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THE IDENTIFICATION OF TOXIC COMPOUND EMISSION SENSITIVITY AS A DIAGNOSTIC PARAMETER DURING DYNAMIC PROCESSES OF THE MARINE ENGINE

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Abstract

Abstract: Changing some parameters of the engine structure alters the emission of harmful components in the exhaust gas. This applies in particular to the damage of charge exchange system as well as fuel system and engine supercharger. These changes are much greater during the dynamic states and their accompanying transitional processes. The different sensitivity of diagnostic parameters to the same force, coming from the engine structure, but realized in other loading conditions can be discussed. Presented in the paper is a model of the engine diagnostic, in which symptoms are indicators of diagnostic and emission characteristics of gaseous exhaust components. For the purpose of the paper the parameters were taken as the dominant structure in the change of fuel injection timing. The diagnostic engine model, based on the theory of multi-equation models, was supplemented by the results of the tests on the single-cylinder research engine ZS. Also proposed is a measure of the sensitivity of the diagnostic parameter during dynamic processes. The following paper is building on the problem previously published by the authors in [X].

Keywords: *diagnostic, theory of experiments, marine diesel engine, exhaust gas toxicity, multi-equation models*

1. Introduction

Transients are particular states of engine work. They arise in the absence of thermodynamic equilibrium in the cylinders and are an important part of the spectrum engine load, especially traction motors, without affecting the emission of toxic compounds. The engine research in this area is forced on homologation grounds, where the main problem boils down to the optimization of combustion engine with variable load tests described through urban test drives.

In the case of main propulsion of marine engines, the importance of transients, in the above sense, is of less importance due to the relatively small contribution of transients in the spectrum of engine loads. If, however, a movement of individuals in special areas or maneuvering in port will undergo such analysis, the share of transients in the spectrum of the burden will have been growing significantly and is worth separate consideration. In proportion to this growth increases the emission of toxic compounds caused by the impact of these states. It should be explained by the fact that the transient states are disrupting the thermodynamic equilibrium of the cylinder which occurs during fixed loads. It also disrupts the combustion process by temporary changes, primarily, in the stream of fresh load delivered to the cylinder, but also the volume of delivered fuel. Thus the fuel-air relation changes temporarily, which results in changes to the excess air number, which leads to heightened emission of combustion products created by the local oxygen deficiency. Another consequence of a raised amount of CO and unburned hydrocarbons is the lowered combustion temperature which decides the lowered nitric oxide emission.

As it is, the leading factor deciding the value of toxic compound emissions coming from the transient states is, above all, the value of extortion which causes these states. It isn't, however, the only factor. An additional factor forming the toxic compound emission values coming from the transient states that needs to be taken into consideration is the technical state of the engine. This state, described with the structure parameters, undergoes constant changes while the engine is in use, for which wear processes are responsible. This intensifies the changes in formation of toxic compounds during transient states, since these processes, despite their short duration, are so dynamic that the temporary concentrations of ZT largely exceed the value of the steady states. Therefore, it is expected that an engine with structure parameters modified due to wear will be more sensitive to the effects of transients and thus it will be easier to determine its technical condition [2,4]. At the same time, however, the problem of unambiguous identification arises, not for diagnostic parameters, but their sensitivity. This is of particular importance in the case of a large amount of research material, as well as high volatility of transients. Said sensitivity of the diagnostic parameter can be defined as the capacity of information and, thanks to it, the parameters that best describe the phenomenon can be specified.

The main parameter determining the correctness of the combustion process in ignition engines is the fuel injection timing. Even a small deviation results in significant changes of the main indicators in operation of the engine, including exhaust emission factors. In the case of classic engine design, "self-acting" change of the fuel injection timing is rather unlikely. However, in the modern constructions, where most of the control parameters are electronically controlled, a situation is possible that results in damage to the control system and the change of the injection timing settings.

The work is a continuation of issues discussed and published by the authors in [13]. Currently, the authors focus their attention on defining and testing information capacity of the diagnostic parameter, which is, as previously mentioned, indicators and characteristics of the emission of gaseous exhaust components. The analysis of this issue is based on the results of the experiment conducted on an experimental engine, as well as transient modeling using multi-equation models that have been built based on the results of this experiment. Used here is the fundamental advantage of multi-equation models, which is the ability to saturate the structure of the models with data from an empirical experiment.

