STOCHASTIC MODEL OF THE PROCESS OF DIESEL ENGINE OPERATION

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Abstract

The most significant problem of operating Diesel engines is the problem of rational (and especially optimum) decision control over the process of the engines operation. The statistic theory of decision or the theory of controlled decision processes of semi-Markov may be applied for such control. Application of the second theory for taking operation decisions demands, among others, elaboration of a semi-Markov model of the process of the engines operation. Therefore, a formal description of the process of Diesel engines operation has been presented in the paper, as well as a model of this process in a form of a two-dimensional stochastic process of which coordinates are semi-Markov processes of finite sets of states. The first of these processes describes a process of changes of technical conditions of the engines and the second one – a process of changes of their operation conditions. A one-dimensional model of the process of Diesel engines operation has also been proposed. Diesel engines' technical and operating states, being of an essential practical meaning, are the values of the process.

1. Introduction

Process of operating the Diesel engines belongs to the most significant processes proceeding in the phase of their operation. This process is created by the engines' technical and operating states occurring in succession and being connected casually in time. The course of the process should be rational, so it should come from the accepted optimizing criterion of e.g. expected value of the engines operation costs or coefficient of their readiness to start working in any moment. In every such a moment, an order may come for task performance that will demand proper (reliable) work of these engines [4, 8]. A control enabling such a course of the process of Diesel engines operation can be realized only if such a model of the process is such elaborated that enables application of one of the theories of making decisions. In case of Diesel engines there are two theories of essential meaning: statistic theory of decision and theory of controlled semi-Markov (decision) processes [3, 4, 5, 9]. Recently, for solving different problems on durability, reliability and decision control over machines operation there is more and more often and successfully used the theory of controlled semi-Markov (decision) processes. This theory may also be applied in case of solving similar problems related to Diesel engines operation, including these connected with control over the process of these engines operation. From this reason, a semi-Markov model of this process has been proposed in this paper as well as a model of changes of technical and operating conditions

From the definition of a semi-Markov process results [1, 9, 10, 13, 14] that it is a stochastic process of a discrete set of states and its realizations are functions of constant intervals (of equal values in the operating time intervals, which are random values), right-hand continuous. It also follows from the definition that this process is determined only if its initial distribution $P_i = P\{Y(0) = s_i\}$ is known, as well as its functional matrix $Q(t) = [Q_{ij}]$ of which elements are the probabilities of the process transition from the state „s_i" into the state „s_j" in no longer time than t ($i \neq j$; $i, j = 1, 2, \ldots, k$), which are non-decreasing functions of variable t and are designated with the symbol $Q_{ij}(t)$ [3, 5, 9].

Semi-Markov model of any real process may be created only when states of the process can be defined in such way that duration of the state existing in the moment τ_n and the state possible to-be-reached in the moment τ_{n+1} does not depend in stochastic term on the states proceeded previously as well as their duration intervals.

Building a semi-Markov model $\{W(t): t \geq 0\}$ of a real process of changes of technical states proceeded in the phase of operating Diesel engines is a necessary condition to apply the theory of semi-Markov processes. The characteristics of the models are as follows [3, 5, 9, 14]:

1) Satisfaction of the Markov condition saying that future evolution of any examined system (e.g. of a process of changes of technical or operating states in the phase of the system operation), for which a semi-Markov model has been built, would depend only on its state in the given moment and not on its operation in past, so the future of the system would not depend on its past, but on the present time.
2) Random values: T_i (stating for duration of the state s_i independently on which state is followed by) and T_{ij} (stating for duration of the state „s_i" under the condition that it will be followed by the state „s_j") having distributions other than exponential.

Thus, for creating models, which should lead to elaboration of a semi-Markov model of the process of changes of technical states of Diesel engines, it should be taken into account an analysis of state changes of the real process, so the changes of the technical states proceeding in the phase of operating the mentioned engines.

