Normalized values of diagnostic variables and value of the synthetic variable

Plan system	z_{i1}	z_{i2}	z_{i3}	z_{i4}	z_{i5}	z_{i6}	z_{i7}	Q_i
1	2	3	4	5	6	7	8	9
1100P(50-70)	0,5071	0,1178	0,3531	0,7443	0,4104	0,5418	0,5460	3,2205
1100P(30-50)	0,7355	1	0,8560	0,2688	0,6361	0,4326	0,8523	4,7813
1100P(20-30)	0,2676	0,1692	0,4050	0,4372	0,2849	0,4714	0,4043	2,4396
1100P(10-20)	0,0058	0,9571	0	0,0117	0	1	0	1,9746
1100W(50-70)	0	0,9764	0,0250	0	0,0020	0,9761	0,0013	1,9808
1100W(30-50)	1	0	1	1	1	0	1	5,0
1100W(20-30)	0,2284	0,9293	0,7909	0,2785	0,3750	0,2822	0,4350	3,3193
1100W(10-20)	0,0613	0,7302	0,2676	0,0316	0,2154	0,7148	0,0838	2,1047

By analyzing table 2 it can be noted that the highest values are achieved in the plan system of the 1100W (30-50) experiment, which is the nonstationary state accomplished with the rotational speed of 1100 r/min, with the load change from 30 to 50 Nm and for the accelerated angle of fuel injection which was 30 °OWK. It may indicate that this system carries the greatest information values. The next system in the information value ranking (not far behind the first entry), considering the changes of the structure parameters of the fuel supply system, will be the 1100P (30-50) system. It should be noted that in both cases they are not the systems with the highest moment load value. To mind comes the assumption that during the creation of the diagnostic tests, measuring systems with average loads might play a vital role. Only the third system in the ranking is a system which is realized using the maximum moment load.

5. Summary.

The numerically similar values of the *Hm* index do not provide answers as to which of the experiment plan systems carry the maximum information value, considering the changes in the test subject structure, especially when they only adhere to one parameter or one combination of said parameters. However, a ranking reflecting multi-criteria evaluations (encompassing all of the parameters and their combinations) is easily one of the fundamental premises of making accurate diagnostic decisions. Of course, it is viable to build a more in-depth ranking, taking into consideration, for example, a nominant diagnostic variable and its subset of nominal values, which will mirror the state of the engine in its full aptitude. It is also possible to create a more complex set of illustrative and illustrated variables so that the ranking could encompass all of the toxic compound parameters registered during the course of the testing, including the excess air number λ.

Directly regarding the results of the ranking, a regularity should be noted. The higher values of synthetic variable *Qi* were observed, except for the very highest value, for the delayed angle of fuel injection (22 °OWK), which has its substantial justification, as the delayed angle of injection unfavorably influences the change in the combustion conditions. At first the value of the excess air number lowers, which causes the creation of incomplete combustion products, i.e., an increase of HC concentration, which comprised the main subject of this analysis.

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