2. The study of dynamic processes of the engine fuel supply system using the multi-equation models

The subject of the study was the fuel supply system (fuel injection timing) of a single-cylinder research engine 1-SB installed in the Laboratory of the Exploitation of Marine Power Plants at the Naval Academy [10]. The experimental material was collected in accordance with a complete trivalent plan [12]. The implementation of individual measuring systems (measuring points) of the above-mentioned plan of the experiment was carried out using a programmable logic controller, allowing for a high reproducibility of dynamic processes. The duration of the dynamic process was an interval between the onset of distortion of the injection system components and the re-stabilization of output quantities. This timing was chosen experimentally and it amounted to about 106 seconds.

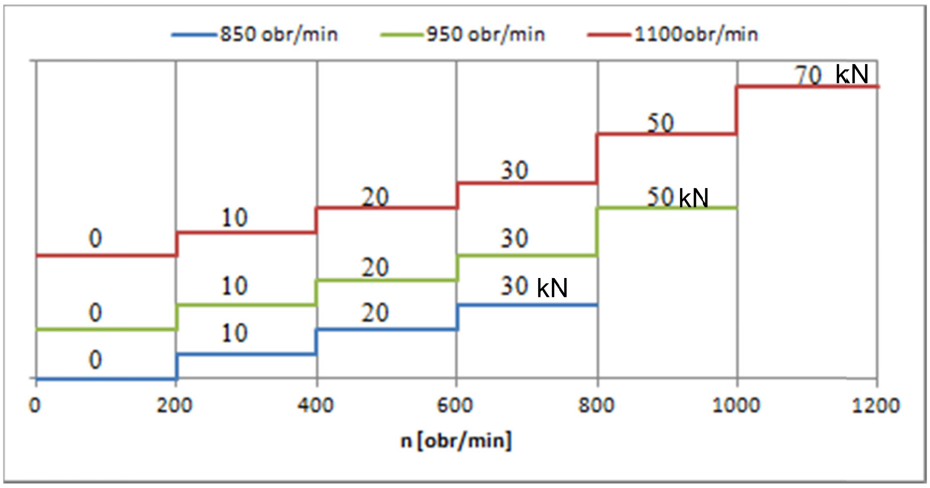

Fig.1. The implementation scheme of the research program

In order to identify the impact of the technical condition of the fuel supply system on the parameters of engine power during dynamic processes, sets of input parameters (parameters asked) and the size of the output (observed parameters) were defined. For the purposes of this paper, a set of input values X was limited to three elements, ie .: x_1 - engine speed n [rev / min]; x_2 - engine torque T_{tq} [N·m]; x_3 - fuel injection timing α_{ww} [ºOWK]. The study was conducted in accordance with the adopted complete plan, for three values of speed, ie .: 850, 950 and 1,100 [rev / min]. For each speed, torque T_{tq} was increased, thereby causing the transient, respectively for the load 10, 20, 30, 50, 70 [Nm]. In the case of rotational speed of 850 rev / min, in fear of a large motor overload, a load of 50 and 70 Nm was abandoned. Similarly, this was done for the speed of 950 rev / min and a load of 70 Nm. Fuel injection timing was changed by ± 5ºOWK, yielding three values, ie .: the nominal value – N, accelerated angle – W, delayed angle – P. This resulted in 36 repetitive transients. The graphic interpretation of the test program is shown in Fig. 1.

Similar was the treatment of a set of output quantities Y, limiting the number of its elements to just the primary toxic compounds in the exhaust manifold: y_1 - the concentration of carbon monoxide in the flue gas exhaust manifold C_{CO} [ppm]; y_2 - the concentration of hydrocarbons in the exhaust manifold C_{HC} (k) [ppm]; y_3 - the concentration of nitrogen oxides in the flue gas exhaust manifold C_{NOx} [ppm], y_4 - exhaust gas temperature t_{sp} [ºC], y_5 - excess air ratio λ.

As previously mentioned, a detailed analysis of dynamic processes was used for the measurement data obtained during the active experiment. It allowed to build the multi-equation model, with the obvious assumption that process changes in exhaust emissions occur at a time, which means it has dynamics. Therefore, the multi-equation model can be described using a system of linear difference equations. Taking into consideration the amount of times the structure of the multi-equation models [6,7,8,9,10,11,12] was presented by the authors in their previous works, it was decided to omit it and have their attention focused on the analysis of results obtained using these models.

