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IDENTIFICATION OF INDICATORS SENSITIVITY OF EMISSIONS AS A DIAGNOSTIC PARAMETER DURING THE DYNAMIC PROCESS OF MARINE DIESEL ENGINE

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Abstract

The change of some parameters of an engine structure affects emission of harmful components in engine's exhaust. This applies first of all to damages in a charge exchange system as well as in a fuel system and an engine supercharging system. These changes are significantly greater during dynamic states and in the time transient processes. It is possible to talk about different sensitivities of emission factors understood here as diagnostic parameters for the same extortion from the structure of the engine but executed in other load states. The article presents a diagnostic model of the engine in which the diagnostic symptoms are indicators and characteristics of the emission of gaseous exhaust components. The model was supplemented with the results of tests on the real object, which was a marine diesel engine. Propose measures of the sensitivity of the diagnostic parameter during dynamic processes - processes characterized by high variability of waveforms, which variability causes problems not only of measurement nature, but also often interpretive.

Keywords: marine diesel engine, exhaust gas toxicity, dynamic states, emission

IDENTYFIKACJA WRAŻLIWOŚCI WSKAŹNIKÓW EMISJI JAKO PARAMETRÓW DIAGNOSTYCZNYCH PODCZAS PROCESÓW DYNAMICZNYCH OKRĘTOWEGO SILNIKA SPALINOWEGO

Streszczenie

Zmiana niektórych parametrów struktury silnika wpływa na zmianę emisji składników szkodliwych w spalinach. Dotyczy to przede wszystkim uszkodzeń następujących w układzie wymiany ładunku a także w układzie paliwowym i układzie doładowania silnika. Zmiany te są zdecydowanie większe podczas trwania stanów dynamicznych i towarzyszących im procesów przejściowych. Można więc mówić o różnej wrażliwości wskaźników emisji rozumianych tutaj jako parametrów diagnostycznych na te same wymuszenia pochodzące od struktury silnika, ale realizowane w innych stanach obciążenia. W referacie przedstawiono model diagnostyczny silnika, w którym symptomami diagnostycznymi są wskaźniki i charakterystyki emisji gazowych składników spalin. Model uzupełniono wynikami badań na obiekcie rzeczywistym, którym był okrętowy silnik spalinowy. Zaproponowano również miary wrażliwości parametru diagnostycznego podczas procesów dynamicznych – procesów charakteryzujących się dużą zmiennością przebiegów, która to zmienność powoduje problemy nie tylko natury pomiarowej, ale również często interpretacyjnej.

Słowa kluczowe: okrętowy silnik spalinowy, toksyczność splin, stany dynamiczne, emisja

1. INTRODUCTION

In the operation of each ships, we can distinguish three basic modes: a cruise, a hoteling and maneuvers [4]. The duration of this modes depends on the type of ship and tasks to which it was designed. Commercial vessels carrying cargo between ports, transient states will represent a small share of time in the entire operational coverage. However, when considering special vessels whose main task is to operate in port areas, the share of these states is a significant part of their operation [2, 8, 10]. During the implementation of these conditions, there is an increased emission of harmful compounds that often exceeds the emission of their cruise mode [9, 17]. It should also be noted that transients are carried out by ships in port areas close to human agglomerations, which also adversely affect people living in these areas and therefore should be subject to separate considerations [5, 12].

Dynamic states of the engine are caused by forced dynamic operating conditions. It is mainly connected with the variable moment of resistance acting mainly from a propeller and a rudder of the vessel [1]. These changes are mainly caused by the crew. However, there are also extortions independent of control and are related to external conditions prevailing in an operating area and these are atmospheric conditions including wind force and sea state. During this time, the dynamic properties of processes occurring in marine diesel engines are visible [13]. The increased load is accompanied by the increasing dose of fuel, which determines changes in the harmful compounds emission [5, 6, 7]. However, during the measurements, the position of the probe should also be taken into account [3].