2. Semi-Markov models of changes of technical states of Diesel engines

In case of each Diesel engine the process of changes of its technical states is a process, of which time intervals of its every state s_i duration are random values. The random values' realizations depend on many factors, as wear of engine tribological systems. In case of Diesel engines it has been found a fact that wear of engine sliding tribological systems is slightly correlated with time [3, 6, 8, 13, 20, 30]. This notice was very important, because the engines usability is depended mainly on the technical state (so – wear degree) of their tribological systems. It made it possible to forecast technical state of the mentioned engines taking into consideration only their present state excluding the previous states. Explanation of this fact would enable elaborating (in the result of applying the theory of semi-Markov processes) more adequate probabilistic mathematical models needed to forecast technical states of particular engines. For this purpose the following hypothesis: (H) may be formulated: ***state of any sliding tribological system of any Diesel engine and its time duration depends significantly on the previous state and not on earlier states or their time duration, because the engine's load as well as implicated speed and wear are the processes of asymptotic independent values.***

The statement included in this hypothesis that ***because the engine's load as well as implicated speed and wear are the processes of asymptotic independent values*** follows from the two obvious facts:

1) There is a strict dependence between the load on sliding tribological systems of Diesel engines and their wear [11, 12, 16],

2) There is lack of monotonic changes of load of Diesel engines' tribological systems in a long term of their operation, so it can be accepted that these systems' load is stationary [2, 11, 12, 15].

The stationary load (in wider meaning), means in each case, that all multi-dimensional functions of density probability depend only on the reciprocal distance of moments τ_1, τ_2, ..., τ_n, but do not depend on them themselves [2]. Thus, one-dimensional function of density probability of the load value does not depend on the moment, which the value refers to and the two-dimensional function of density probability depends only on the difference between moments, in which the observed load values appeared. But, in a narrow meaning, the stationary load (total stationary) is understood as such one of which all possible statistic moments of higher orders as well as total moments of the load (as the process of energetic, thermal and mechanical interaction) are not dependent on time. In practice the stationary load *in the wider meaning* is of significant meaning. However, testing the load of tribological systems to verify the mentioned characteristics is not necessary in this case. From the up-to-now tests of not only engines but also different machines it is known that the load of their tribological systems changes permanently in such way that its particular values measured after very small time intervals are strongly correlated between each other. But, when the time interval between the measures of the load increases, the correlation between the loads decreases. From this reason load values measured in moments considerably far from each other can be considered as independent. This feature is called asymptotic independence of the load value measured in the moment e.g. τ_{i+1} from the value measured in the moment τ_i when the time interval $\Delta\tau = \tau_{i+1} - \tau_i$ is big enough. Such understood asymptotic independence between values of the load recorded in the moment τ_i and τ_{i+1} reflects the fact, that the larger time interval $\Delta\tau$, the lower dependence between them. Whereas, from the principles of Diesel engines work it is also known that in longer term of proper work of these engines their load does not undergo (and cannot undergo) any changes monotonically increasing or decreasing. Thus, it can be accepted that maximal load values occurs in determined moments incidentally, always with determined probability. This lack of monotony of engines' load in longer operating time may be called the stationarity of their load.

Verification of the presented hypothesis (H) requires determining (forecasting) the consequences of which occurrence can be identified empirically if the hypothesis is true. Consequences (K), which can be drawn (inferred) from this hypothesis (taking into account the mentioned characteristics of load of Diesel engines and their sliding tribological systems, are as follows [2, 11, 16]:

- K_1 – irregular course of realizations of sliding tribological systems wear;
- K_2 – interleaving realizations of processes of sliding tribological systems wear,
- K_3 – course of correlation function for determined sliding tribological systems wear, that the bigger range $\Theta = t_i - t_{i+1}$, is the function decreases quickly at the beginning and then oscillates around zero level with relatively not big amplitude, getting smaller and smaller at increasing $\Delta\tau$,
- K_4 – nearly normal gains distribution of tribological systems wear for enough long time interval of their correct work,
- K_5 – linear dependence of variances of the tribological systems wearing process from their operation time.

The presented consequences may be substantiated in the way that if the characteristics of load of Diesel engines as well as their tribological systems are just like these it should exist irregular course of the systems wear realization. This gives a ground for accepting that the wear gains recorded in time intervals considerably distant from each other are asymptotically independent and that the higher the time (of the range θ, at which e.g. $\theta = h\Delta\tau$, $h = 1, 2, \ldots, n$) is between these intervals the lower the dependence between the mentioned wear gains. Thus, the processes of the systems wear can be taken for the processes of asymptotically independent gains [2].

