THE USE OF THE START-UP PROCESS ANALYSIS IN THE ESTIMATION OF THE TECHNICAL STATE OF DIESEL ENGINE

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Summary

This article presents the propositions and the assumptions of the estimation method of the diesel engine technical state. The proposed evaluation method uses the analysis of the diesel engine start-up stages and is based on the calculation of the probability value of the successful start-up modeling as the homogeneous discrete Markov process with continuous time.

Keywords: diesel engine start-up, Markov process.

WYKORZYSTANIE ANALIZY PROCESU ROZRUCHU
W OCENIE STANU TECHNICZNEGO SILNIKA O ZAPŁONIE SAMOCZYNNYM

Streszczenie

Niniejszy artykuł przedstawia propozycję i założenia metody oceny stanu technicznego samochodowego silnika o zapłonie samoczynnym. Proponowana metoda oceny wykorzystuje analizę etapów rozruchu tego silnika oraz opiera się na określeniu wartości prawdopodobieństwa udanego rozruchu modelowanego jako jednorodny, dyskretny proces Markowa.

Słowa kluczowe: rozruch silnika o zapłonie samoczynnym, proces Markowa.

1. INTRODUCTION

The diesel engine start-up is one of the functional states during its operation. The start-up of the combustion engine is a process in which, through providing external energy and forcing performance of working processes, the engine is transited from standstill to the state of independent operation.

Nowadays because of its simplicity and accuracy of measurement the analysis of the current intensity consumed by the starter is used as a diagnostic signal checking the tightness of engine combustion chamber. During this estimation the crankshaft of the warm engine is driven only by the electrical starter when the fuelling is cut out. Then the maximum values of current intensities consumed by the starter are compared to each other when the pistons transit the top dead centers. Additionally the amplitude of the current is compared to its mean value and the changes of the angular velocity of crankshaft are analyzed. Too low amplitude of the current (below 30A) occurring when the angular velocity grows indicates that cylinder wear increases [4, 5, 6].

The analysis of the current consumed by the starter can be used in the technical state of its bearing system estimation either. It was stated that as the bearing bushes wear the resistance of motion occurred in bearing starter rotor increases. It is the reason why the mean value of the current consumed by the starter grows [1, 2].

We should pay the attention on the fact that during the previously described diagnostic methods the engine is not transited from standstill to the state of independent operation. So the engine is not put in the real start-up process. At present the diagnostic methods of the engine technical state estimation which use the analysis of its real start-up process are not realized. This article presents the propositions and the assumptions of the estimation method of the diesel engine technical state. The proposed estimation uses the analysis of the diesel engine start-up stages and is based on the calculation of the probability value of the successful start-up modelling as the homogeneous discrete Markov process with continuous time.

2. THE STAGES OF THE DIESEL ENGINE START-UP PROCESS

The fact that the start-up of a diesel engine should be perceived as a multi-stages process results from the analysis of the course of change of the engine crankshaft angular velocity, as well as of the current consumed by the starter at the stage of meshing the starter with the crankshaft flywheel. Publication [3] enumerates four stages of the start-up of the diesel engine. The stage no. 1 begins when the pinion of the electric starter couples with the engine crankshaft flywheel. This puts the engine movable mechanism into motion. The stage no. 2 consists of the crankshaft turning with nearly constant angular velocity, with the help of the starter. Thus, these first two stages constitute the engine activation process. At the stage no. 3, irregular combustion of air-fuel mixture in the engine cylinders may be observed, as well as the misfiring of the starter work. The stage no. 4 consists of air-fuel mixture ignitions alone, as well as the angular velocity of the crankshaft which, after an initial rapid increase and achieving local maximum, stabilizes at one level [3]. The suggested four stages were identified during the start-up of the diesel engine, which has been presented in figure 1.

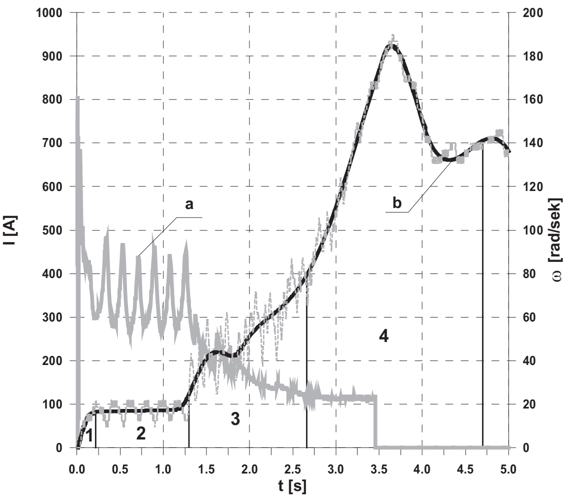

Fig. 1. The course of angular velocity of the crankshaft and its mean value, as well as current intensity consumed by the starter at the four stages of the start-up of 4CT90 engine;
a – intensity, b – angular velocity

It must be noticed that in conditions of regular vehicle use it is possible that start-ups of diesel engine occur in which, for example, stage no. 2 does not appear at all or it comes again after stage no. 3. Other transitions between the start-up stages are also possible. These transitions have random character [3].