Statistical identification, of both empirical and model data, was made using GRETL [1]. Estimation of coefficients in the equations of individual output variables was performed using the least squares method and it had to verify the relevance of its parameters, resulting in the rejection of insignificant values, which in turn led to a significant simplification of models. As a measure of strength and direction of the correlation between the examined variables (Y, X) the Pearson correlation coefficient (1) was adopted:

$$r_{yx_k} = \frac{\sum_{i=1}^{N}(x_{ik} - \bar{x}_k)(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{N}(x_{ik} - \bar{x}_k)^2 \sum_{i=1}^{N}(y_i - \bar{y})^2}} \tag{1}$$

where:

r_{yx_k} – the correlation coefficient between the dependent variable (output) Y and the explanatory variable (input) X_k,

x_{ik} , y_i - i-th observation of variables, respectively, X_k, and Y,

$\bar{x}_k$, $\bar{y}$ - mean values of variables, respectively, X_k, i Y,

N – number of observations.

The values of the correlation coefficient r_{yx_k} are in the $\langle -1; 1 \rangle$ range, whose sign indicates the direction of correlation, while the absolute value $|r_{yx_k}|$ | shows the strength of this relation.

Correlation coefficients r_{yx_k} between the variable Y and the variable X_k form a vector of correlation coefficients $\boldsymbol{R}_0$, while correlation coefficients $r_{y_k x_s}$ form a matrix of correlation coefficients $\boldsymbol{R}$ between explanatory variables (X_k, Y_s):

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

Analysis of vector values of correlation coefficients $\boldsymbol{R}_0$ for individual dependent and explanatory variables provides interesting observations, and so in the case of equations describing the changes in carbon monoxide and hydrocarbons, they depend significantly on the excess air ratio λ (y_5), a parameter directly associated with a structure parameter, which was fuel injection timing (x_3). Both CO and HC significantly depend on one another. Furthermore, in the case of CO, speed has a greater impact, whereas in the case of HC it is the load, which seems to be logical keeping in mind the creation processes of the compounds in the cylinder.

Specific relations, along with the study of fitting the model to the values obtained as a result of the experiment on the engine are described in detail in [13].

The presented analysis of the test results highlights a significant advantage of multi-equation models, i.e. the possibility of multi-output size analysis in the case where these values are in mutual correlation. Analysis of these relations in a single model reflects reality more accurately (because there are obvious interactions between, for example, CO and HC and, for example, λ) and thus allows for a wider interpretation of a given problem.

Despite the obvious advantages, multi-equation models do not provide direct information as to the quality of the changes, in the presented case, the change in the concentration of individual toxic compounds due to changes in the fuel injection timing. Only juxtaposing of waveforms of the experiment, or analysis of the obtained models, gives a picture of the phenomenon. Nonetheless, the analysis remains difficult due to the similarity, irrespective of the value of extortion, of transient waveforms.

In this case, it is desirable to use criteria which would be helpful in objectively assessing the comparative concentrations or emissions from transients. The use of evaluative indicators is one of the methods commonly used in such cases. The basic and most commonly used evaluative indicator is an hourly emission of the individual components of toxic fumes. Its use in the analysis of transients has been presented in [5,13]. However, the above method has a major drawback, namely it averages the results. This is particularly evident with a poor selection of analysis time, or the amount of the test phases - in a test with a small number of phases the averaging is high, while using a multiphase test (a substantial number of tests), the results are affected by information noise.

As mentioned previously, concentrations of individual toxic compounds coming from transients are characterized by a certain regularity and repetitiveness, and therefore it was necessary to find a tool that would be deprived of the disadvantages of the above-mentioned indicators, while being able to describe in an accurate and objective way the nature of changes in individual concentration of the compounds toxic. It seems that to analyze the correlation of individual transients is such a method. In this method, the correlation between the tested transient and the transient adopted as a model describing the phenomenon is determined. The analysis of the correlation function allows to specify the degree of correlation, and its character. Analyzing the function, conclusions can be drawn about the components of the mentioned character of the transient, namely the participation and intensity of each of its phases.

