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Ryszard ZADRĄG
Tomasz KNIAZIEWICZ

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Identification of diagnostic parameter sensitivity during dynamic processes of a marine engine

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. Model is complemented with the tests on the single-cylinder research engine ZS. Also proposed is a measure of the sensitivity of the diagnostic parameter during dynamic processes.

Key words: *engine exhaust components, marine engines, engine diagnostics*

Identyfikacja wrażliwości parametrów diagnostycznych podczas procesów dynamicznych okrętowego silnika spalinowego

Zmiana niektórych parametrów struktury silnika wpływa na zmianę emisji szkodliwych składników w spalinach. Dotyczy to przede wszystkim uszkodzeń występujących w układzie wymiany ładunku a także w układzie paliwowym i układzie doładowania silnika. Zmiany te mają zdecydowanie większe wartości podczas trwania stanów dynamicznych i towarzyszących im procesów przejściowych. Można więc mówić o różnej wrażliwości parametrów diagnostycznych na te same wymuszenia pochodzące od struktury silnika, ale realizowane w innych stanach obciążenia. W artykule przedstawiono model diagnostyczny silnika, w którym symptomami diagnostycznymi są wskaźniki i charakterystyki emisji gazowych składników spalin. Model uzupełniono wynikami badań na stanowisku jednocylindrowego silnika badawczego ZS. Zaproponowano również miary wrażliwości parametru diagnostycznego podczas procesów dynamicznych..

Słowa kluczowe: *składniki spalin silnika, silniki okrętowe, diagnostyka silników*

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.

In the paper will be presented the transient modeling with variable injection timing angle and its impact on fundamental changes in the concentration of toxic compounds. Their information capacity will also be identified.

2. Assumptions

Using the previous experience of the authors [5, 6, 7, 8, 9] with modeling concentrations of toxic compounds, it was decided to implement multi-equation models, proven during steady state, for analysis of dynamic processes, whereby it is assumed that the process of change in exhaust emissions occurs over time, which means it is dynamic. Therefore, the multi-equation model can be described using a system of linear difference equations. Since the measurement of the concentration of toxic compounds is a discrete measurement, discrete signal in time (time series) is a function whose domain is the set of integers. Thus, a discrete signal in time is a string of numbers. This kind of strings will continue to be recorded in the functional notation $x[k]$. Adopting such a notation affects the desire to minimize errors connected to, inter alia, approximation of functions that would occur when using continuous functions.

Discrete signal in time $x[k]$ is often determined by a sampling of a continuous signal $x(t)$ in time. If the sampling is uniform, then $x[k] = x(kT)$, where T is the sampling period. The run of the dynamic process in time depends not only on the input functions at the moment, but also on the values of these input functions in the past. Thus, the dynamic process (system) has a memory in which are stored the effects of past interactions [1, 3].

The relation between input signals $x_1[k], x_2[k], \cdots, x_n[k]$, and output signals $y_1[k], y_2[k], \cdots, y_m[k]$, $k = 0,1,2,\ldots$, in matrix form looks as follows:

$$\mathbf{y}[k+1] = \mathbf{A}\mathbf{y}[\mathbf{k}] + \mathbf{B}\,\mathbf{x}[\mathbf{k}] + \xi \tag{1}$$

where:

$$\boldsymbol{A} = \begin{bmatrix} a_{11} & a_{12} \cdots & a_{1m} \\ a_{21} & a_{22} \cdots & a_{2m} \\ \cdots & \cdots \; \cdots & \cdots \\ a_{m1} & a_{m2} \cdots & a_{mm} \end{bmatrix}, \boldsymbol{B} = \begin{bmatrix} b_{11} & b_{12} \cdots & b_{1n} \\ b_{21} & b_{22} \cdots & b_{2n} \\ \cdots & \cdots \; \cdots & \cdots \\ b_{m1} & b_{m2} \cdots & b_{mn} \end{bmatrix}$$

$$\boldsymbol{y}[k] = \begin{bmatrix} y_1[k] \\ y_2[k] \\ \cdots \\ y_m[k] \end{bmatrix}, \; \boldsymbol{x}[k] = \begin{bmatrix} x_1[k] \\ x_2[k] \\ \cdots \\ x_n[k] \end{bmatrix}, \; \boldsymbol{\xi} = \begin{bmatrix} \xi_1 \\ \xi_2 \\ \cdots \\ \xi_m \end{bmatrix}$$

Later denoting:

$$\boldsymbol{C} := [\boldsymbol{A}|\boldsymbol{B}] = [c_{ij}]_{m\mathrm{x}(m+n)} \tag{2}$$

and

$$\boldsymbol{z}[k] := \begin{bmatrix} \boldsymbol{y}[k] \\ \boldsymbol{x}[k] \end{bmatrix},$$

the system of equations (1) is shown in reduced form

$$[k+1] = \boldsymbol{Cz}[k] + \boldsymbol{\xi} \tag{3}$$

Identification of equations (1) and (3) will involve the selection of the coefficients of input and output signal values, determined with measurements on a real object. The problem of the selection, the aforementioned authors present, among others, in [8, 9, 10, 11].

