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Markov approach to early diagnostics, reliability assessment, residual life and optimal maintenance of pipeline systems

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ABSTRACT

In this paper the pipeline degradation – simultaneous growth of many corrosion defects and reduction of pipe residual strength (burst pressure) is described by Markov processes of pure birth and pure death type, respectively. *This allows considering collective (joint) behavior of the set of actively growing defects in the pipeline as a distributed system, and to eliminate restrictions of the classical approach.*

On the basis of constructed Markov models following methods are proposed: (1) a method for assessing the probability of failure (POF)/reliability of a single defective pipeline cross-section and of a pipeline as a distributed system; (2) a practical assessment of the gamma-percent residual life of pipeline systems (PS); (3) an adequate economic model for assessing the optimum time for performing the next inline inspection (ILI) or PS maintenance/repair, which minimizes maintenance expenditures; (4) method of estimating the information entropy generated by degradation of the defective pipeline cross-section. This permits establishing relations between different physical and probabilistic states of the PS and opens new possibilities for its early diagnostics and optimizing its maintenance.

1. Introduction

The main cause of the degradation of pipeline systems is destruction of pipe walls due to corrosion, fatigue damage accumulation, effects of shock loads, etc. The distinctive feature of degradation of such systems is, as a rule, the presence of multiple actively growing defects, each of which is a potential threat to its integrity. Violation of pipeline integrity usually leads to enormous losses, which can reach several million dollars per accident. There are two types of pipeline integrity loss: leak and rupture.

In general, a distributed system is a system for which the location of its elements (or groups of its elements) plays an important role from the standpoint of its functioning and, therefore, its analysis.

In classical structural reliability theory the pipeline systems is modeled as a chain of series-connected elements (defects). In this case the probability of failure (POF) of a PS is equal to the product of the POFs of all the elements in the structure. The reliability of such a system is lower than the reliability of its elements and with increase of the number of elements (defects) the system reliability rapidly decreases. If the number of elements in the system is large, it is practically impossible to create a system with required (high) reliability. The main cause of this is that in the chain model all defects are involved in the POF calculation and essentially influence its value. But, in distributed pipeline systems not all the defects present are capable of creating an input into its POF.

To account for this circumstance it was suggested to take into consideration only «significant»defects which can actually affect the system reliability. At the same time there are no recommendations on to how to select the «significant»defects. Practically, to select from the entire set of defects, those which possess this quality, it is necessary to perform fairly complex calculations.

From the above it is clear that in order to consistently describe and analyse pipeline reliability a mathematical model is needed which is able to simultaneously account for each defect and at the same time, for the *collective behavior* of the whole system of defects present in the pipeline. One of the most suitable models for this are Markov processes.Among them, simplest are Markov chains (discrete states, discrete time).

Markov chains are used in [1] for describing cumulative damage in the form of fatigue cracks and wear in structures and its elements, using the so called B-models. In [2,3] the theory of Markov models was applied to assess the state of high pressure pipelines. In [2] the growth of corrosion pittings is considered as

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Nomenclature

DEMC	differential equation and Monte-Carlo (method)	SDE	system of differential equations
MSOP	maximum safe operating pressure	SF	safety factor

a Markov chain. In [3] a Markov chain in the form of the Yule model was chosen for consideration because it is the simplest model, which operates with only one transition intensity.

However, Markov processes (with a discrete number of states and continuous time) are more universal and adequately describe the true state of thin-wall pipeline systems. Markov processes are described by systems of differential equations and do not depend on the nature of objects and their physical properties. In this sense they are universal and are widely and successfully used in various fields of science and technology: nuclear physics, biology, astronomy, queueing theory, reliability theory, etc. [4–9,1]. Unlike Markov chains, they permit assessment of the probability of finding the system in each of the states and the intensity of transition from one state to another at any time.

Examination of literature shows [10–13] that there are no studies on the construction of such Markov models as pure birth (death) Markov process (MP) which describe the degradation of the bearing capacity of a distributed system with a finite set of discrete defects. In order to use these processes, the transition probabilities must not depend on the past, and the sojourn time for a process to be in any particular state should be exponentially distributed. Multiple empirical studies show [10–13] that both conditions take place in most types of technical systems, including pipelines. Assessment of reliability of such systems usually is based on an exponential distribution of pipeline defective cross sections uptime, and does not depend on the previous time of safe operation.

