Physical aspects of application and usefulness of semi-Markovian processes for modelling the processes occurring in operational phase of technical objects

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ABSTRACT

In the paper usefulness of semi-Markovian processes for modelling real processes which occur in the operational phase of various technical objects, is considered. The usefulness of this theory was proved by presenting specific features of the semi-Markovian processes and physical aspects of their use as models of the processes occurring in the operational phase of the objects in question. The specific features were described with taking into account the process of changing the technical states of such objects. The physical aspects of models in the form of semi-Markovian processes were justified by postulating a hypothesis by which wear process of tribological units of crucial sub-assemblies of machines, can be explained. Also, the consequences logically resulting from the hypothesis and necessary to its verification, are discussed. A method for its verification is also attached. It was proved possible to model the real processes in question by means of the continuous semi-Markovian processes of finite set of states.

Key words : technical object, semi-Markovian process, tribological unit, wear

INTRODUCTION

The theory of semi-Markovian processes gains more and more widespread applications in engineering sciences and in operation of technical objects (e.g. diesel engines, gas turbines, screw propellers, pumps, compressors, coolers, filters, ship propulsion systems). It makes it possible to elaborate models of various real processes, including processes of changes of technical and operational states as well as operational processes of any technical objects.

The models are elaborated in the form of special stochastic processes, i.e. semi - Markovian ones, and recently also decision-related (controlled) semi-Markovian processes whose realizations depend on decisions made in the instants of changing their states [4, 6, 8, 11]. However it is not easy to apply the processes because of their specific features. Not taking them into account may result in building such models of real processes in the form of semi-Markovian ones whose investigations cannot provide any new information about a modelled process, regarding e.g. durability and reliability of technical objects, their load spectra etc. Therefore it is worthwhile to indicate the physical aspects of application of semi-Markovian processes as models of real processes related to technical objects, at least with taking as an example the process of changing technical states during operation of such objects.

SPECIFIC FEATURES OF SEMI-MARKOVIAN PROCESSES

The semi-Markovian processes are stochastical ones of peculiar features. In the literature there are different definitions of semi-Markovian process, which have different ranges of generality and exactness. For purposes of the modelling of operation of technical objects the semi-Markovian process (family of random variables)

$$\{Y(t) : t \in T\} \text{ at } T = [0 , + \infty]$$

can be defined by means of the so - called uniform Markovian renewal process. Such definition proposed by F. Grabski [9] is close to those given by other authors [13, 19, 20, 1].

From the definition it results that it is stochastic one of a discrete set of states and its realizations are right-hand continuous functions constant within intervals (of uniform values within operational time intervals which are random variables). Such process is defined only when its initial distribution $P_i = P\{Y(0) = s_i\}$ as well as the functional matrix $\mathbf{Q}(t) = [Q_{ij}]$ is known; the matrix elements are the probabilities of transition from the state s_i to the state s_j, within the time not greater than t ($i \neq j$; i, j = 1, 2,..., k), being the non-decreasing functions $Q_{ij}(t)$ of variable t, namely :

$$Q_{ij}(t) = P\{Y(\tau_{n+1}) = s_j \, , \, \tau_{n+1} - \tau_n < t \,|\, Y(\tau_n) = s_i\} \quad (1)$$

A semi-Markovian model of an arbitrary real process can be formed only when states of the process can be defined in such a way that duration time of a state appearing in the instant τ_n as well as a state possible to be reached in the instant τ_{n+1} do not depend stochastically on the preceding states and their duration time intervals.

For elaborating the semi-Markovian model $\{W(t) : t \in T\}$ of a given real process it is necessary to apply the theory of semi-Markovian processes. It makes it possible to determine probabilistic characteristics of an arbitrary random process (if only such model is formed), which may be of a practical importance. Such process may be a real process of changing technical states of any technical object. An example model of such process can be presented in the form of a graph of changing the states of the object (Fig.1). The model is one of the crucial components of the operational model of every technical object. One of the possible realizations of the process of changing the technical states, $\{W(t) : t \in T\}$, is presented in Fig. 2.