3. 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.

tions 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.

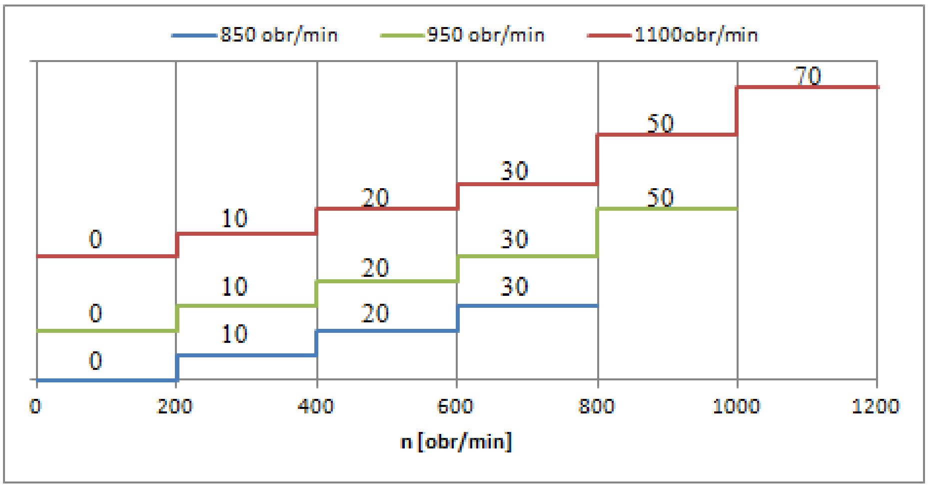

Fig.1. The implementation scheme of the research program

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, i.e.: 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, i.e.: 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, i.e.: 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.

It was similar with 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.

Statistical identification was made using GRETL [1]. Estimation of coefficients in the equa-

As a measure of strength and direction of the correlation between the examined variables (Y, X) the Pearson correlation coefficient (4) was adopted:

$$r_{yx_k} = \frac{\sum_{i=1}^{N}(x_{ik}-\bar{x}_k)(y_i-\bar{y})}{\sqrt{\sum_{i=1}^{N}(x_{ik}-\bar{x}_k)^2\sum_{i=1}^{N}(y_i-\bar{y})^2}} \tag{4}$$

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 $r_{y_kx_s}$ form a matrix of correlation coefficients $\boldsymbol{R}$ between explanatory variables (X_k, Y_s):

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

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 [10,11].

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 main evaluative indicator is the hourly emission of the individual components of toxic fumes, which is calculated using the formula [2]:

$$E_{i,j} = a_j \cdot C_{j,i} \cdot G_{sp,i} \ \text{[g/h]} \tag{5}$$

where:

j – CO, HC, NO_x,

a_i – characterization factor for a given compound j:

a_{CO}=0,000966, a_{HC}=0,000478, a_{NOx}=0,001587,

$C_{j,i}$ – concentration of individual compounds [ppm];

$G_{sp,i}$ – expenditure of emissions [kg/h].

This indicator is, however, difficult to apply in the case of transient process analysis, because defining the exhaust gas flow would necessitate its estimation, and thus it introduces significant errors, which obviously excludes this method. Another approach was proposed by the authors of [2], using the evaluation of the following relation:

$$W_i = a_i \int_0^t C_{j.i}(t)dt \tag{6}$$

where:

$C_{j,\,i}$ *(t)* – concentration of any toxic compound in time t [ppm]

t - the duration of the transient [s].

Thus, by integrating the area under the curve obtained from the experiment or from a model, an indicator which accurately describes the direction of change was obtained. On the other hand, the indicator still does not describe the nature of the change. As is known from the observation, depending on the value of waveforms, the course of the transient can vary significantly. These differences depend largely on the intensity of the experience of individual phases of the transient. Most often, in the course of a typical transient state, two phases can be noted. The first, characterized by the highest growth rate, accompanied by a sharp increase in the concentration of ZT, usually several times greater than the concentration in steady state. The second phase of the transient is characterized by a much less violent course; it is monotonic in nature and approaches a value of steady-state concentrations in a asymptotic manner.