The technical condition of the ship's engine also affects the change in emission intensity in dynamic load conditions. During its operation, its structure parameters change and have an impact on its performance described by the set of output parameters. Mutual relations between structure parameters and output parameters, under certain conditions allow to treat output parameters as symptoms of the technical condition of the engine [14, 16]. Physicochemical processes occurring during the working process and the quantities describing them can be observed and measured from outside, so the symptoms of the technical condition of the engine can be measured without dismantling it. These values include the intensity of emission of harmful compounds.

The correct operation of the power supply determines the correct course of the combustion process in the engine cylinder. The correctness of the start and end of injection in classic power systems largely protects the high pressure fuel pump. It is realized by regulatory parameters such as: fuel dose and injection advance angle. This angle should be treated as the basic parameter determining the correctness of the combustion process in diesel engines. Even small deviations cause changes in the main engine operation indicators as well as emission factors. The injector, or more precisely the parameters that describe its operation, are responsible for the correctness of the injection process. The most important regulatory parameter, decisive for the shape of injection, its correctness, and above all repeatability, is the opening pressure of the injector. This parameter, compared to the aforementioned ones, undergoes the most frequent changes during the use of the engine, and although its effect on the combustion process is incomparably smaller than, for example, the angle of advance of fuel injection and it must be taken into account when analyzing the combustion process. This parameter determines the quality of the fuel atomization, and thus the preparation of a homogeneous combustible mixture in the cylinder, which is particularly important in dynamic states forced by dynamic operating conditions, mainly variable moment of resistance, when extortions concerning the supply system are particularly important. The remaining parameters remaining on the injector side, affecting the injection process, concentrate on the parameters describing the geometric parameters of the atomizer, which, as is known, also undergoes changes during use, for example as a result of erosive fuel interaction [13].

Taking the above into account, the analysis of engine dynamic states aimed primarily at their comparison, taking into account their high variability, should focus on the unambiguous determination of both the beginning and end of the dynamic state and its course. In this case, it is desirable to use criteria that would be helpful in objective comparative assessment of concentration or emissions from dynamic states. The use of assessment indexes is one of the commonly used methods in such cases.

The paper is a continuation of the previous work of authors and has been extended by chain dynamics indicators applied from the emission of harmful compounds of a marine combustion engine, which were presented in the last part of the paper.

2. EVALUATION INDICATORS OF DYNAMIC STATES

Besides static states where emission level is relatively constant, dynamic states are also present. The nature of these changes depends on various extortions. These extortions can generally be divided into controllable ones, which are related to a way of controlling a ship and external extortion - dependent on atmospheric conditions.

The following relationship can be used to evaluate the dynamic state [14]:

$$W_i = a_i \int_o^t C_{j,i}(t)dt \qquad (1)$$

where:
W_i – emission rating indicator,
$C_{j,i}(t)$ – concentration of any toxic compound at time t [ppm],
a_i – factor characteristic for a given compound j: a_{CO}=0,000966, a_{HC}=0,000478, a_{NOx}=0,001587,
t – time duration of transient state [s].

By integrating an area under a curve obtained from experiment or model, an integration curve is determined which describes a direction of changes in dynamic state. On the other hand, this indicator still does not describe a nature of changes. As is known from observation, depending on a value of extortion, a course of transient can significantly differ. These differences usually depend on an intensity course of individual phases in a transient state. Usually, two phases can be specified in course of a typical transient. The first one, characterized by the greatest dynamics of changes, which is accompanied by a sharp increase in harmful compounds concentration, as a rule, many exceeding the steady-state concentration. The second phase of transient state is characterized by a much less rapid course, it is monotonic in character and asymptotically approaches values of concentrations from steady states.