The mentioned consequences $K_i (i = 1, 2, \ldots, 5)$ show the probabilistic law of wear of sliding tribological systems. They are not reciprocally contradictory and their logic truthfulness does not create any doubts. In this way, the condition of consequences' non-contradiction is satisfied, so the mentioned consequences can be used for empirical verification if the presented hypothesis (H) is true. Such verification consists in empirical testing the sliding tribological systems wear and checking if the consequences $K_i (i = 1, 2, 3, 4, 5)$ are true, what is equal to stating if the consequences (facts) occur or do not occur. Verification of the hypothesis H requires accepting the following syntactic implication as the truth [7]:

$$H \Rightarrow K_i (i = 1, 2, 3, 4, 5) \qquad (1)$$

Then, a non-deductive (inductive) inference may be applied according to the following diagram [7]:

$$[K_i (i = 1, 2, 3, 4, 5), H \Rightarrow K_i (i = 1, 2, 3, 4, 5)] \vdash H \qquad (2)$$

Logic interpretation of the inference diagram is the following: if empirical verification of the consequences $K_i (i = 1, 2, 3, 4, 5)$ confirms their rightness, and if implication (1) is true, the hypothesis H is also true and can be accepted. Inductive inference running in accordance with the diagram (2) is called a reductive inference. This inference, as each other one belonging to this inference group, does not lead to reliable conclusions but only probable ones [5, 7].

From the presented hypothesis (H) it follows, that the models for the process of changes of Diesel engines' technical states $\{W(t): t \geq 0\}$ may be stochastic processes of a discrete set of states and continuous time duration of distinguished technical states of these engines. The considered processes of changes of the engines' technical states, in mathematical aspect, are functions mapping the set of the moments T into a set of technical states S. Elaboration of such a model demands fixing a finite set of changes of the engines' technical states. Taking the usability of Diesel engines to perform tasks as a criterion for selecting the states there can be distinguished a set of classes (subsets) of technical states called directly states (being of essential meaning in operating practice) [7]

$$S = \{s_i; i = 1, 2, 3, 4\} \qquad (3)$$

of the following interpretation:

- s_1 – state of full ability (total ability), so such technical state of a Diesel engine when the engine may be operated at full load range for which was destined in the phase of designing and producing,
- s_2 – state of partial ability (not full, not total ability), so such technical state of a Diesel engine which enables performing all tasks (just like the state s_1) but at lower values of operating indexes (for instance, at lower usable efficiency, so at higher fuel consumption),
- s_3 – state of task disability, so such technical state of a Diesel engine which enables performing only some tasks (for instance such state which makes impossible operation of engine on the characteristic of external power rating),

- s_4 – state of full disability (total disability) of a Diesel engine which makes impossible performing any task from the set of tasks, for which this engine was destined in the phase of designing and producing (for instance, such state of engine which is the reason of shut down of one of its cylinders).

Elements of the set $S = \{s_i; i=1, 2, 3, 4\}$ are values of the process $\{W^*(t): t \geq 0\}$, created by occurring successive states $s_i \in S$, being (as it is known) in casual connection with each other.

Differentiation of states $s_i \in S$ $(i = 1, 2, 3, 4)$, in case of Diesel engines is significant as it is essential the way of using the engines (especially, the ship main engines) when they are in the state s_1 or s_2. In the second case these engines should be used for the shortest time, if possible, after which they should be subjected to renewal.

The presented variant predicts situations, when a user may take a risk to try to perform a task at the engine state s_2 or even try to perform some tasks at the state s_3.

In case when in the taken strategy of operating Diesel engine it is not important to differentiate the state s_1 and s_2, a more simply process $W(t)$: $t \geq 0\}$ of changes of engine technical states may be considered, that is a model of a set of states [3, 5, 7]:

$$S = \{s_1, s_2, s_3\} \tag{4}$$

of the following interpretation of these states:

- state of full ability s_1, which enables operating an engine in each conditions and range of load for which the engine was destined in the phase of designing and producing;
- state of partial ability s_2, which enable operating an engine in limited conditions and range of load lower than the load for which the engine was destined in the phase of designing and producing
- state of disability s_3, which make impossible operating an engine in accordance with its destination (e.g. because of a failure, performing preventive works on its subsystems, etc).

