RELIABILITY MODEL OF TWO-SHAFT TURBINE COMBUSTION ENGINE WITH HEAT REGENERATOR

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Abstract

The paper presents a possibility of applying the theory of the semimarkovian processes to describe reliability of a ship turbine combustion engine. The considerations concern a two-shaft engine with heat regenerator, consisting of the following systems: compressor with air filter, combustion chamber, heat regenerator, combustion gas generator turbine and power turbine. Formulas have been derived which determine a limiting distribution of the process of changes of technical states, regarding this type of engines. The distribution consists of probabilities of turbine engine staying in ability state as well as in states of disability caused by failures of any of the mentioned systems. Probability of staying the considered combustion engine in ability state can be interpreted as the factor of engine availability for starting and using in compliance with its destination. The elaborated reliability model which enables determining the mentioned probabilities is of the form of a semimarkovian seven-state process which is continuous in time. Attention has been paid that consideration of serial structure in reliability researches on the mentioned engines and application of the formulas known in the classical theory on technical machines reliability can give advantageous results. Acceptance of such assumptions requires proper justification. The presented proposal to define reliability of a two-shaft turbine combustion engine with heat regenerator assumes that the researches will concern such systems of the engines, like: compressor with air filter, combustion chamber, heat regenerator, combustion gas generator turbine and power turbine.

Keywords: *transport, diesel engine, reliability, semimarkovian process, turbine combustion engine*

MODEL NIEZAWODNOŚCIOWY DWUWAŁOWEGO TURBINOWEGO SILNIKA SPALINOWEGO Z REGENERATOREM CIEPŁA

Streszczenie

W artykule przedstawiono możliwość zastosowania teorii procesów semimarkowskich do opisu niezawodności turbinowego silnika spalinowego. W rozważaniach uwzględniony został silnik dwuwałowy, z regeneratorem ciepła, składający się z następujących urządzeń: sprężarki z filtrem powietrza, komory spalania, regeneratora ciepła, turbiny wytwornicy spalin oraz turbiny napędowej. Wyprowadzone zostały wzory określające rozkład graniczny procesu zmian stanów technicznych takiego silnika. Rozkład ten stanowią prawdopodobieństwa przebywania turbinowego silnika spalinowego w stanie zdatności oraz w stanach niezdatności wskutek uszkodzenia dowolnego z wymienionych jego urządzeń. Prawdopodobieństwo przebywania rozpatrywanego silnika spalinowego w stanie zdatności może być interpretowane jako współczynnik gotowości tego silnika do uruchomienia i zastosowania zgodnie z przeznaczeniem. Opracowany model niezawodnościowy, umożliwiający określenie wspomnianych prawdopodobieństw ma formę procesu semimarkowskiego siedmiostanowego, ciągłego w czasie. Uzasadniono, że model ten jest lepszym modelem niezawodnościowym tego rodzaju silników spalinowych niż model w formie struktury niezawodnościowej szeregowej. Zwrócono uwagę, że uwzględnienie w badaniach niezawodnościowych wspomnianych silników struktury szeregowej i korzystanie z wzorów znanych w klasycznej teorii niezawodności urządzeń technicznych może dać dobre rezultaty, gdy są spełnione ściśle określone założenia a mianowicie: przedziały czasu poprawnej pracy każdego z badanych *turbinowych silników spalinowych są zmiennymi losowymi wzajemnie niezależnymi, w czasie postoju tego rodzaju silników nie zachodzą uszkodzenia jego urządzeń, w czasie obsługiwania tych silników ich urządzenia zdatne nie ulegają uszkodzeniom, zaś uszkodzone elementy wspomnianych urządzeń nie są naprawiane, lecz wymieniane na nowe. Na ogół takie założenia nie mogą być przyjęte w badaniach niezawodnościowych tego rodzaju silników. Przyjęcie takich założeń wymaga odpowiedniego ich uzasadnienia. W przedstawionej propozycji określenia niezawodności turbinowego silnika spalinowego dwuwałowego z regeneratorem ciepła przyjęto, że badania będą dotyczyć takich jego urządzeń jak: sprężarka z filtrem powietrza, komora spalania, regenerator ciepła, turbina wytwornicy spalin oraz turbina napędowa.*