The following relationship can be used to identify the beginning and end of a dynamic state:

$$S_i = \frac{dC_{j,i}}{dt} \quad (1)$$

where:
S_i – indicator of the beginning and end of the dynamic state,
$C_{j,i}(t)$ – concentration of any toxic compound at time t [ppm],
t – time duration of transient state [s].
In order to correctly identify dynamic states, analysis of concentration selected harmful compounds registered during a 30 minute cruise of navy ship was carried out. The concentration changes are shown in Figure. 1. The measurements were carried out using the portable TESTO 350 analyser (Fig. 2). The analyzer data are presented in the table 1.

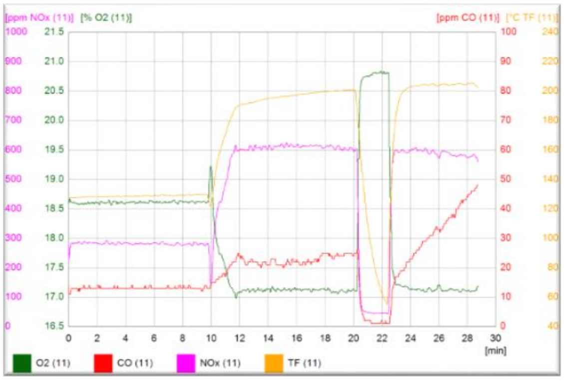

Fig. 1. Concentrations of harmful compounds during ship's operating

Fig. 2. Portable TESTO 350 analyser

Table 1. Parameters and measuring ranges of the TESTO 350 analyser

Parameter	Measuring range	Tolerance
°C (exhaust gas)	-40 to + 1000°C	max. ± 5K
O_2	0 to 25 wart. %	According to MARPOL, Annex VI or NOx Technical Code
CO	0 to 3000 ppm	
NO	0 to 3000 ppm	
NO_2	0 to 500 ppm	
SO_2	0 to 3000 ppm	
CO_2 (IR)	0 to 40 wart. %	
P_{abs}	600 to 1150 hPa	± 5 hPa in 22°C ± 10 hPa w -5 to +45°C

The first step in analysing recorded concentrations (Fig. 1) was identification of static and dynamic states. For this purpose, histograms were built that grouped concentration values of individual compounds in characteristic classes. A graphical example of this analysis is the histogram of nitrogen oxides concentration (Fig. 3).

To make an histogram it is necessary to determine size of data set (measurements), then determine data range and specify number of intervals. Due to the relatively large data set (registration time 30 min, sampling frequency of the analyser 1 s), the so-called Smirnov pattern:

$$m = 1 + 3{,}322 \, lnN \quad (2)$$

where:
m – number of intervals (classes),
N – number of observations (measurements).

Then width of compartment is determined according to relationship:

$$\Delta x = \frac{x_{max} - x_{min}}{m} \quad (3)$$

where:
x_{min} – minimum value of data,
x_{max} – maximum value of data,
m –number of intervals.

Let χ_i represents the output data variable x then:

$$\chi_i = x_{min} + 0{,}5 \cdot \Delta x + i \cdot \Delta x \quad (4)$$

for i = 0,1,…,m-1.

Defining i-th interval, which is to be a range of values from to, but is not including:

$$\Delta_i \in (\chi_i - 0{,}5 \cdot \Delta x, \chi_i + 0{,}5 \cdot \Delta x,) \quad (5)$$

for i = 0,1,…,m-1.

The function defined will have the form:

$$y_i(x) = \begin{cases} 1, & if \ x \in \Delta_i \\ 0, & elsewhere \end{cases} \quad (6)$$

Finally, the histogram sequence is evaluated:

$$h_i = \sum_{j=0}^{n-1} y_i(x_j) \quad (7)$$

for i = 0,1,…,m-1

where:
n – number of input elements of the histogram.

The histogram analysis of nitrogen oxide concentrations shows that during the cruise there were three steady states in which concentrations reached the following values: 0-50 ppm, 250-300 ppm and 550-600 ppm. The ship lasted the longest in a state where it reached 550-600 ppm, while the shortest was in the state in which concentrations reached value of up to 50 ppm. During this time, main engine of the ship was running idle. Other histogram values are assumed as dynamic states (Fig. 3).