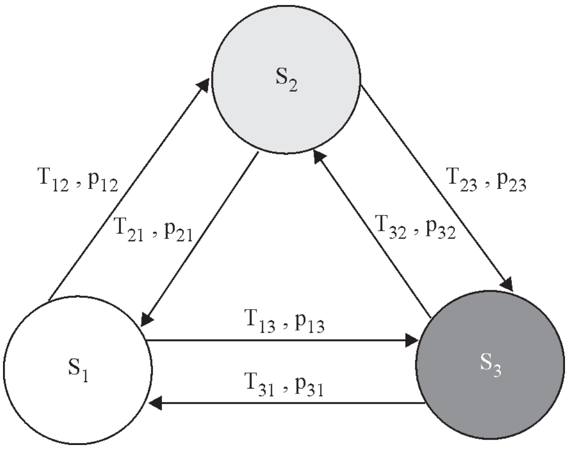

Fig. 1. *A graph of changing the states of an arbitrary technical object : s_1 - full serviceability state, s_2 - partial serviceability state, s_3 - unserviceability state, p_{ij} - probability of passing the process from the state s_i to the state s_j , T_{ij} - duration time of the state s_i provided the process passed to the state s_j ; i, j = 1, 2, 3*

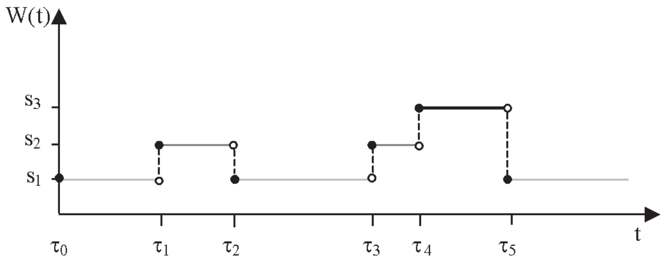

Fig. 2. *An example realization of the process $\{W(t) : t \in T\}$ of an arbitrary technical object : $\{W(t): t \in T\}$ - process of changing the technical states, t - time of operation; s_1 - state of full serviceability, s_2 - state of partial serviceability, s_3 - state of unserviceability*

In reality the process of changing the technical states of any technical object is stochastic, continuous in time and throughout the states. It means that the realizable kinds of technical state form a set of technical states of a given object, which is infinite one.

Identification of all technical states of many technical objects (e.g. combustion engines, boilers, pumps, compressors, ship prpulsion systems) is neither possible nor purposeful, both due to technical and economical reasons. Hence it is necessary to split the set of states of technical objects into a few number of classes (sub-sets) of technical states.

Assuming, as a splitting criterion, usefulness of a given technical object for realization of tasks (serviceability) one can distinguish the following classes (sub-sets) of technical states, shortly called "states" [4, 6, 8] :

- ★ the state of full serviceability, s_1 , which makes it possible to use the object in any conditions and in any range of loads, to which it was adjusted in the phases of its designing and manufacturing
- ★ the state of partial serviceability, s_2 , which makes it possible to use the object in limited conditions and in a range of loads lower than those to which it was adjusted in the phases of its designing and manufacturing
- ★ the state of unserviceability, s_3 , which does not make it possible to use the object in accordance with the purpose for which it was intended (e.g due to its failure, carrying out maintenance operations on its subassemblies etc.).

Therefore it is a three-state process
of continuous realizations (continuous with time).

The technical objects which are in the full serviceability state (s_1) can be used in any instant and conditions to which it was adjusted in the designing and manufacturing phases, and under various loads. And, the technical objects which are in the partial serviceability state (s_2) can be used or maintained depending on a decision-making situation (control strategy), whereas the unserviceable technical objects (in the state s_3) due to their failure are always maintained provided it would be cost-effective. However the technical objects unserviceable because of realization of preventive maintenance, are unserviceable only during the time of realization of these operations which require the object's structure to be trespassed by disassembling some of their devices.

The particular states $s_i \in S$ (i = 1, 2, 3) can be identified by means of an appropriate diagnostic system (SD) whose usefulness depends on quality of an applied diagnosing system (SDG) as well as on its capability of identifying the states of the technical object considered as a diagnosed system (SDN).

It can be assumed that if whichever of the states s_2 or s_3 does not occur then the object in question is in the state s_1.