One of the methods for the selection of explanatory variables (values of input variables of the experiment design) for the model, based on values of correlation coefficients, is the Hellwig method of capacity information indicators [13]. This method involves selecting such a combination of variables for which information capacity is the greatest, and assume all potential explanatory variables as information storage media. The experiment design system itself imposes an adequate number of possible combinations, in this case, with three sizes of input adopted, $K = 3$ (x_1 - engine speed n [rev / min]; x_2 - engine torque T_{tq} [N·m]; x_3 - angle fuel injection timing α_{ww} [ºOWK]) will be:

$$L(K) = 2^K - 1 \tag{4}$$

The following combinations are created (for each dependent variable - output):

- single-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 above-described combinations, individual index of information capacity h_{mx_k} is defined for the variable X_k in the m-th combination of variables:

$$h_{mx_k} = \frac{r_{yx_k}^2}{1 + \sum_{\substack{k,s \in K_m \\ k \neq s}} |r_{x_k x_s}|} \tag{5}$$

where:

r_{yx_k} - the coefficient of correlation between the dependent variable Y and explanatory variable X_k (correlation coefficient matrix $\mathbf{R_0}$),

$r_{x_k x_s}$ - the coefficient of correlation between the explanatory variables (correlation coefficient matrix $\mathbf{R}$),

m - the number of combinations,

k - the number of explanatory variable X_k, for which the index of individual capacity information h_{mx_k} is calculated.

The next step of the Hellwig analysis is to calculate, for each combination of integral capacity indicator, H_m

$$H_m = \sum_{k \in K} h_{mx_k} \tag{6}$$

The highest value of this indicator is the criterion for selecting the appropriate combination of explanatory variables. In view of the substantial amount of empirical material in the following analysis of variation of the information capacity was limited to a single engine speed, i.e. .: n = 1100 [rev / min].

Of course, taking into account the purpose of analysis, ie.: the identification of the sensitivity of diagnostic parameters, namely the concentration of various exhaust gas components (but the air ratio and the temperature of the exhaust was also considered), on the parameter changes of the structure which was injection timing. Analyzed with particular attention were the combinations of input parameters which include a structure parameter. Those structures are C3, C5, C6 and C7.

The highest values of the H_m index were observed for the excess air ratio λ, then for the concentration of carbon monoxide (CO) and unburnt hydrocarbons (HC). The lowest H_m values were for NOx.

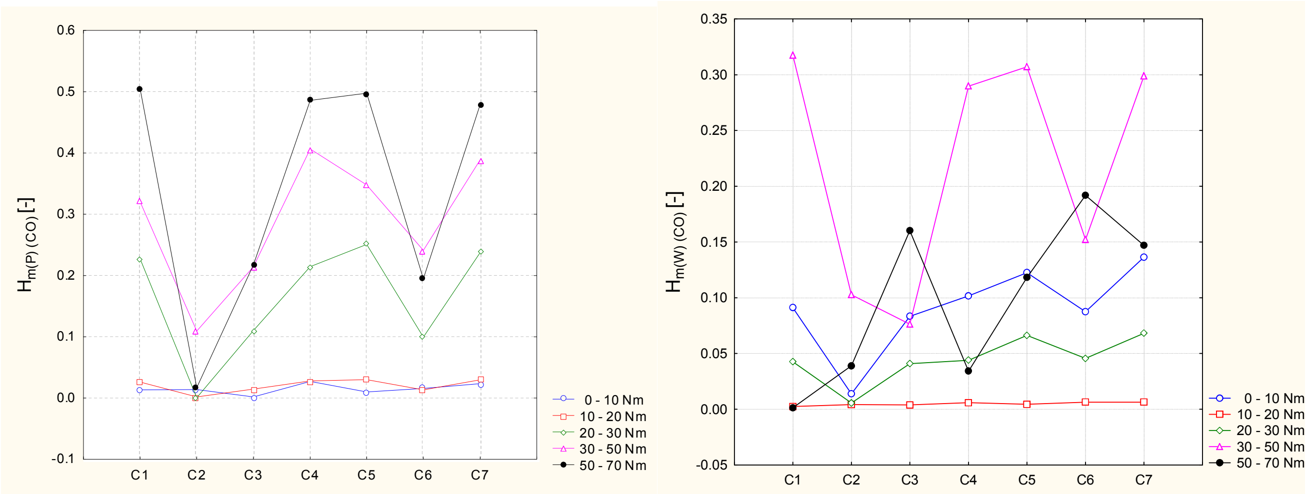

Fig. 2. The indicator values of information capacity H_m for CO and transient with $n = 1100$ rev / min and load change from $T_{tq} = 0$ Nm to $T_{tq} = 70$: P - delayed injection timing, C1 – C7 - combinations of explanatory variables