2. Formal description of the pure birth (death) Markov process

In reliability analysis of technical systems, their operation is generally regarded as a random process of transition from one state to another, caused by the degradation and failure of its components (elements). This process under certain conditions can be quite strictly described by a Markov process.

Consider a system S, which can be in one of the following states $S_0, S_1, S_2, \ldots$, which form a set that is finite or countable and the time t is continuous, i.e., the transition of the system from one state to another is occurring at random unknown beforehand moments of time t.

Denote as $S(t)$ the state of system S at the moment of time t. The probability $P_i(t)$ of the system being in the i-th state at time t is called "probability of an event", which consists in that at the moment of time t the system S is in the S_i state:

$$P_i(t) = P[S(t) = S_i].$$

A random process that evolves in the system S with discrete states $S_0, S_1, S_2, \ldots$, is called a Markov process, if for any arbitrary moment of time t_1 the probability of each of the system states in the future (at $t > t_1$) depends only on the current state the system is in (at $t = t_1$), and does not depend on when and how did the system enter this state, i.e., does not depend on system's behavior in the past (at $t < t_1$).

The system S is changing only by transition from one state to the closest, adjacent state (from S_n to S_{n+1} or to S_{n-1}). If at some moment of time t the system S is in the state S_n, then the probability that during an incremental time Δt, which immediately follows t, a transition $E_n \to E_{n+1}(E_{n-1})$ will take place, is approximately equal to $\lambda_n(\mu_n)\Delta t$, where the quantity $\lambda_n(\mu_n) \geq 0$ $[1/time]$ and does not depend on how the system S arrived at the current state. This means that the process in consideration is a Markov process [4]. The probability that during the small time span of Δt more than one transition will occur is of higher order of magnitude smaller than Δt. The quantity $\lambda_n(\mu_n)$ for the pure birth (death) Markov process is called «transition intensity»of system S from one state to another.

3. Pure birth Markov model of corrosion defects growth

This section presents a new effective model which describes simultaneous growth of a set of independent corrosion defects (see Fig. 1).

Divide the pipe wall thickness into M non-overlapping intervals with numbers $i = 1, \ldots, M$. The defect depth at moment of time t is the random value $d(t)$, which takes values from the interval $(0; wt]$, where wt is the pipe wall thickness.

The process of the depth growth of a set of defects is considered as a pure birth Markov process. The defect depth with time can only monotonically grow, i.e., at random moments of time can transit from the i-th state only to the $(i+1)$-th state.

The system of differential equations (SDE) describing this process, which is characterized by a discrete number of states and continuous time, has the form

$$\begin{cases} \frac{dP_1(t)}{dt} = -\lambda_1 P_1(t); \\ \frac{dP_i(t)}{dt} = \lambda_{i-1} P_{i-1}(t) - \lambda_i P_i(t), \; i = 2, \ldots, M, \end{cases} \tag{1}$$

where $P_i(t)$ is the probability that the defect depth is in the i-th state at time t, λ_i is the intensity of transition of the defect depth from the i-th state to the $(i+1)$-th state.

Carry out a consistent solution of the system of differential equations (1) with initial conditions corresponding to the distribution of states (intervals) of defects depths at the initial moment of time $t = 0$:

$$P_i(T_0) = p_i^*, \; i = 1, \; 2, \ldots, \; k,$$
$$P_i(T_0) = 0, \; i > k.$$

Here

$$p_i^* = \frac{n_i^*(0)}{N^*(0)}, \; i = 1, \; 2, \ldots, \; k, \tag{2}$$

p_i^* is the frequency of occurrence of defect depth in the i-th interval at the initial time $t = 0; n_i^*(0)$ and $N^*(0)$ is the number of defects,

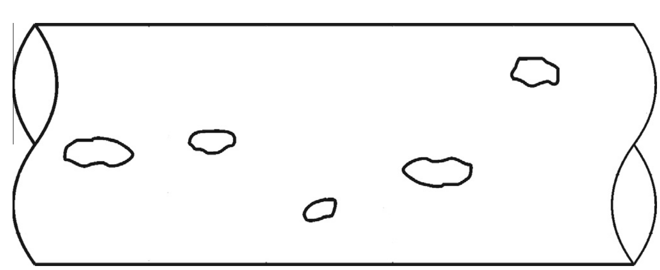

Fig. 1. Pipeline segment with multiple corrosion type defects.