Thus, this process is a three-state process of continuous realizations (a process continuous in time). It can be accepted that if the state s_2 or s_3 does not occurs an engine finds itself in a state s_1.

Thus a set of technical states $S = \{s_1, s_2, s_3\}$ may be considered as a set of values of the stochastic process $\{W(t): t \geq 0\}$ of constant intervals and realizations right-handed continuous.

The presented above technical states of Diesel engines are connected with proper operating states of these engines. These states (technical and operating) implicate reciprocally each other [3, 5, 7]. So, in order to make possible considering these kinds of states jointly, a model of the operating states changes process needs to be elaborated for Diesel engines.

3. Semi-Markov model of changes of operating states of Diesel engines

Each Diesel engine may find itself in one of the following technical states proceeding in time of its operation and belonging to the set [3, 5, 7]

$$E = \{e_1, e_2, e_3, e_4\} \tag{5}$$

of the following interpretation of the states:

– state of active use (e_1): work of propulsion system when the main engine develops the moment M_o at the rotational speed n where the general propulsion system efficiency equals $\eta_o \neq \eta_{o(max)}$; or work of the propulsion system then the main engine develops the moment M_o at the rotational speed n, where the general propulsion system efficiency equals $\eta_o = \eta_{o(max)}$ etc.,

– state of passive use (e_2): propulsion system standstill at the ambient temperature (temperature in the engine room as well as of shaft lines) $t_s \leq 0$ °C or propulsion system standstill at the ambient (temperature in the engine room as well as of shaft lines) $t_s > 0$ °C, etc.,

– state of scheduled service (preventive) (e_3): preventive control of quality of atomizing the fuel through injectors and adjustment, if necessary, of injection pressure or preventive adjustment of inlet/outlet valve clearances, etc.,

– state of not-scheduled service (forced by failures) (e_4): exchange of an injector with broken spring into a new one, exchange of broken piston rings into new ones, exchange of injection pump with worn plungers in a cylinder into a new one, etc.

The set of operating states $E = \{e_1, e_2, e_3, e_4\}$ may be considered as a set of values of the stochastic process $\{X(t): t \geq 0\}$ of constant intervals and right-handed continuous realizations.

The model of the technical states changes process $\{W(t): t \geq 0\}$ and the model of operating states changes process $\{X(t): t \geq 0\}$ of Diesel engines are the processes reciprocally dependent, which proceed in the same time in the engine operation phase. From this reason, a model of the process of simultaneous states changes of the processes $\{W(t): t \geq 0\}$ i $\{X(t): t \geq 0\}$ should be elaborated. Such process of which states would be the simultaneously proceeding states $s_i \in S$ of the process $\{W(t): t \geq 0\}$ as well as the states $e_j \in E$ of the process $\{X(t): t \geq 0\}$ can be called a model of the process of operating the Diesel engines.

4. Semi-Markov model of the process of operating Diesel engines

The process of operating a Diesel engine is a joined process of simultaneous changes of technical and operating states of the engine [3, 5, 7].

The most simply model of the process of operating Diesel engines may be a two-dimensional stochastic process$\{Y(t): t \geq 0\}$, of which the coordinates are: the process of changes of technical states $\{W(t): t \geq 0\}$ and the changes of operating states $\{X(t): t \geq 0\}$ of these engines. The values of the process $\{W(t): t \geq 0\}$ may be elements of the set of technical states $S = \{s_1, s_2, s_3\}$, and the values of the process $\{X(t): t \geq 0\}$ – elements of the set of operating states $E = \{e_1, e_2, e_3, e_4\}$ of the mentioned engines. Description of the process $\{Y(t): t \geq 0\}$ requires founding its joined distribution. The joined distribution of probability of the two-dimensional process $Y(t) = [W(t), X(t)]$ may be presented in the following way:

$$p(s_i, e_j, t) = P\{W(t) = s_i, X(t) = e_j\} \tag{6}$$

Distribution of the probabilities $p(s_i, e_j, t)$ can be shown in a form of the following matrix (7) [3]:

$$Q = \begin{bmatrix} p(s_1, e_1, t) & p(s_1, e_2, t) & 0 & 0 \\ p(s_2, e_1, t) & 0 & p(s_2, e_3, t) & 0 \\ 0 & 0 & p(s_3, e_3, t) & p(s_3, e_4, t) \end{bmatrix} \tag{7}$$