Słowa kluczowe: *niezawodność, proces semimarkowski, turbinowy silnik spalinowy*

1. Introduction

In the last years there appeared turbine combustion engines of high energy efficiency. The *General Electric* company is a manufacturer of internal combustion turbines type LMS 100 having the power 100 MW, of which thermal efficiency reaches 46% [6]. However, apart from the energy advantages, the engines must be highly reliable Therefore, there is a need to tend to describe their reliability.

Models of the classical reliability theory can be applied for describing the reliability of power units with turbine combustion engines. In this case different structures are employed, including serial ones as the most often. Comparing, however, these models to reliability models like graphs of states – transitions, it may be observed that the last ones are more useful for reliability description of the mentioned engines. They enable more sophisticated research on reliability of the engines than the models of the classical reliability theory, because they reflect changes resulting from specific operation of the engines and their components (compressors, combustion chamber, emission generator turbine and power turbine). That is also the reason why the models of graphs of transitions are called the reliability-functional models of turbine combustion engines and their components. In addition to this, usability of the models follows from the possibility of easy determination of reliability indexes for the engines and their components. The indexes can be obtained applying analytical dependences or computer simulation method. If there are satisfied proper assumptions on properties of distributions of random quantities (variables) probabilities and other properties characterizing the engines as an object of reliability researches the theory of semimarkovian processes can be employed [2, 4].

The paper presents an attempt to prove that for description of reliability of a two-shaft turbine combustion engine with heat regenerator the reliability-functional models are of higher usability than reliability structures of the classical theory of systems reliability.

2. Formulation of problem

Turbine combustion engines of different functional structure [5] can be applied for ship power units. However, reliability description of given turbine combustion engine can be presented in each case according to the same rules. Therefore, further considerations on reliability of turbine combustion engine of ship main propulsion system are conducted on example of a two-shaft turbine combustion engine with heat regenerator, consisting of ex. four main components (as reliability elements) [3, 5]: compressors, combustion chambers, emission generator turbine and power turbine (Fig. 1). Additionally, such significant systems, like: air filter and heat regenerator, being indispensable for efficient operation of the mentioned engine, can be (and must be) taken into account. Scheme of such configuration consisting of the mentioned systems, including air filter and heat regenerator is presented on the Fig. 2.

Serial structure is applicable for reliability description of each turbine combustion engine. The conclusion is that such combustion engine is in ability only when all its components are in ability.

Such structure is a result of functional structure of the engine. Scheme of the structure, in case of engine with the section shown on the Fig. 1, is presented on the Fig. 2. Thus, the reliability function for such an engine is as follows:

$$R(t) = P\{T \geq t\} = \prod_{i=1}^{6} R_i(t)\,. \tag{1}$$

Applying the formula (1), it should be remembered that the formula describes reliability of these systems of turbine combustion engine, which (just like their components mentioned above) can find themselves in only two, mutually exclusive, states: ability and disability, and any other (intermediate) state is not possible. It is obvious that this condition, in reference to turbine combustion engines of ship main propulsion system, is difficult to accept in operational practice.