The considered process of changing the technical states of technical object is, in mathematical terms, a function which maps the set of the instants T into the set of technical states, S. Such process can be modelled by means of the stochastic processes of discrete set of states and continuous duration time of distinguished technical states of the object.

Therefore the set of technical states :

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

can be considered as the set of values
of the stochastic process

$$\{W(t) : t \in T\}$$

whose realizations are constant within time intervals
and right-hand-side continuous, Fig.2.

In the case of the process of operation of technical objects the following characteristics may be of a practical importance :

- ➢ the one-dimensional distribution of the process (instantaneous distribution), whose elements are the functions $P_k(t)$ representing the probability of the event that in the instant t the process will enter the state s_k
- ➢ the limiting distribution of the process $P_j = \lim_{t\to\infty} P\{Y(t) = s_j\}$
- ➢ the conditional probabilities, i.e. those of transition of the process from the state s_i to the state s_j , $P_{ij}(t) = P\{Y(t) = s_j / Y(0) = s_i\}$ (transition probabilities)

- the distribution of the time of the first transition of the process from the state s_i to the sub-set of the states A ($\Phi_{iA}(t)$), and if this sub-set contains only one element – to the state s_j, i.e. the distribution $\Phi_{ij}(t)$
- the distribution of return time of the process to the state s_j, i.e. the distribution $\Phi_{jj}(t)$
- the asymptotic distribution of the renewal process $\{V_{ij}(t) : t \geq 0\}$, generated by return time intervals of semi-Markovian process (to the state s_j available from the state s_i), which at the instant t, obtains a value equal to number of "coming-in" events of that process to the state s_j
- an approximate distribution of the total time of maintaining the process Y(t) in the state s_j provided the state s_i is that initial one
- the expected value $E(T_i)$ of the duration time T_i of the state s_i of the process irrespective of the state to which transition occurs at the instant τ_{n+1}
- the variance $D^2(T_i)$ of the duration time T_i of the state s_i
- the expected value $E(T_{ij})$ of the duration time T_{ij} of the state s_i of the process provided the state s_j is the next one
- the expected value $E(\Theta_{jj})$ of the random variable Θ_{jj} which represents the return time of the process to the state s_j
- the expected value $E\{V_{ij}(t)\}$ of the random variable $V_{ij}(t)$ which represents the number of "coming-in" events of that process to the state s_j within the time interval [0 , t]
- the variance $D^2\{V_{ij}(t)\}$ of the random variable $V_{ij}(t)$
- the average number of "coming-in" events, $\lambda_{ij}(t)$, of the process to the state s_j, related to a unit of time, provided the state s_i of the process is that initial one (i.e. the intensity of the " coming-in" events of the process to the state s_j provided $Y(0) = s_i$)
- the limiting intensity of the "coming-in" events of the process to the state s_j, i.e. the intensity $\lambda_{ij} = \lim_{t\to\infty} \lambda_{ij}(t)$.

To obtain numerical values of the above mentioned characteristics is possible if two following conditions will be satisfied :

- if appropriate statistical data whose values would represent estimation of the transition probability p_{ij}, of the expected value $E(T_i)$, etc, will be collected
- if a semi-Markovian model of operation process of technical objects having a small number of its states and mathematically simple functional matrix **Q**(t) will be elaborated.

The second condition is important in the case of calculating the instantaneous distribution of states of the process $P_k(t)$. The distribution can be calculated if the initial distribution of the process and its functions $P_{ij}(t)$ are known. The calculating of the probabilities $P_{ij}(t)$ consists in solving the set of Volterra second-kind equations in which the functions $Q_{ij}(t)$ being elements of the process functional matrix **Q**(t), are known quantities [9].

In the case when number of process states is small and the functional matrix of the process – rather simple, that set can be solved by using the Laplace transform method [9, 10, 20]. However when number of process states is large or when its functional matrix (core of the process) is very complex, only an approximate solution of the set of the equations is available. Such (numerical) solution does not make it possible to determine values of probabilities of occurrence of process particular states if t is of a large value (theoretically if $t \to \infty$). The numerical solution does not provide any answer to the question very important for operational practice, namely : in which way do the probabilities of semi-Markovian process states change if t is large?