In order to carry out a correct concentration analysis of harmful compounds during dynamic states, it is necessary to perform filtration of individual time transitions and subject them to further processing eliminating accidental errors and errors related to measurements. For this purpose, a low-pass Butterworth filter has been used. This filter, in relation to other filters, is characterized by the fact that it has a flat course of the amplitude characteristic in a bandwidth. Dynamic state analysis was performed based on the LabVIEW development environment.

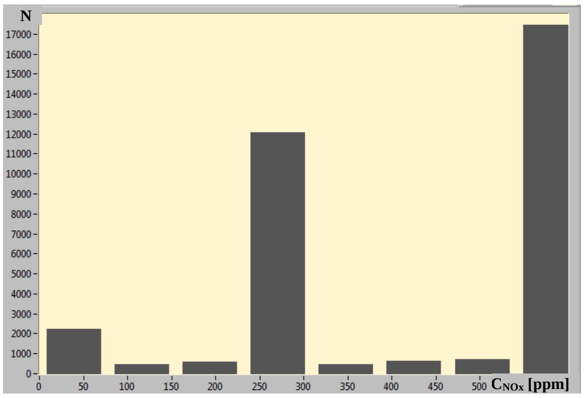

Fig. 3. Histogram of nitrogen oxide concentrations in steady states

Figure 4 shows course of nitrogen oxides concentration after filtration.

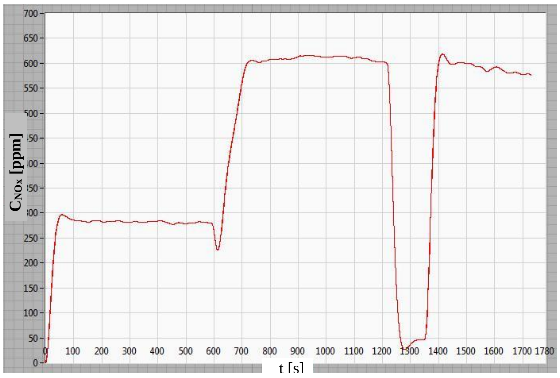

Fig. 4. Filtered course of nitrogen oxides concentration

By identifying the beginning and end of dynamic state, nitrogen oxides concentration in time course was differentiated to obtain waveform shown in Figure 5.

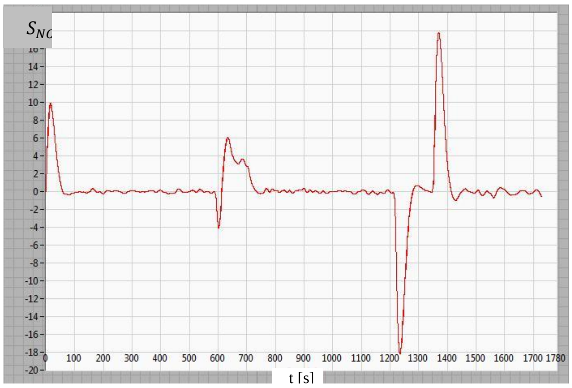

Fig. 5. Derivative course of nitrogen oxides concentration

Figure 6 shows integrated time course of nitrogen oxides concentration. In order to carry out a more thorough analysis, integrating defined ranges of transient states should be performed, however, according to goal set by authors, determine the beginning, end and direction of changes in dynamic state, course of obtained curve is sufficient.

From presented runs, it is possible to define time intervals in which dynamic states occurred during ship's cruise. In first minutes of the cruise there is a transitory state which will not be taken into consideration due to the lack of initial data. The values of differentials show speed of changes in harmful compounds emission. They also show direction of changes in dynamic state. The obtained data presented, at time t=600 s acceleration of the ship, which ended after time t=200 s. Subsequent changes in the ship's movement occurred between t_p=1200 s i t_k=1300 s. At that time, the ship stopped, then accelerated (from t_p=1350 s to t_k=1450 s) and then carried out next stages of ship's task.