It should be noted that there is a occurring regularity, namely the higher value of the H_m index observed for delayed fuel injection angle (22 ºOWK), which of course has its substantive justification, since the late injection angle significantly affects the change in combustion conditions. Firstly, the value of the excess air ratio is reduced, which in turn results in the formation of products of incomplete combustion and, therefore, increases the concentration of CO and HC.

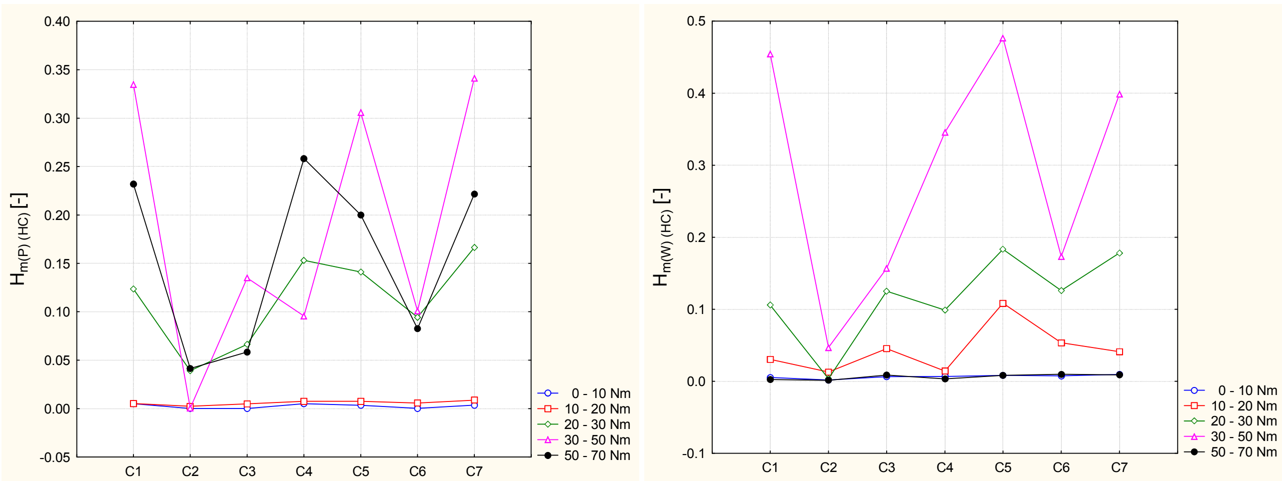

Fig. 3. The indicator values of information capacity H_m for HC and transient with $n = 1100$ rev / min and load change from $T_{tq} = 0$ Nm to $T_{tq} = 70$: P - delayed injection timing, C1 – C7 - combinations of explanatory variables

A correct estimation of the model is proved by an inverse correlation, both in the case of the excess air ratio and the NOx, because the local oxygen deficiency is a factor in reducing the concentration of this compound.