In this situation a process of operating a Diesel engine may be considered as a stochastic process $\{Y(t): t \geq 0\}$ of values from the set $Z = \{z_1, z_2, z_3, z_4, z_5, z_6\}$, of which interpretation is as follows [3, 7]: $z_1 = (s_1, e_2)$, $z_2 = (s_1, e_1)$, $z_3 = (s_2, e_1)$, $z_4 = (s_2, e_3)$, $z_5 = (s_3, e_3)$, $z_6 = (s_3, e_4)$.

Characteristics of the process of operating Diesel engines implicate strictly defined form of a graph of changes of its states $z_i \in Z\,(i = 1, 2,..., 6)$ [7]. This process is a semi-Markov process of components which are the process of changes of the technical states $\{W(t): t \geq 0\}$ and the process of changes of operating states $\{X(t): t \geq 0\}$ of these engines. The values of the process $\{W(t): t \geq 0\}$ are elements of the set of technical states s¹ $S = \{s_1, s_2, s_3\}$, and the values of the process $\{X(t): t \geq 0\}$ – elements of the set of operating states $E = \{e_1, e_2, e_3, e_4\}$ of the mentioned engines.

A model of the process of operating Diesel engines as a one-dimensional semi-Markov process $\{Y(t): t \geq 0\}$ is a process of the states set $Z = \{z_1, z_2, z_3, z_4, z_5, z_6\}$, of which interpretation is the following [3, 5, 7]: $z_1 = (s_1, e_2)$, $z_2 = (s_1, e_1)$, $z_3 = (s_2, e_1)$, $z_4 = (s_2, e_3)$, $z_5 = (s_3, e_3)$, $z_6 = (s_3, e_4)$.

Initial distribution of the considered process $\{Y(t): t \geq 0\}$ is defined by the formula:

$$P_i = P\{Y(0) = z_i\} = \begin{cases} 1 \;\; dla \;\; i = 1 \\ 0 \;\; dla \;\; i = 2,\ 3,\ 4,\ 5,\ 6 \end{cases} \tag{8}$$

and the functional matrix of the process is of the following form:

$$Q^Y(t) = \begin{bmatrix} 0 & Q_{12}^Y(t) & 0 & 0 & 0 & 0 \\ Q_{21}^Y(t) & 0 & Q_{23}^Y(t) & Q_{24}^Y(t) & Q_{25}^Y(t) & Q_{26}^Y(t) \\ 0 & 0 & 0 & Q_{34}^Y(t) & Q_{35}^Y(t) & Q_{36}^Y(t) \\ Q_{41}^Y(t) & 0 & 0 & 0 & 0 & Q_{46}^Y(t) \\ Q_{51}^Y(t) & 0 & 0 & 0 & 0 & Q_{56}^Y(t) \\ 0 & Q_{62}^Y(t) & 0 & 0 & 0 & 0 \end{bmatrix} \tag{9}$$

For the presented process $\{Y(t): t \geq 0\}$ of initial distribution (8) and functional matrix defined by the formula (9) it is possible, just like in the previous cases of considering the semi-Markov processes, to determine its limiting distribution being of the following form:

$$\left.\begin{aligned} P_1^X &= \frac{[p_{21}^Y + p_{41}^Y(p_{24}^Y + p_{23}^Y p_{34}^Y) + p_{51}(p_{25}^Y + p_{23}^Y p_{35}^Y)]E(T_1^Y)}{H}; \\ P_2^Y &= \frac{E(T_2^Y)}{H};\; P_3^Y = \frac{p_{23}^Y E(T_3^Y)}{H};\; P_4^X = \frac{(p_{24}^Y + p_{23}^Y p_{34}^Y)E(T_4^Y)}{H}; \\ P_5^Y &= \frac{(p_{25}^Y + p_{23}^Y p_{35}^Y)E(T_5^Y)}{H}; \\ P_6^Y &= \frac{[1 - p_{21}^Y - p_{41}^Y(p_{24}^Y + p_{23}^Y p_{34}^Y) - p_{51}^Y(p_{25}^Y + p_{23}^Y p_{35}^Y)]E(T_6^Y)}{H} \end{aligned}\right\} \tag{10}$$