From the semi-Markovian process theory it results that the probabilities, in the case of the ergodic semi-Markovian processes, tend along with time to strictly determined constant numbers. They are called the limiting probabilities of states and their sequence forms the limiting distribution of the process. The distribution makes it possible to define the availability factor of technical object as well as the income or cost per unit time of its operation. The quantities serve as criterion functions in solving problems of operation process optimization of technical objects. Such distribution can be calculated much easier than the instantaneous one.

Similar difficulties are associated with solving the set of integral equations which make it possible to calculate the distribution of the random variable Θ_{iA} which determines the time of the first transition of the process from the state s_i to the sub-set of states, A, or (if the state A contains only one element) – to the random variable Θ_{ij} which determines the time of the first transition of the process from the state s_i to the state s_j.

PHYSICAL ASPECTS OF APPLICATION OF SEMI-MARKOVIAN PROCESSES FOR MODELING THE PROCESSES OCCURRING IN THE PHASE OF OPERATION

From the presented considerations it results that the semi-Markovian models are characteristic of the following features [7, 9, 10, 19, 20] :

- Firstly, is satisfied the Markov condition that future evolution of the investigated object (e.g. the process of changing the technical states in the object's operational phase), for which the semi-Markovian model has been elaborated, should depend only on its state at a given instant but not on the functioning of the object in the future, i.e. that the *future* of the object would not depend on its *history* but only on its *present*.
- Secondly, the random variables T_i (determining duration time of the state s_i regardless which state will occur after it) as well as T_{ij} (determining duration time of the state s_i provided the next state of the process will be the state s_j) have their distributions different from exponential ones.

Therefore in the modeling aimed at elaboration of a semi-Markovian model of the process of changing the object's technical states, an analysis of changing the states of real process, i.e. those occurring in the operational phase of the object in question, should be taken into account.

In the case of every technical object the process of changing its technical states is that where the duration time intervals of each its state are random variables. Particular realizations of the random variables depend on many factors, a.o. on the technical object's wear.

In the case of such technical objects as e.g. diesel engines, compressors or pumps, it was observed that wear of their sliding tribological units is weakly correlated with time [3, 8, 16, 17, 23, 24]. The observation is important because serviceability of such machines depends mainly on the technical state (i.e. on wear) of their tribological units. This made it possible to predict technical states of such machines with taking into account solely their present state and neglecting those earlier occurred. An explanation of the fact would make it possible to elaborate (by applying the theory of semi-Markovian processes) more adequate mathematical probabilistic models for predicting the technical states of particular machines. To this end the following hypothesis (H) can be offerred :

A state of an arbitrary sliding tribological unit as well as its duration time essentially depend on the state preceding it and neither on the earlier occurred ones and nor their duration time intervals because its load and both rate and increments of wear, implicated by it, are the processes of asymptotically independent values.

The last statement of the hypothesis (because its load...) results from two obvious facts :

- there is a strict relationship between loading on sliding tribological units and their wear [15, 17, 23]
- there is a lack of monotonic changes of loading on tribological units of machines within longer time of their operation, hence their loading can be assumed stationary [3, 17, 21, 22, 23].

The load stationarity (in a broader sense) means in every case that all multi-dimensional probability density functions depend only on mutual distances of the instants $\tau_1, \tau_2, ..., \tau_n$, and not on their values [5]. Therefore the one-dimensional probability density function of load values does not depend on the instant related to a given value, and the two-dimensional probability density function depends only on difference of the instants in which observed loading values occurr.

And, in a narrower sense, the fully stationary loading is understood as that whose all possible statistical moments of higher orders as well as the total moments of loading considered as a process, are not time - dependent. In the case of the fully stationary process (*in a narrower sense*) its characteristic quantities are as follows :

the expected value $m(t) = m = const$
variance $D^2(t) = \sigma^2 = const$
autocorrelation $A(\tau_1, \tau_2) = A^*(\tau_2 - \tau_1) = A^*(r)$
and autovariance $K(\tau_1, \tau_2) = K^*(\tau_2 - \tau_1) = K^*(r)$.