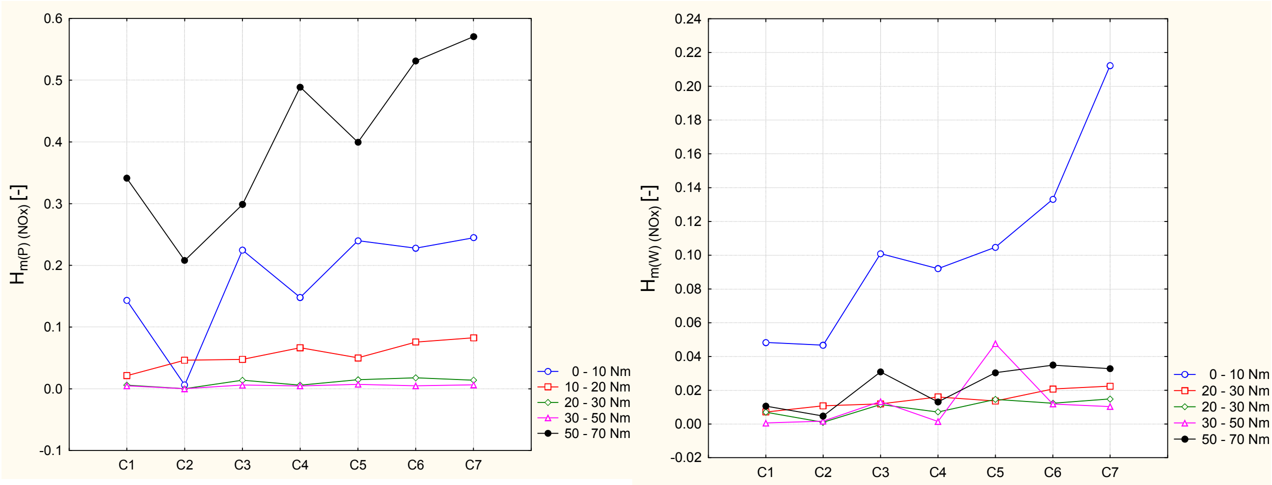

Fig. 4. The indicator values of information capacity H_m for NO_x and transient with
n = 1100 rev / min and load change from T_{tq} = 0 Nm to T_{tq} = 70: P - delayed injection timing, C1 – C7 - combinations of explanatory variables

The largest H_m index value mainly appear in the combination of C_5, which binds together the engine speed (x_1) and a structure parameter of the engine, which was the changed fuel injection timing (x_3), both the accelerated and delayed fuel injection. Slightly smaller H_m index values appear for a combination of C_7, which combines three input quantities of the experiment design.

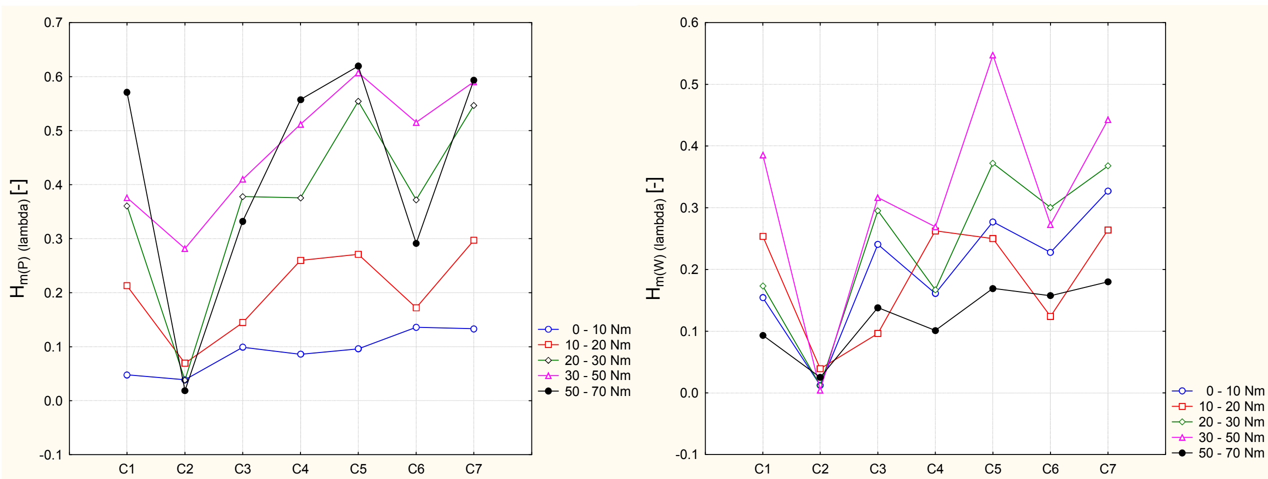

Fig. 5. The indicator values of information capacity H_m for λ and transient with
n = 1100 rev / min and load change from T_{tq} = 0 Nm to T_{tq} = 70: P - delayed injection timing, C1 – C7 - combinations of explanatory variables

The analysis of the integral information capacity H_m index value not only provides the opportunity to correctly estimate the model (which is what its purpose in fact is), but thanks to this analysis, with a very large data set, it is possible, in addition to the specification of relevant variables, to determine the conditions under which these have the greatest impact on the test object. As observed during the experiment, the most impact, i.e. the largest increase in concentrations of

ZT, occurred not at the highest input (the highest point), and with a transient caused by a load change from 30 to 50 Nm, which represents 0.7 torque.