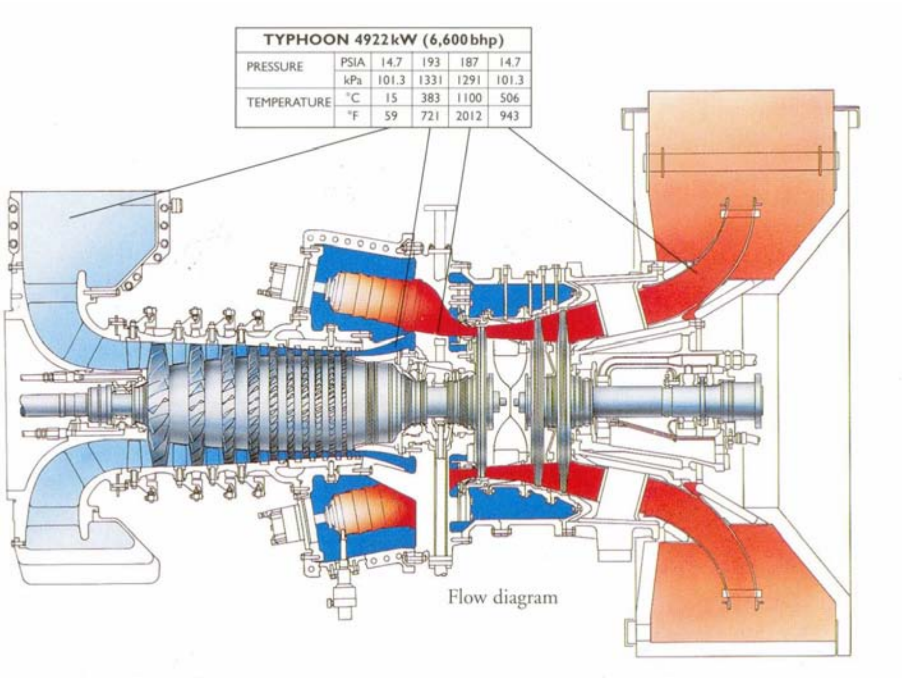


Fig. 1. Section of a two-shaft turbine combustion engine consisting of reliability elements, like: compressor, combustion chamber, emission generator turbine and power turbine [7]

To evaluate $R_i(t)$ it is necessary to know distributions of time of correct work of particular systems of the engine $F_i(t)$ or their risk function $\lambda_i(t)$, because [4]:

$$R_i(t) = 1 - F_i(t), \quad t > 0\,, \tag{2}$$

or

$$R_i(t) = \exp\left[-\int_0^t \lambda_i(t)\,d\tau\right],\ t > 0\,, \tag{3}$$

Thus, the reliability functions of turbine combustion engine are the following:

$$R(t) = \prod_{i=1}^{6} \left[1 - F_i(t) \right] \tag{4}$$

or

$$R(t) = \exp\left[-\sum_{i=1}^{6} \int_0^t \lambda_i(\tau) d\tau \right]. \tag{5}$$

Application of the formulas (4) or (5) is reasonable when the following assumptions can be accepted:

- random variable $T_i (i = 1, 2, ..., 6)$ which are intervals of time of correct work of components (systems) of turbine combustion engine with distributions $F_i(t)$, are mutually independent;
- in time of standby operation mode none of the engine's systems gets failure;
- in time of refurbishment service on the combustion engine, elements being in ability state do not get failures
- failed elements of the engine are not refurbished but exchanged into new parts.