at:

$$H = [p_{21}^{Y} + p_{41}^{Y}(p_{24}^{Y} + p_{23}^{Y}p_{34}^{Y}) + p_{51}^{Y}(p_{25}^{Y} + p_{23}^{Y}p_{35}^{Y})]E(T_1^Y) + E(T_2^Y) + + p_{23}^{Y}E(T_3^Y) +$$
$$+ (p_{24}^{Y} + p_{23}^{Y}p_{34}^{Y})E(T_4^Y) + (p_{25}^{Y} + p_{23}^{Y}p_{35}^{Y})E(T_5^Y) +$$
$$+ [1 - p_{21}^{Y} - p_{41}^{Y}(p_{24}^{Y} + p_{23}^{Y}p_{34}^{Y}) - p_{51}^{Y}(p_{25}^{Y} + p_{23}^{Y}p_{35}^{Y})]E(T_6^Y)$$

where :

P_1^Y, P_2^Y, P_3^Y, P_4^Y, P_5^Y, P_6^Y – probability that the engine finds itself adequately in states z_1, z_2, z_3, z_4, z_5, z_6;

p_{ij}^{Y} – probability of engine transition from the state z_i into the state z_j;

$E(T_i^Y)$ – expected value of the state z_i duration

The limiting probabilities P_i^Y, $i =$ 1, 2, 3, 4, 5, 6 are of considerable significance in operation of Diesel engines, because they characterize reliability of engines.

Practical usability of the presented model of the process of operating a Diesel engine can also be motivated by forwarding a successive hypothesis (H^*) of the following contents [7]: ***the process of operating Diesel engine (understood as a random function, of which argument is time and values – a random values denoting technical and operating states of this engine, proceeding in a rational operating system (i.e. in such a system, for which optimizing calculus is applied) is a process, of values being independent asymptotically because its state considered in any time t_n ($n = 0, 1, \ldots ,m.$; $t_0 < t_1 < \ldots < t_m$) is dependent on the state being directly before and is not stochastically dependent on states occurred earlier nor their time duration intervals..***

This hypothesis, just like this formulated as for sliding tribological systems, also explains why it is possible, in case of knowing the state of the process in a given moment τ_n, to forecast the course of the process in successive moments. By this way it also explains a fact observed in operating practice, consisting in forecasting (by intuition or according to already known tendency of changes), enough accurate for practical needs, about time of correct work of engines at the only knowledge of their current state and conditions for performing a task as well as material and power resources.

Formulation of a hypothesis may also be presented in the following way: ***forecasting about the state of the process of the engine operation in the moment $\tau_n + \tau$, when it is known in the moment τ_n, is possible as the engine state considered in any moment τ_n ($n =$ 0, 1, ... , $m.$; $\tau_0 < \tau_1 < \ldots < \tau_m$.) depends essentially on the state being directly before and does not depend on states that occurred earlier nor their time duration intervals.***

This formulated hypothesis does not enclose any of such contradictions, which could make it false yet before its verification. Verification of this hypothesis demands specifying consequences resulting from it. The consequences are the following:

- K^*1 – probabilities (p_{ij}; $i \neq j$; $i, j \in N$) of transition of engine operation process from a state z_i, in which it currently finds itself to a successive state z_j does not depend on earlier states of the process;
- K^*2 – intervals of unconditional duration of particular states z_i of the engine operation process are random values (T_i; $i \in N$) independent in stochastic terms;
- K^*3 – intervals of duration of each possible-to-occur state z_i of engine operation process under condition that the following state will be one of the rest states of the process, are random values (T_{ij}; $i \neq j$; $i, j \in N$) independent in stochastic terms.