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 analyzing 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 [1]. 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:

$$L(K) = 2^K - 1 \tag{7}$$

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:

$$h_{mx_k} = \frac{r_{yx_k}^2}{1 + \sum_{\substack{k,s \epsilon K_m \\ k \neq s}} \left| r_{x_k x_s} \right|} \tag{8}$$

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, the H_m information

$$H_m = \sum_{k \epsilon K} h_{mx_k} \tag{9}$$

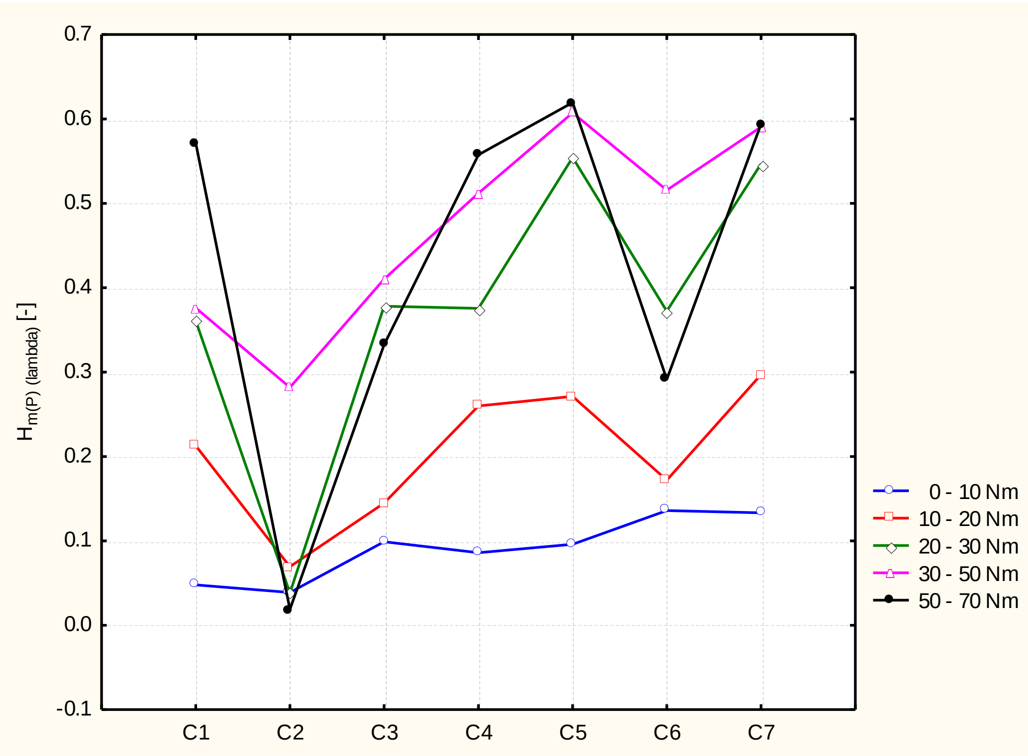

Fig. 2. The indicator values of information capacity H_m for λ and transient with n = 1100 rev / min and load change from T_{tq} = 0 Nm to T_{tq} = 70: P - delayed injection timing, C1 – C7 - combinations of explanatory variables