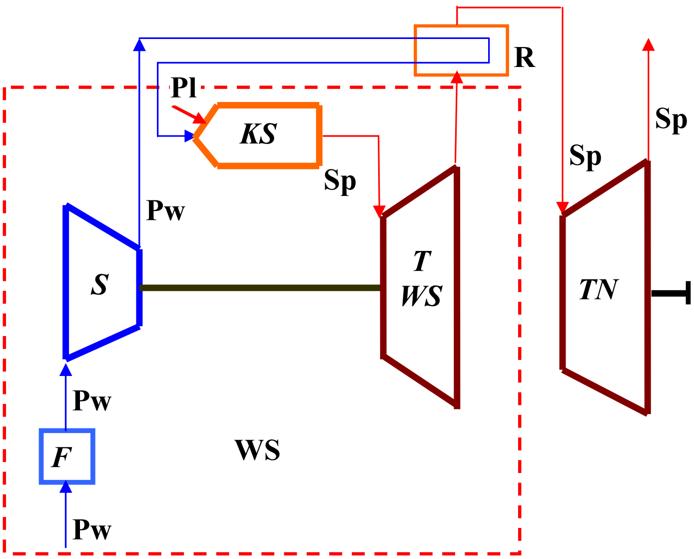
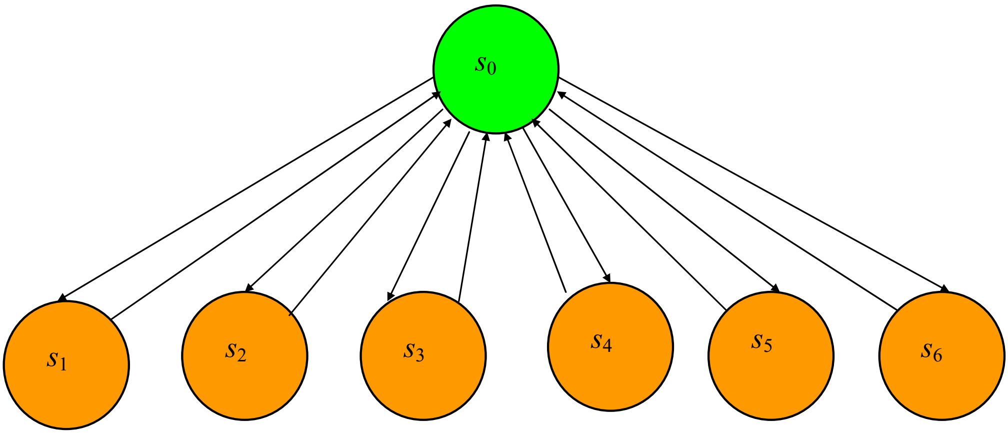


Fig. 2. Structure of operation of two-shaft turbine combustion engine: F – air filter, S – compressor, KS – combustion chamber, R – heat regenerator, TWS – exhaust gases generator turbine, WS – exhaust gases generator, TN – power turbine, Pl – fuel, Pw – air, Sp – exhaust gases [5]

In practice, failed elements of turbine combustion engine are usually refurbished (of course, if it is beneficial) through performing proper services. That means that the last assumption is not right in general. However, the first three assumptions can be regarded as reasonable. Additional restriction in the scope of applying serial reliability structure for description of reliable turbine combustion engine, is necessity to accept, as it was already mentioned before, only two-value reliability state. (i.e. able - unable) of the engine and its particular components.

Application of semimarkovian model of the process of changes of states of the mentioned combustion engine enables considering prevention services on the engine and taking into account more than two reliability states of engine, as well as its elements. In the three-state reliability model of self-ignition engine, presented in the paper [1], the following states are distinguished: full (total) ability, partial (not full, not total, limited) ability and disability. It is obvious that there can be such number of states of intermediate ability (so the states between full ability and full disability) which is necessary to obtain useful for practical needs the reliability description of engine and its elements. In this situation there is no need to distinguish different states of disability, like full (total) and not full (not total). In case of turbine combustion engine the same three-state model can be considered.

The semimarkovian model of the process of changes of reliability states of a combustion turbine engine can also be considered as a semimarkovian process $\{W(t): t \geq 0\}$ with range of states $S = s_i$; $i = 0, 1, \ldots ,6$. Interpretation of states $s_i \in S (i = 0, 1, \ldots ,6)$ is as follows : s_0 – state of full ability of turbine combustion engine, s_1 –state of air filter disability, 2) s_2 – state of compressor disability, s_3 – disability state of combustion chamber, s_4 – disability state of heat regenerator, s_5 – disability state of exhaust gases generator turbine, s_6 – disability state of power turbine. Changes of the mentioned states s_i $(i = 0, 1, \ldots, 6)$ proceed in successive moments t_n $(n \in N)$, while in the moment $t_0 = 0$ the turbine combustion engine finds itself in the state s_0. State s_0 lasts as long as any component of the engine gets failure. The states $s_i (i = 1, \ldots, 6)$ last as long as a refurbished or replaced component gets failure and further refurbishing is not beneficial. It can be accepted that state of turbine combustion engine in the moment t_{n+1} and the time interval of duration of the state reached in the moment t_n do not depend on states which proceeded in the moments $t_0, t_1, \ldots, t_{n-1}$ and the time intervals of their duration. Thus, the process $\{W(t): t \geq 0\}$ is a semimarcovian process [3, 4] with graph of states, presented on the Fig. 3.