3. THE DIESEL START-UP PROCESS AS THE HOMOGENEOUS DISCRETE MARKOV PROCESS

When we distinguish six essential states in the diesel engine start-up process {„0" –the unsuccessful start-up (the engine come back to the standstill), „1" – the stage no. 1 of the start-up, „2" – the stage no. 2, „3" – the stage no. 3, „4" – the stage no. 4 of the start-up, „5" – the successful start-up (the engine is independent's operation)}.

Specifying other permissible transitions between these states we can make an assumption that the homogeneous discrete Markov process with continuous time is the model of the start-up phenomenon. This assumption about Markov character of the diesel engine start-up is true for the first daily start-up. The first daily diesel engine start-up is "the most difficult" and best characterizes the engine technical state. The set **S** of this Markov process states is an ensemble of six elements:

$$\mathbf{S} = \{0, 1, 2, 3, 4, 5\} \qquad (1)$$

The graph of this process is shown on figure 2.

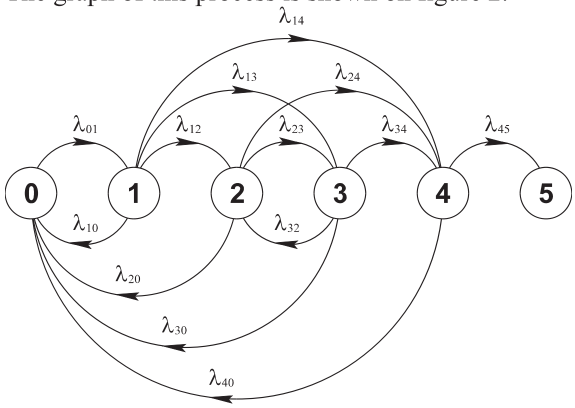

Fig. 2. Graph of the homogeneous Markov process with six states;
0 – engine standstill, 1– stage no. 1,
2 – stage no. 2, 3 – stage no. 3,
4 – stage no. 4 of start-up,
5 – engine independent operation;
λ_{ij} – the transition intensity from state i to state j, $i, j \in \mathbf{S}$, $i \neq j$

The reliability of the engine start-up is defined by the distributions of the random variables $X(t)$, $t \geq 0$ (t– time), which can receive the values from the **S** set of the state process. In the homogeneous discrete Markov process the intensity transitions among states don't depend on the time. The transition intensity matrix $\mathbf{\Lambda}$ of the process, which is shown on the figure 2, is the numerical matrix:

$$\Lambda = \begin{bmatrix} \lambda_{00} & \lambda_{01} & 0 & 0 & 0 & 0 \\ \lambda_{10} & \lambda_{11} & \lambda_{12} & \lambda_{13} & \lambda_{14} & 0 \\ \lambda_{20} & 0 & \lambda_{22} & \lambda_{23} & \lambda_{24} & 0 \\ \lambda_{30} & 0 & \lambda_{32} & \lambda_{33} & \lambda_{34} & 0 \\ \lambda_{40} & 0 & 0 & 0 & \lambda_{44} & \lambda_{45} \\ 0 & 0 & 0 & 0 & 0 & \lambda_{55} \end{bmatrix}, \qquad (2)$$

which diagonals elements (intensity out of state i) perform the formula:

$$\lambda_{ii} = -\sum_{k \in \mathbf{S} - \{i\}} \lambda_{ik} \,, \; i \in \mathbf{S}. \qquad (3)$$

Therefore

$$\lambda_{00} = -\lambda_{01},\ \lambda_{11} = -(\lambda_{10} + \lambda_{12} + \lambda_{13} + \lambda_{14}),$$
$$\lambda_{22} = -(\lambda_{20} + \lambda_{23} + \lambda_{24}),$$
$$\lambda_{33} = -(\lambda_{30} + \lambda_{32} + \lambda_{34}),\ \lambda_{44} = -(\lambda_{40} + \lambda_{45}),\ \lambda_{55} = 0.$$

All the elements in the matrix (2) that don't belong to cardinal diagonal are non-negative. The result of this is that all diagonal elements of matrix $\mathbf{\Lambda}$ are the non-positive numbers. The transition intensity matrix includes all information about the discrete Markov process probabilistic characteristic $\{X(t);\, t \geq 0\}$.

We can accept in the considered model of the diesel engine start-up process that the time T_{jk} of the object being in the state j before immediate transition to state k is exponentially distributed with the parameter λ_{jk}, for each ordered pair $(j,k) \in \mathbf{S}^2$ and $j \neq k$. The value of the λ_{jk} can be assign from estimation the expectation value the random variable T_{jk} because

$$\mathrm{E}\,T_{jk} = \frac{1}{\lambda_{jk}} \tag{4}$$

(E – the operator of the expected value). The estimator of the expectation value is average from test. That is why:

$$\lambda_{jk} = \frac{n}{\sum_{s=1}^{n} t_{jk}^{(s)}}, \tag{5}$$

where n is size random test and $t_{ij}^{(s)}$ – the time of the being by the object in the state j before immediate transition to state k measure in s realization.