However the stationary process *in a broader sense* is characteristic of :

$m(t) = m = const$ as well as $A(\tau_1, \tau_2) = A^*(\tau_2 - \tau_1) = A^*(r)$.

In practice the loading stationarity in a broader sense is important. And, in this case to investigate the loading on tribological units in order to reveal the enumerated properties, is not necessary, as it is known from investigations of different machines, which have been performed so far, that the loading on their tribological units continously changes in such a way that its particular values measured after very short time intervals are strongly correlated to each other. However when the time interval between measurements of loads increases, the correlation between the loads decreases. Therefore the loading values measured in the time intervals (or instants) very distant apart can be considered as independent ones. This feature is called the asymptotic independence of a loading value measured in the instant, e.g. τ_{i+1}, from that measured in the instant τ_i, when the range $\Delta\tau = \tau_{i+1} - \tau_i$ is large enough.

The so understood asymptotic independence between loading values either measured or calculated in the instants τ_i and τ_{i+1}, is manifested by that their mutual dependence decreases along with increasing the range $\Delta\tau$. Moreover, from work principles of particular machines it is also known that their loading considered within a longer time of their correct operation, does not (and cannot) show any monotonically increasing or decreasing changes. Therefore one can assume that the maximum loading values appear in the specified instants accidentally, always with some probability only. This lack of monotonicity of the loading is called its stationarity.

In order to verify the presented hypothesis (H) it is necessary to predict the consequences whose occurrence can be confirmed empirically if the hypothesis is true. The consequences (K) which can be derived from the hypothesis (with taking into account the mentioned features of loading on ship power plant machines and their sliding tribological units) are the following [3] :

- K_1 - irregular course of realization of wear process of particular sliding tribological units
- K_2 - interweaving realzations of wear processes of sliding tribological units
- K_3 - such course of autocorrelation function for a given sliding tribological unit that at first the function fast decreases along with the range $\theta = h\Delta\tau$ (h = 1, 2,..., n) increasing, and next it oscillates about zero, at relatively small amplitude smaller and smaller along with $\Delta\tau$ increasing
- K_4 - almost normal distribution of wear increments of sliding tribological units for a sufficiently long time interval (Δt) of their correct operation
- K_5 - linear relationship of variance of wear process of sliding tribological units and their operation time values.

The above described consequences are graphically illustrated in Fig. 3 ÷ 6.

The presented consequences can be justified as follows :

If the features of the loading on machines and thus their tribological units are such as those above described, then the course of realization of wear of the units will have to be irregular. This forms the basis to assume that the wear increments recorded in the time intervals much distant from each other,

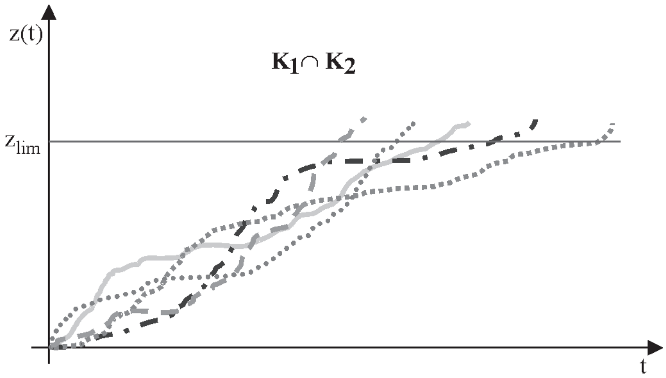

Fig. 3. *Example realizations of wear processes of sliding tribological units : z - wear, z_{lim} - limiting wear value, t - object's operation time*

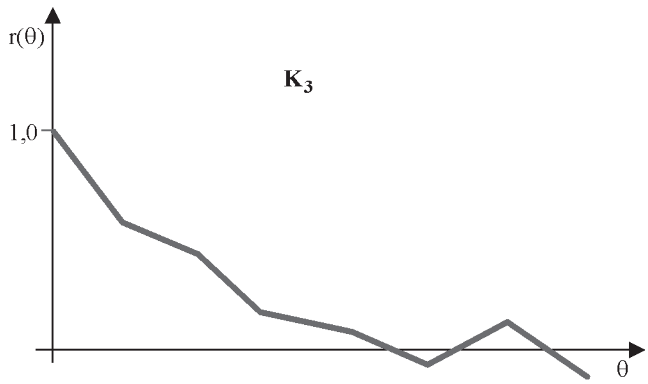

Fig. 4. *Example course of the autocorrelation function r(θ) where : θ - the range between time intervals (within which wear was investigated)*

are asymptotically independent, and along with increasing the time (time range θ, where : $\theta = h\Delta\tau$, h = 1, 2,..., n) between the intervals the relationship between the increments in question will be weakening. Hence the wear processes of such units can be considered as those of asymptotically independent increments [3].