Rys. 3. Graph of changes of states of the process {W(t): t ≥ 0}

The initial distribution of the process is as follows:

$$P\{W(0) = s_i\} = \begin{cases} 1 \quad dla \quad i = 0 \\ 0 \quad dla \quad i = 1,\ 2,\ 3,\ 4,\ 5,\ 6 \end{cases} \tag{6}$$

and the functional matrix has the form:

$$\mathbf{Q(t)} = \begin{bmatrix} 0 & Q_{20}(t) & Q_{20}(t) & Q_{30}(t) & Q_{40}(t) & Q_{50}(t) & Q_{60}(t) \\ Q_{10}(t) & 0 & 0 & 0 & 0 & 0 & 0 \\ Q_{20}(t) & 0 & 0 & 0 & 0 & 0 & 0 \\ Q_{30}(t) & 0 & 0 & 0 & 0 & 0 & 0 \\ Q_{40}(t) & 0 & 0 & 0 & 0 & 0 & 0 \\ Q_{50}(t) & 0 & 0 & 0 & 0 & 0 & 0 \\ Q_{60}(t) & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}. \tag{7}$$

The functional matrix $Q(t)$ is the model of changes of reliability states of a turbine combustion engine.

Non-zero elements $Q_{ij}(t)$ of the matrix $Q(t)$ depend on distribution of random variables which are time intervals of being the process $\{W(t)\colon t \geq 0\}$ in states $s_i \in S(i = 0, 1,..., 6)$. The elements are probabilities of transition of the process from the state s_i to the state s_j ($s_i, s_j \in S$) at time no longer than t, defined in the following way:

$$Q_{ij}(\mathrm{t}) = P\{W(\tau_{n+1}) = s_j,\ \tau_{n+1} - \tau_n < t | W(\tau_n) = s_i\} = p_{ij}F_{ij}(t)\ , \tag{8}$$

where:

p_{ij} – probability of one step transition of homogeneous Markov chain,

$p_{ij} = P\{Y(\tau_{n+1}) = s_j | Y(\tau_n) = s_i = \lim_{t\to\infty} Q_{ij}(t)$,

$F_{ij}(t)$- distribution of a random variable T_{ij} determining time of the state s_i of the process $\{W(t)\colon t \geq 0\}$ under condition that the successive state of the process is the state s_j.

Thus, the matrix of probability of transition of the Markov chain inserted into the process is as follows [3, 4]:

$$\mathbf{P} = \begin{bmatrix} 0 & p_{01} & p_{02} & p_{03} & p_{04} & p_{05} & p_{06} \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}. \tag{9}$$

So, considering the properties of a stochastic process, its limiting distribution

$$P_j = \lim_{t\to\infty} P_{ij}(t) = \lim_{t\to\infty} P\{W(t) = s_j\}\,,\ s_j \in S(j = 0, 1, ...,4) \tag{10}$$

is of the following form [4]:

$$P_j = \frac{\pi_j E(T_j)}{\sum_{k=1}^{4} \pi_k E(T_k)}\,. \tag{11}$$

Probabilities $\pi_j(j = 0, 1,..., 4)$ in the formula (11) are limiting probabilities of the Markov chain. Determining a limiting distribution (11) needs solution of the following system of equations:

$$\left.\begin{array}{l}[\pi_0, \pi_1, \pi_2, \pi_3, \pi_4, \pi_5, \pi_6]\,\mathbf{P} = [\pi_0, \pi_1, \pi_2, \pi_3, \pi_4, \pi_5, \pi_6] \\ \sum_{k=1}^{6} \pi_k = 1\end{array}\right\}. \qquad (12)$$