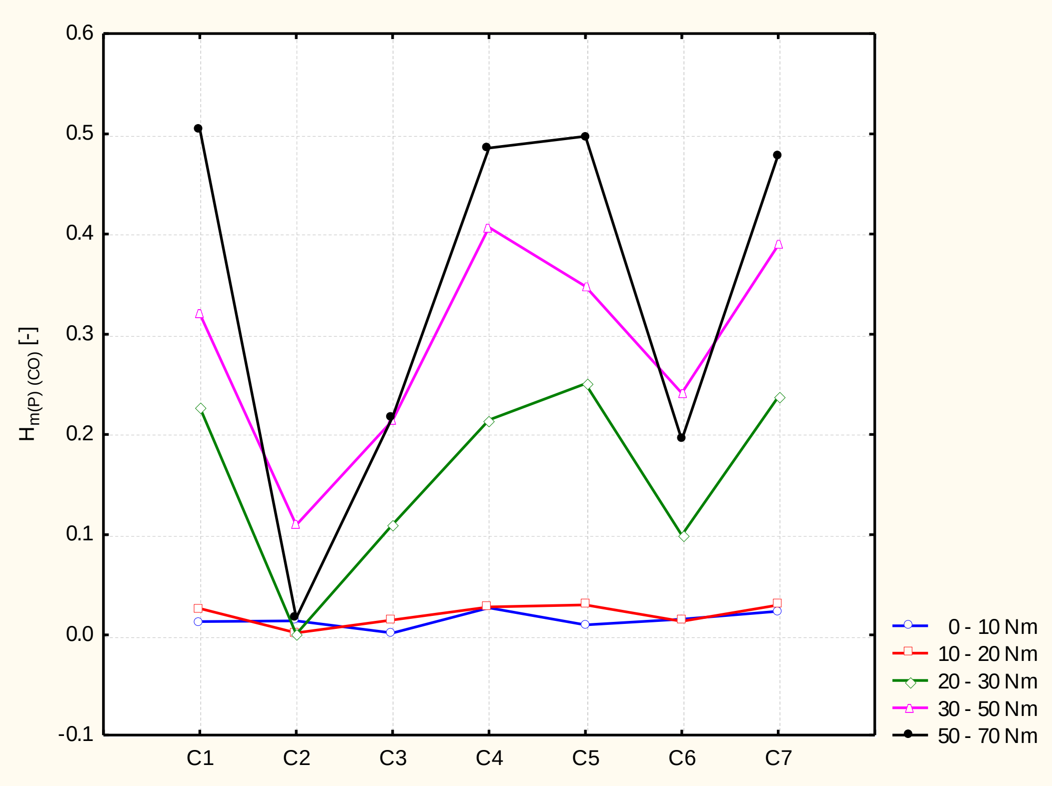

Fig. 3. The indicator values of information capacity H_m for CO and transient with n = 1100 rev / min and load change from T_{tq} = 0 Nm to T_{tq} = 70: P - delayed injection timing, C1 – C7 - combinations of explanatory variables

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].

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.

It should be noted that there is an 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. 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.

The largest H_m index value mainly appears 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.

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.

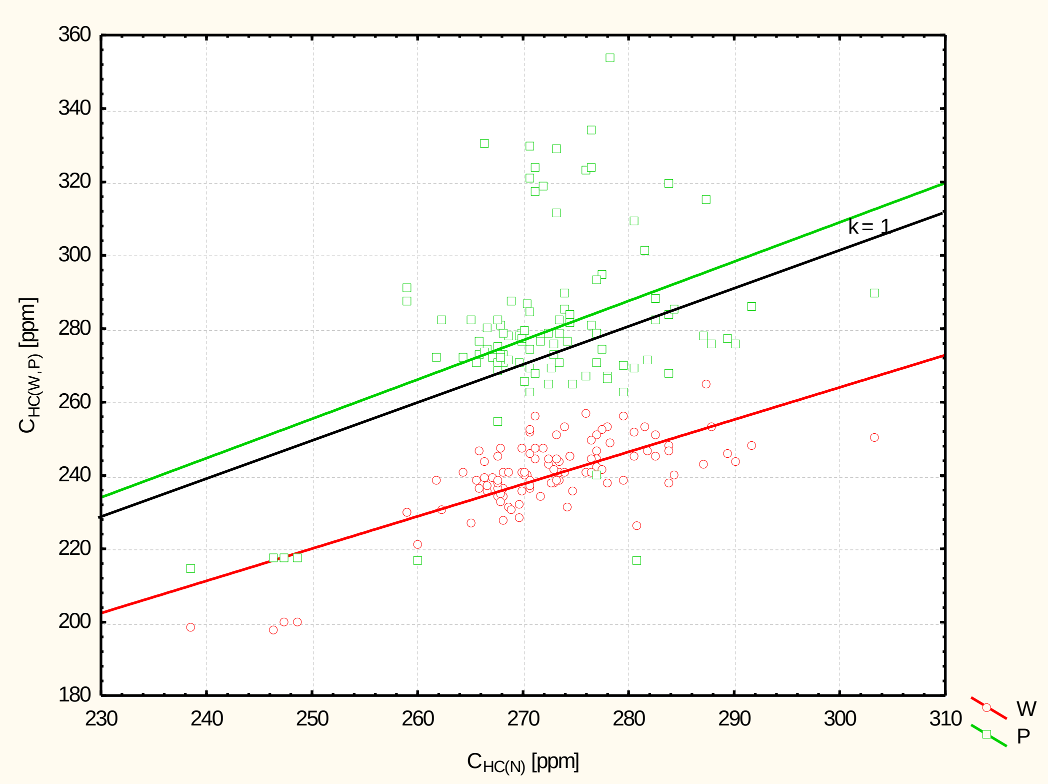

Fig. 4. The indicator values for information capacity H_m for λ and transient where n = 1100 rev / min and load change from T_{tq} = 0 Nm to T_{tq} = 70 Nm: P - delayed injection timing, $C_{HC\ (N,\ W,\ P)}$ - concentration of HC for (N) nominal, (W) accelerated, (P) delayed injection timing

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 coefficient was r = 0.75. 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).

5. 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, i.e. 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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Mr Ryszard Zadrąg, DEng. – Doctor in the Faculty of Ocean Engineering and Ship Technology at Gdansk University of Technology.

Dr inż. Ryszard Zadrąg – adiunkt na Wydziale Oceanotechniki i Okrętownictwa Politechniki Gdańskiej

Mr Tomasz Kniaziewicz, DSc., DEng. – Doctor in the Faculty of Mechanical and Electrical Engineering at the Polish Naval University.

Dr hab. inż. Tomasz Kniaziewicz- adiunkt na Wydziale Mechaniczno-Elektrycznym Akademii Marynarki Wojennej