In the considered model the probability of being by the object in the state i $P_i(t) = \Pr\{X(t) = i\}$, $i \in \mathbf{S}$, in the stationary moment of the time t $(t \geq 0)$, performs the Chapman-Kolmogorov equation:

$$\frac{dP_i(t)}{dt} = \sum_{k \in \mathbf{S}} P_k(t) \cdot \lambda_{ki}, \; i \in \mathbf{S}, \tag{6}$$

with the initial condition

$$P_0(0) = 1, P_i(0) = 0, i = 1, \ldots, 5. \tag{7}$$

Moreover the probabilities perform the standard condition

$$\sum_{i \in \mathbf{S}} P_i(t) = 1. \tag{8}$$

The dependence (3) implies that $\lambda_{55} = 0$. It means that last row in the transition intensity matrix (2) includes only zero values. The system of equations (6) and (8) can be solved solving the first order linear homogeneous differential equations with constant coefficients

$$\mathbf{P}'(t) = \mathbf{P}(t) \cdot \mathbf{L}, \tag{9}$$

where:

$$\mathbf{L} = \begin{bmatrix} \lambda_{00} & \lambda_{01} & 0 & 0 & 0 \\ \lambda_{10} & \lambda_{11} & \lambda_{12} & \lambda_{13} & \lambda_{14} \\ \lambda_{20} & 0 & \lambda_{22} & \lambda_{23} & \lambda_{24} \\ \lambda_{30} & 0 & \lambda_{32} & \lambda_{33} & \lambda_{34} \\ \lambda_{40} & 0 & 0 & 0 & \lambda_{44} \end{bmatrix},$$

$$\mathbf{P}(t) = (P_0(t), P_1(t), P_2(t), P_3(t), P_4(t)),$$

$$\mathbf{P}'(t) = \frac{d\mathbf{P}(t)}{dt},$$

with the initial condition

$$\mathbf{P}(0) = (1, 0, 0, 0, 0).$$

Using the equality (8) the probability $P_5(t)$ (the finish of the successful start-up behind of time t) we can make calculation from dependence

$$P_5(t) = 1 - \sum_{i=0}^{4} P_i(t),$$

the solution of the system of equations (9) are on right side of these equation.

4. THE PROPOSAL OF THE METHOD OF THE ESTIMATION OF THE TECHNICAL STATE OF DIESEL ENGINE

The probability of the first daily successful diesel engine start-up after assumption its t_{max} time of duration is a basis of the proposal of the method of its technical state estimation. The time t_{max} is arbitrary defined for each type of the vehicle and engine. For example basing on the norm [7] we can assumption the immediate start-up and accept that $t_{max} = 3$ s.

The function $R(\tau)$ is the measure of the reliability of the first daily successful start-up and we can define:

$$R(\tau) = P_5(t_{max}, \tau) \tag{10}$$

where $P_5(t_{max}, \tau)$ is the probability of the transition of the engine to the state no. 5 (successful engine start-up) after t_{max} when the time of vehicle work is τ.

We can assume that for the beginning of the maintenance when $\tau = 0$ the probability

$$R(0) = P_5(t_{max}, 0)$$

is equal 0. Because in the first period of the diesel engine maintenance the value of the probability of the first daily successful engine start-up is equal 1. After some time of the maintenance the analyzing value of the probability begins to systematically decrease. It's the result of the wear of engine cylinders which conduct to getting worse for the creation and combustion of the air-fuel mixture. When the probability of the first daily successful diesel engine start-up exceed the boundary value p_{gr} the user can make a decision about the finish of its maintenance or the engine renewal. The theoretical changes of the value of the reliability of the first daily successful diesel engine start-up are shown on figure 3.

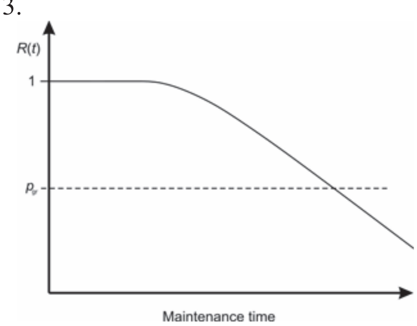

Fig. 3. The changes of the probability of the first daily successful diesel engine start-up during the vehicle maintenance

The probability of the first daily successful diesel engine start-up $P_5(t_{max}, \tau)$ decreases (look at the figure 3) when the duration times of the particular engine start-up stages increase. The increase of the duration time of the first daily diesel engine start-up process is the indication of the deterioration of the engine technical state. It is caused by the defect of the elements of the fuel supply system, the leaky of the combustion chamber or other inefficient appearance in the engine.

5. CONCLUSION

The method of the estimation of the vehicle diesel engine technical state is proposed in this article. This method uses the analysis of the value of the probability of the first daily successful diesel engine start-up. The carried out analysis can be helpful to take the proper maintenance decision connected with the estimation of the diesel engine technical state. To purpose practically application of this estimation method we should conduct more researches which the authors intend to carry out.

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