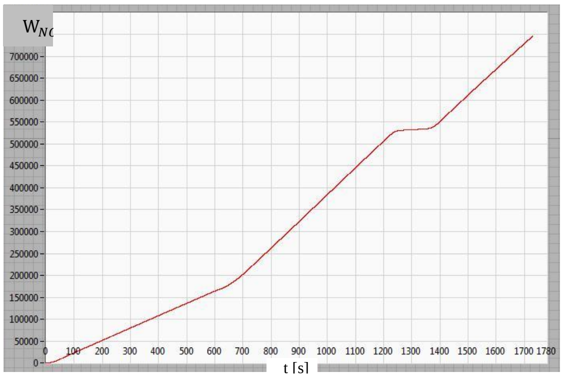

Fig. 6. The integrated course of nitrogen oxides concentration

In Figure 7, integrated and differentiated waveforms were placed with indication of dynamic states during the cruise of navy ship.

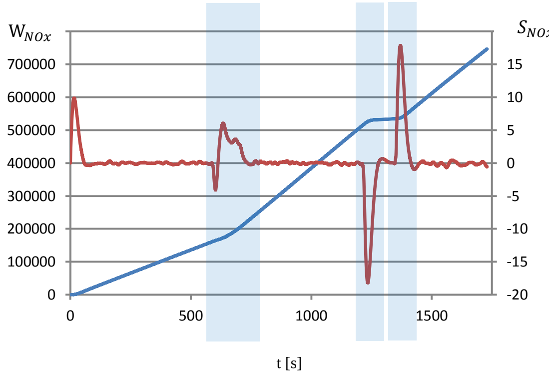

Fig. 7. Dynamic changes in the concentration of nitrogen oxides

Simple dynamics indicators may be used to describe dynamics of harmful compounds concentrations in which a given time series can be analysed. These include single-base and string indexes. These indexes are widely used, for example in econometrics, but can be successfully used and in other applications.

Dynamics indexes are defined as follows [11]:

$$I = \frac{x_n}{x_0} \ or \ I = \frac{x_n}{x_0} \cdot 100\% \tag{8}$$

where:
x_n – a level of phenomenon during tested period,
x_0 – a level of phenomenon during reference period.

These indexes are characterized by the following properties:
- indexes are non-negative numbers ($i \geq 0$),
- indexes are non-dimensional numbers,
- if a level of phenomenon is equal, they are equal to one ($x_n = x_0$),
- in the case of reducing a value by 100%, we get information about percentage of level of phenomenon in n-th period being higher or lower than in an initial period.

Analysing a given time series of harmful compounds concentrations in a form $C_{j,1}$, $C_{j,2}$,…, $C_{j,n}$ could be used single-base index or chain index strings.

The one-base indexes represent changes that occurred in level of phenomenon in subsequent periods in relation to period assumed as basic (base time). With regard to analysis of harmful compounds concentrations, single-base index is as follows [11]:

$$I_{n/0} = \frac{C_{j,n}}{C_{j,0}} \cdot 100\% \tag{9}$$

where:
$C_{j,n}$ – harmful compound concentration during tested period,
$C_{j,0}$ – harmful compound concentration during reference period.

Chain indexes inform what changes occurred in period considered in relation to previous period. For analysis of harmful compounds concentrations, chain index is as follows [11]:
where:

$$I_{n/n-1} = \frac{C_{j,n}}{C_{j,n-1}} \cdot 100\% \tag{10}$$

$C_{j,n}$ – harmful compound concentration during tested period,
$C_{j,n-1}$ – harmful compound concentration in previous period.