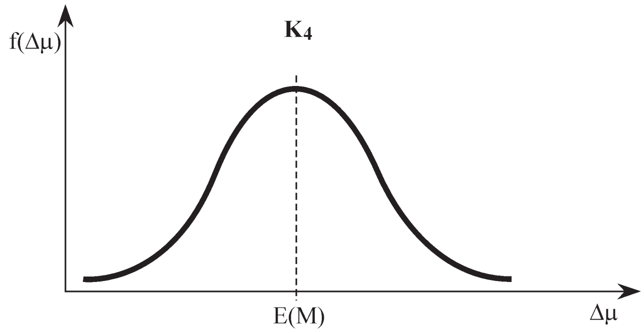

Fig. 5. Example form of the density function f (Δμ) of the asymptotically independent wear increments Δμ of sliding tribological units, for sufficiently long time interval (Δt) of their correct operation

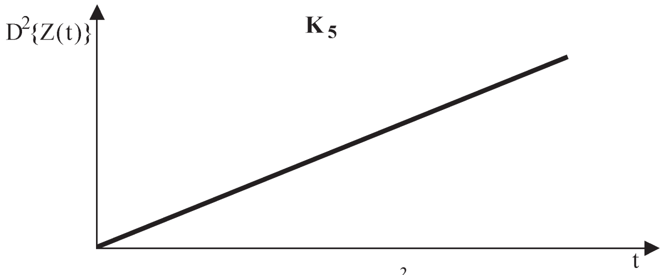

Fig. 6. Example relationship of the variance $D^2\{Z(t)\}$ of the wear process Z(t) of sliding tribological units of asymptotically independent increments, and their operation time t

One of the most important characteristics of every stochastic process (including wear processes) is the autocorrelation function r(θ) = f(θ), where : r - autocorrelation coefficient, θ - time range. If r(θ) decreases then wear process of a given tribological unit can be considered as that of asymptotically independent increments. Hence for tribological units in question an almost normal distribution of wear increments should be expected in a sufficiently long time interval. Moreover, if wear process is of asymptotically independent increments its variance $D^2\{Z(t)\}$ increases linearly along with correct operation time, in accordance with the relationship (2) :

$$D^2\{Z(t)\} = At + B \quad (2)$$

where :
A and B - process constants

The above mentioned consequences K_i(i = 1, 2,..., 5) reveal the probabilistic principle of wear of sliding tribological units. They are not contradictory to each other, and their logical veracity is doubtless. Hence it is possible to consider all of them as one consequence K and to use it for empirical proving if the presented hypothesis (H) is true or false. Such verification consists in experimental testing of wear of sliding tribological units and checking if the consequence K is true, which is equivalent to checking if the consequences K_i (the facts) appear or do not appear. Such verification of the hypothesis H makes it necessary to accept the veracity of the following syntactic implication [8, 12, 18] :

$$H \Rightarrow K \quad (3)$$

Then the non-deductive (inductive) reasoning may be used in accordance with the following scheme [8 , 18] :

$$(K , H \Rightarrow K) \vdash H \quad (4)$$

where :
$K = \{K_i , i = 1, 2,..., 5\}$

Its logical interpretation is as follows : if the empirical testing of the consequence K confirmed its veracity, then if the implication (3)is true, the hypothesis H is also true and acceptable. The reasoning in accordance with (4), called reductive one, does not lead to any firm conclusions but only to probable ones [12 , 18].

Semi-Markovian model of an arbitrary operational process can be applied in the case of machines even by using the diagnostic systems (SDG) where the reductive reasoning can be applied. Hence when reasoning on a diagnosis (conclusion) concerning the state of a given technical object being a diagnosed system (SDN) the statement K (stating that this – and not another – vector of values of diagnostic parameters is observed) is deemed to be a fully firm premise.