The listed above consequences $K_k^*(k = 1, 2, 3)$ show a probabilistic law of state changes of the Diesel engine operation process. They are reciprocally contradiction and their logic truthfulness does not cause any doubts. Thus, the condition of consequences' consistency is satisfied, so there is no obstacle to apply the mentioned consequences for empirical verification if the stated hypothesis (H^*) is true, in other words, for its verification if it is true or false (of course, in a logic aspect). Such verification consists in experimental testing on occurring operating states of engines and checking if the consequences $K_k^*(k = 1, 2, 3)$ are true, what is equal to determination if the consequences (as facts) occur or do not. Verification of the hypothesis H^* demands accepting the following syntactic implication as truth [5, 7]:

$$H^* \Rightarrow K_k^*(k = 1, 2, 3) \tag{11}$$

Then, non-deductive (inductive) inference may be applied, according to the following scheme [7]:

$$[K_k^*(k = 1, 2, 3), H^* \Rightarrow K_k^*(k = 1, 2, 3)] \vdash H^* \tag{12}$$

Logic interpretation of the inference scheme is as follows: if empirical verification of the consequences $K_k^*(k = 1, 2, 3, 4, 5)$ confirms they are right and the implication (11) is true, the hypothesis H^* is also true and can be accepted. Inductive inference according the above scheme (12) is called a reducing inference. This inference, like each other from this group of inferences, does not lead to reliable conclusions, only to probable conclusions [5, 7].

From the presented hypothesis (H^*) follows that the models of Diesel engine operation process may be stochastic processes of discrete sets of states and continuous duration of distinguished technical states of the engine. The considered models of the process of changes of engine technical states, in mathematical aspect, are functions mapping a set of moments T into a set of technical states Z.

4. Final remarks and conclusions

The presented above considerations show that the process of changes of Diesel engines' technical states, as well as the process of changes of their operating states are reciprocally dependent and that is why they can be considered jointly as components of a resultant process, which can be called the engines' operation process.

Rational control of the Diesel engines' operation process is not possible without having elaborated an adequate-to-the-process model being as simple as possible and satisfying at least two conditions:

– it should operate (work) just like the original, that means: perform analogical functions;

– basing on tests of its performances and construction, it should make possible to reveal new and unknown up to this moment and not visible features (characters) of a real operation process of the mentioned engines, which is mapped by this model.

From the presented hypothesis follows that the process of Diesel engines' operation may be investigated with the help of models formed as semi-Markov processes.

Technical state of each Diesel engine changes continuously and this is a reason there can be considered countable sets of states of these engines, so sets consisting of infinite number of elementary technical states. Diagnosing all technical states of engines is not possible or purposeful in either technical or economic aspect. Thus, a need occurs to divide this set of their states into some quantity of classes (subsets) of technical states. Taking usability of Diesel engines for work as a criterion of division of the mentioned set of states there can be distinguished the following classes (subsets) of Diesel engines' technical states, called directly the states of full ability s_1, state of partial ability s_2, state of disability s_3. The set of states $S = \{s_1, s_2, s_3\}$ can be considered as the set of values of the stochastic process $\{W(t): t \geq 0\}$ of realizations being constant and right-handed continuous. This process then, in mathematical aspect, is a function mapping the set of moments T into the set of technical states S. Similarly, in a mathematical aspect, the process of changes of operating states is a function mapping the set of moments T into the set of operating states E. In case of Diesel engines the most significant are states of the following interpretations: e_1 – state of active use, e_2 – state of passive use, e_3 – state of scheduled service (preventive), e_4 – state of not-scheduled service (forced by failures). The set of operating states $E = \{e_1, e_2, e_3, e_4\}$ may be considered as a set of values of the stochastic process $\{X(t): t \geq 0\}$ of realizations being constant and right-handed continuous intervals.

The processes: $\{W(t): t \geq 0\}$ and $\{X(t): t \geq 0\}$ presented above have enabled creating the Diesel engines' operation process $\{Y(t): t \geq 0\}$ of values from the set $Z = \{z_1, z_2, z_3, z_4, z_5, z_6\}$, having the following interpretation [3, 7]: $z_1 = (s_1, e_2)$, $z_2 = (s_1, e_1)$, $z_3 = (s_2, e_1)$, $z_4 = (s_2, e_3)$, $z_5 = (s_3, e_3)$, $z_6 = (s_3, e_4)$.

The processes: $\{W(t): t \in T\}$, $\{X(t): t \in T\}$ and $\{Y(t): t \in T\}$ may be considered as semi-Markov models of real processes of changes of technical and operating states as well as of the process of Diesel engines' operation [3, 7].

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