Figures no. 8-10 present changes in nitrogen oxides and carbon dioxide concentration during dynamic states. One-base indexes were used for analysis, while relative values of dynamics index were left. The first state refers to the time interval from t_p = 500 s do t_k = 800 s cruise mode depicted in Figure 2. During this time the ship carried out a maneuver of increasing velocity. The presented characteristics show that during manoeuvre, a course of changing nitrogen oxide index is larger than the carbon dioxide index. The concentration of nitrogen oxides index has more than doubled and the carbon dioxide index more than 1.5 times compared to initial state. This may indicate that during the manoeuvre, thermal load of engine increased due to increase of fuel dose, whereas carbon dioxide concentration (which is closely related to fuel consumption) gently stabilized at set level.

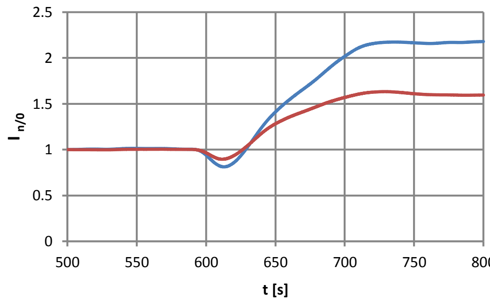

Fig. 8. One-base indexes of nitrogen oxides and carbon dioxide concentrations during acceleration manoeuvre
Blue line – $I_{n/0\ NOx}$. Red line - $I_{n/0\ CO2}$

Figure 9 shows manoeuvre reducing velocity of the ship. This maneuver was carried out from t_p = 1150 s to t_k = 1350 s. The indexes of both concentrations overlap in entire analysed range and set at a new level at the end of manoeuvre.

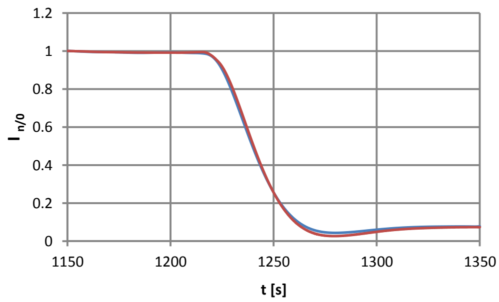

Fig. 9. One-base indexes nitrogen oxides and carbon dioxide concentrations during slowing down velocity
Blue line – $I_{n/0\ NOx}$. Red line - $I_{n/0\ CO2}$

The last maneuver during ship's cruise was acceleration from a place. This maneuver took place from $t_p = 1350$ s to $t_k = 1450$ s. In the first phase of manoeuvre to time t = 1370 s indexes overlap and then there were discrepancies. The curve of nitrogen oxides index is lower than carbon dioxide index. In comparison with acceleration realized in time from $t_p = 500$ s do $t_k = 800$ s, this manoeuvre is characterized by a much more rapid course. The carbon dioxide concentration index was even fourteen times higher than initial value, while the nitrogen oxide index increased thirteen times compared to entry value of manoeuvre. In general, it is assumed an increase in concentration indexes in this range from eleven to fourteen times greater than initial value.

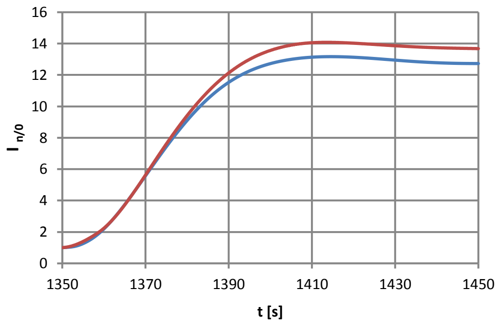

Fig. 10. One-base indexes of nitrogen oxides and carbon dioxide concentrations during acceleration manoeuvre from a place
Blue line – $I_{n/0\ NOx}$. Red line - $I_{n/0\ CO2}$

The analysis of the engine's dynamic states may also use a slightly different approach than the one presented above, based on the use of the chain index. The chain index presented in the time series informs us how the examined phenomenon changed from period to period. If the next elements are greater than 1, this means that the phenomenon is characterized by an increasing gradient. If it is lower than 1, the phenomenon is characterized by a decreasing gradient.