However the statement S (stating that there is this – and not another – state of SDN) is a conclusion formulated on the basis of the statement K during the non-deductive reasoning process which proceeds in compliance with the following scheme :

$$(K , S \Rightarrow K) \vdash S \quad (5)$$

where :
K - fully firm premise
S - conclusion formulated on the basis of the statement K.

From such reasoning the following hypothesis results :
The considered SDN is in the state S because the vector of values of diagnostic parameters, K, is observed.

It can be also formulated in another, equivalent way :
The vector of values of diagnostic parameters, K, is observed because the SDN in question is in the state S.

Such reasoning does not make it possible to formulate firm conclusions but only probable ones. Therefore it is not possible to exactly determine a technical state of a diagnosed system (SDN) and thus to control its operational process in such a way that a future state would depend on many previous states.

FINAL REMARKS AND CONCLUSIONS

❖ The semi-Markovian processes are useful models for investigating the real processes which occur in the operational phase of technical objects. Hence elaboration of a semi-Markovian model of a given process occurring in operational phase of an arbitrary technical object, makes it possible to easily determine probabilistic characteristics of the process in question.

❖ In practice the semi-Markovian processes are more useful than Markovian ones. It means that the semi-Markovian processes of continuous time parameter and finite set of states are characteristic of that the time intervals of staying the processes in particular states are random variables of arbitrary distributions concentrated in the set $R_+ = [0 , \infty]$. This differs them from the Markovian processes whose intervals are random variables of exponential distributions.

❖ A semi-Markovian model of an arbitrary process occurring in the phase of operation of a technical object is that of a finite set of states and continuous time.

❖ An additional benefit from application of semi-Markovian processes (like also of Markovian ones) is the possibility of using professional computer tools for solving different sets of state equations for such models of real processes.

- ❖ Semi-Markovian model of an arbitrary operational process can be applied in the case of machines even by using the diagnostic systems (SDG) where the reductive reasoning can be applied. However such reasoning does not make it possible to formulate firm conclusions but only probable ones.

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Conference

Plenary session of Machine Building Committee held in coast region

On 31 May and 1 June 2004 members of the Machine Building Committee, Polish Academy of Sciences held, this turn in Gdańsk, their plenary session commencing the next tenure of activity of the Committee. It was devoted, apart from organizational matters, to new challenges arising from the entrance of Poland into European Union.

On this occasion took place an open scientific meeting on :

Development prospects of machine building and operation after entrance of Poland into European Union

8 papers were prepared to be presented during the meeting :

- *Poland in the European Space of Science and Education* by Prof. W. Sadowski (Gdańsk University of Technology)
- *Polish Space of Science – prospects of development* by Prof. J. Kiciński (Insitute of Fluid Flow Machinery, Polish Academy of Sciences, Gdańsk)
- *Application trends in EU programs in the area of machine building and operation* – by Prof. A. Mazurkiewicz (Institute of Technical Operation Processes)
- *Contemporary research and education problems of ocean engineering* – towards European Space of Scientific Research – by Prof. J. Szantyr (Faculty of Ocean Engineering and Ship Technology, Gdańsk University of Technology)
- *Proecological activity of Mechanical Faculty concerning machine building and operation, in the frame of EU* by Prof. W. Przybylski (Mechanical Faculty, Gdańsk University of Technology)
- *Attempts to problems of operation of ship engines in the aspect of cooperation in the frames of EU and NATO* by Prof. R. Cwilewicz (Gdynia Maritime University), Prof. L. Piaseczny (Polish Naval University, Gdynia)
- *Integration of doctorate studies* – by Prof. B. Żółtowski (Technical Agricultural Academy, Bydgoszcz)
- *MARIE CURIE individual grants* – basic information by Prof. W. Zwierzycki (Poznań University of Technology)

The two-day meeting was co-organized by the Institute of Fluid Flow Machinery, Polish Academy of Sciences, Mechanical Faculty and Faculty of Ocean Engineering and Ship Technology, Gdańsk University of Technology.