In result of solving the system of equations (12) the following dependences can be obtained applying the formula (11):

$$P_0 = \frac{E(T_0)}{M},\; P_1 = \frac{p_{01}E(T_1)}{M}, P_2 = \frac{p_{02}E(T_2)}{M}, P_3 = \frac{p_{03}E(T_3)}{M},$$

$$P_4 = \frac{p_{04}E(T_4)}{M}, P_5 = \frac{p_{05}E(T5)}{M}, P_6 = \frac{p_{05}E(T_6)}{M} \qquad (13)$$

at which:

$$M = E(T_0) + p_{01}E(T_{01}) + p_{02}E(T_{02}) + p_{03}E(T_{03}) + p_{04}E(T_{04}) + p_{05}E(T_{05}) + p_{06}E(T_{06})\,.$$

Probability P_0 is a limiting probability, that at longer operation time (theoretically at $t \to \infty$) turbine combustion engine stays in the state s_0. Probabilities $P_j(j = 1, 2,..., 6)$ are limiting probabilities of existing states $s_j \in$ S of the mentioned engine at $t \to \infty$, so these are probabilities of being its elements (as well as the engine, because of its serial reliability structure) in ability states.

For operation practice, it is also important the one-dimensional distribution of the process $\{W(t)\colon t \geq 0\}$ of which elements are functions $P_k\,(t)$ being probabilities of that at the time t (any time) the process is in the state $s_k \in S(k = 0, 1, ..., 6)$. The moment distribution can be calculated by applying the moment distribution of the process $\{W(t)\colon t \geq 0\}$ and the function $P_{ij}(t)$ being probabilities of the process transition from the state s_i to the state s_j ($s_i \in$ S, $s_j \in S$, $i \neq j$; $i, j = 0, 1, ..., 6$). Calculation of the probabilities of transition needs knowledge of the function $F_{ij}(t)$ i.e. distributions of random variables $T_{ij}(i = j;\, i, j = 0, 1, ..., 6)$. Therefore, proper reliability researches on ship turbine combustion engines are highly required.

3. Final conclusions

Semimarkovian processes become more and more often applied to solve different problems connected with reliability, mass service and diagnostics of systems..

Application of the processes in practice requires satisfying the two following conditions:

– collection of proper mathematical statistics;

– elaboration of semimarkovian model of changes of reliability states of system having a small number of states and uncomplicated (in mathematical aspect) function matrix **Q(t)**.

The second condition is essential in case of calculating the moment distribution of the process states. As known, the distribution can be calculated having initial distribution of the process of changes of the system reliability states and functions being probabilities of the process transition from its one reliability state to another. If the number of states of the mentioned process is big, or if at a small number of states the function matrix (7) is very complicated, only approximate estimation of limiting distribution of the process $\{W(t)\colon t \geq 0\}$ can be obtained.

The paper presents proposal of determination of reliability of two-shaft turbine combustion engine with heat regenerator, consisting of the following systems: compressor with air filter, combustion chamber, heat regenerator, exhaust gases generator and power turbine. Assumption has been made that reliability of the mentioned systems of engine is known. In case when reliability of the mentioned systems needs to be determined first, it is necessary to carry out the similar decomposition of each of the systems and elaborate their semimarkovian reliability models.

The presented reliability model of a two-shaft turbine combustion engine can be developed by distinguishing additionally an intermediate state called the state of partial ability [2]. Similar proceeding can be taken with reference to particular systems of the engine. Such action may follow from cognitive as well as utilization needs being the result of tendency of engines' producers and users to ensure rational operation of engines.

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