Fig. 11-16 show dynamic states analyzed using chain indexes. The same three cases were considered as in the previous analysis.

The first condition lasting from $t_p = 500$ s to $t_k = 800$ s is shown in Figs 11 - 12. The changes of the chain index and the first order derivative to time and the concentration of nitrogen oxides during the dynamic state were compared (Fig. 11). The observed waveforms are similar and can be used interchangeably in the description of dynamic states. However, as it seems from the above analysis, the more sensitive parameter is the first order derivative to time.

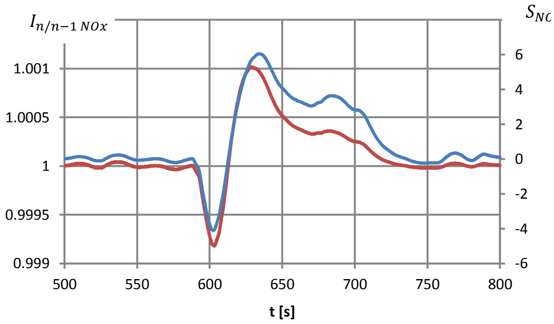

Fig. 11. Comparison of the chain index and differential waveform the nitrogen oxides concentration during the acceleration maneuver
Blue line – S_{NOx}. Red line - $I_{n/n\text{-}1\ NOx}$

In the initial phase a drop is visible, followed by a rapid increase. After reaching the maximum value, stabilization takes place (Fig. 12).

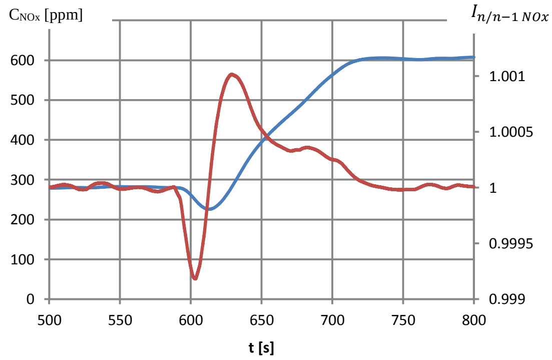

Fig. 12. The course of the nitrogen oxides concentration and the chain index during the acceleration maneuver
Blue line – C_{NOx}. Red line - $I_{n/n\text{-}1\ NOx}$

Fig. 13-14 show the process of decelerating a vessel from $t_p = 1150$ s to $t_k = 1350$ s on the example of changes in the nitrogen oxides concentration. The first phase is presented by a descending gradient followed by the increase and stabilization of the concentration. Comparing the chain index with first order derivative to time, we get discrepancies in the course. The derivative exhibits a more rapid change compared to the index used. Moreover, the shape of both curves is comparable and can also be used interchangeably to describe changes in the dynamic state.

Analogously, the analysis of the nitrogen oxides concentration was carried out during the last state, which the ship accelerated ($t_p = 1350$ s to $t_k = 1450$ s.). In the first phase there is an increase, reaching the maximum value and a gentle stabilization (Fig. 16). As before, the course of the index and derivative curves is similar (Fig. 15).

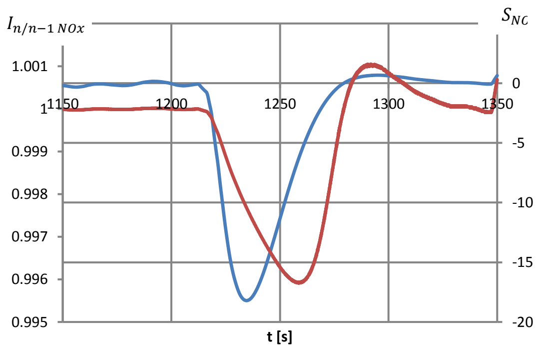

Fig. 13. Comparison of the chain index and differential waveform the nitrogen oxides concentration during slowing down velocity
Blue line – S_{NOx}. Red line - $I_{n/n-1\ NOx}$