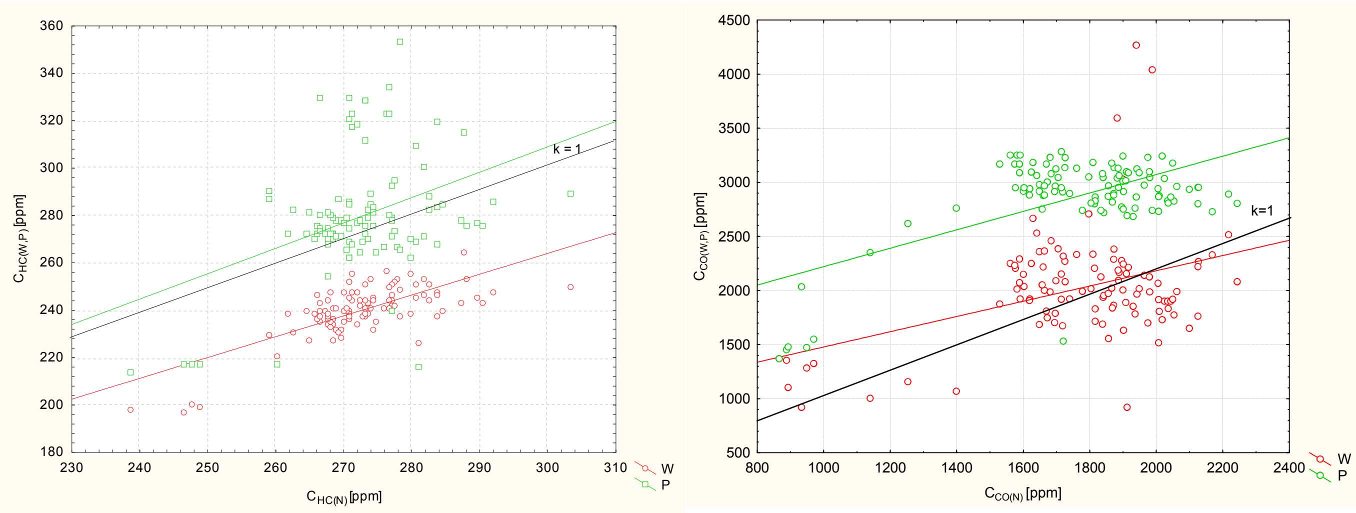

Fig. 4. The concentration values of H_m and CO for the transient, where n = 1100 rev / min and load change from T_{tq} = 0 Nm to T_{tq} = 70 Nm: $C_{HC\ (N,\ W,\ P)}$ – HC concentration, $C_{CO\ (N,\ W,\ P)}$ – CO concentration for (N) nominal, (W) accelerated, (P) delayed injection timing

Graphic portrayal of the correlation analysis is a scattering diagram presented in Fig. 4, which shows a linear correlation function of the concentration of unburned hydrocarbons HC at an early injection timing angle (30 ºOWK - red) to the nominal injection timing (26 ºOWK) where the correlation coefficients were, respectably, HC - r = 0.75, CO - r = 0.73. Green represents the HC concentration correlation function at a delayed angle (22 ºOWK), also with respect to the nominal injection timing. The correlation coefficient in this case was lower and amounted to r = 0.59. Smaller values of the correlation coefficient are influenced by the scattered points around the correlation function, which indicates an unstable transient process (fitting the multi-equation model is, even in this case, significant, because the greatest residual value is 60 ppm).

If the correlation coefficient for the concentration of CO at a delayed angle was r = 0.74, while its higher values were influenced by the higher, compared to HC, density of points around the correlation function. In addition, worth noting is the very similar (twin) nature of the distribution of data points obtained in the course of the transient .

3. Summary.

During the making of this paper, the following conclusions were reached:

- multi-equation models give well fitted results to the empirical data,

- there is a possibility of learning this configuration (combination) of variables, ie. engine speed and load, for which the response of the research object (internal combustion engine) will be the largest, and therefore will be the first step to developing a research test, which is targeted diagnostically,
- the results are encouraging and the authors will direct their attention towards the more advanced methods of determining metrics of diagnostic parameters and their normalization for use in diagnostic applications.

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