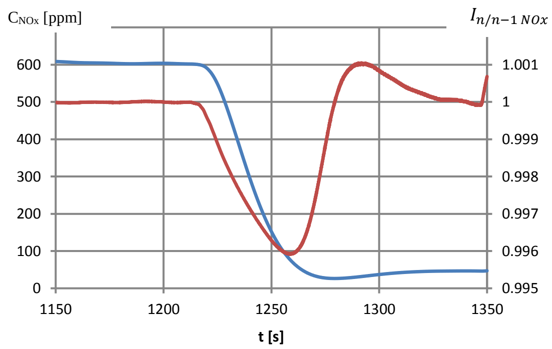

Fig. 14. The course of the nitrogen oxides concentration and the chain index during slowing down velocity
Blue line – C_{NOx}. Red line - $I_{n/n-1\ NOx}$

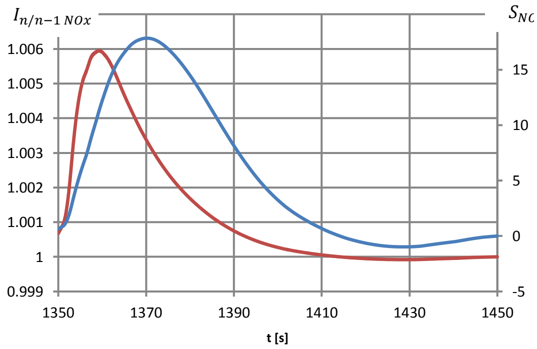

Fig. 15. Comparison of the chain index and differential waveform the nitrogen oxides concentration during acceleration maneuver from a place
Blue line – S_{NOx}. Red line - $I_{n/n-1\ NOx}$

4. CONCLUSION

The paper presents the methodology for identification of dynamic states of toxic compounds concentrations. The use of simple indexes of dynamics as a tool that can describe time courses during transient processes of a marine diesel engine gives great possibilities of identification and then analysis of dynamic states. The chain index presented in the time series informs us how the examined phenomenon changed from period to period. As it has been shown in the graphs, chain indexes can be used alternately with the first order derivative over time, however due to differences between the waveforms, it is recommended to use both tools during analyzing dynamic states.

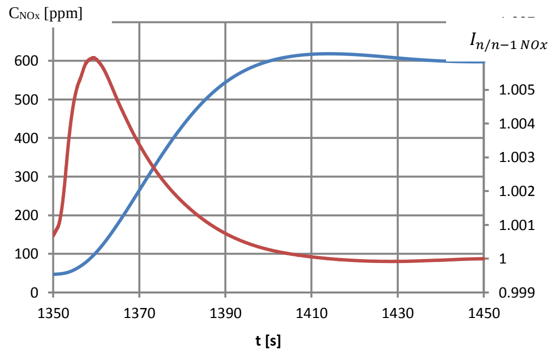

Fig. 16. The course of the nitrogen oxides concentration and the chain index during acceleration manoeuvre from a place
Blue line – C_{NOx}. Red line - $I_{n/n-1\ NOx}$

Due to the important role of extortion values as well as dynamics of their changes in future research, it would also be necessary to consider dynamic states related to changing an engine load and perform a comparative analysis with harmful compounds emission in synchronized time intervals of measuring instruments (e.g. sensor connected to the load indicator of governor with a device for measuring harmful compounds emissions). The obtained data should be subjected to filtration process and then, using tools presented in the paper, carry out a comparative analysis of harmful compounds concentration together with recorded load characteristics.

Further analysis of dynamic states should be focused on:

– carry out searching for indicators of engine's dynamic states, e.g. determining intensity of dynamic states by studying a slant of distributions,
– using neural networks to more accurately analyze dynamic states,
– conducting tests for typical ship engine damage and more accurate analysis of time courses using presented description methods.

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