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Statistical analysis of the nuclear power plant equipment failure data in non-homogeneous flow of events

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Abstract

Operation of technical equipment involves three consecutive stages, each of which is characterized by a particular trend in the behavior of the failure flow parameter (FFP). The FFP value is approximately constant during normal operation. In this case, the equipment operation process is assumed to be temporally homogeneous and the reliability indicators are calculated by conventional methods. At the burn-in stage, the FFP decreases with time while increasing at the aging stage. Therefore, the operating times between two successive failures at the burn-in and aging stages are not similarly distributed random values and the flow of events cannot be assumed to be recurrent. It shall be taken into account in the reliability performance calculation that the flow of failures is temporally inhomogeneous. The paper describes a method to estimate the NPP equipment reliability indicators allowing the potential inhomogeneity of the failure flow to be taken into account. The specific nature of incoming statistical data on failures is shown. The application of the normalizing flow function model for the calculation of required reliability indicators is described. A practical example of an analysis of data on the Bilibino NPP CPS KNK-56 component failures is presented.

Keywords: Flow of failures; Temporally inhomogeneous process; Normalizing flow function; Leading flow function; Failure flow parameter.

Introduction

Operation of technical equipment involves three consecutive stages, each of which is characterized by a particular trend in the behavior of the failure flow parameter (FFP). Thus, for example, the FFP value is approximately constant during normal operation. In this case, it is assumed that the equipment operation process is temporally homogeneous and the reliability indicators are calculated by conventional methods. At the burn-in stage, the FFP decreases with time, while increasing at the aging stage (more complex dependences may occur though). Therefore, the operating times between two successive failures at the burn-in and aging stages are not similarly distributed random values, and the failure flow cannot be assumed to be recurrent [1–4]. Due to this, it is not correct to use conventional methods to calculate the reliability performance at the given stage. It shall be taken into account in the reliability performance calculations that the failure flow is temporally inhomogeneous. Hence, the task is to develop methods for estimating the reliability indicators in a situation when the renewal process is temporally inhomogeneous, i.e., its probability indicators change over time. Such methods will provide more adequate estimations of the reliability indicators.

We shall consider literary sources the authors of which touch upon the problems dealing with the failure flow inhomogeneity. The state of the art in the mathematical theory of reliability is described in [2]. The key aspects addressed in this manual include investigation of different models for taking into account aging processes, degradation processes, accelerated test models, etc. The current state of the theory of renewal processes is reviewed and studied in [4]. A

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number of models of inhomogeneous processes and models to take into account aging in equipment operation are described in [5]. The monograph [6] is concerned with the study of various models for inhomogeneous recovery processes such as inhomogeneous Poisson processes, gamma-processes (first considered in [7]), trend renewal processes, geometric processes, Kijima processes and processes described by the normalizing function flow (NFF) model. In [8–12], new results are presented for geometric processes which are a form of inhomogeneous processes. The models of Kijima–Sumita inhomogeneous point processes make it possible, in particular, to simulate an incomplete renewal process (see [13,14]). The model of trend renewal processes (TRP) is fairly new and it is the closest to the NFF model. It first appeared in [15]. The development and study of methods for estimating the reliability indicators in inhomogeneous renewal processes complying with the NFF model are described in [16–19].

An analysis of these sources has shown that the inhomogeneous Poisson processes and NFF model are the headmost and possess the necessary completeness of capabilities. Moreover, it was found that the inhomogeneous Poisson processes, under certain conditions, are a special case of the NFF model. For this reason, it was the latter model of inhomogeneous renewal processes that formed the basis of methods for estimating the reliability indicators in the conditions of the existing inhomogeneity (see [20]).

The purpose of this paper is to describe the procedure for estimating the NPP equipment reliability indicators in order to allow the potential inhomogeneity of the failure flow to be considered and demonstrate the results of the procedure application based on real data obtained from operating experience.

Initial data

The major sources of information on the operation of the nuclear unit objects are "defects registers", passports and technical specifications for equipment, certificates of the technical state of equipment and some other documents.

The procedure used at nuclear plants to collect statistical data on failures makes it possible to identify the date of the object failure detection based on a set of single-type elements and the cause for the failure to have taken place. It is also possible to identify the object that has failed. Statistical data coming in for an analysis is presented as follows: there is a known number of the failure of components (ν_i) out of a set of one-type objects with a given volume (m) implemented in the ith observation interval. After a regular failure, the equipment unit in question is repaired. The time for the object renewal is expected to be negligible as compared to the mean time to failure, and the failed objects are renewed and returned to the system for further operation. Thus, we obtain a grouped failure flow. We shall also assume that the failure rates (ν_i) are distributed unevenly, and there is a certain pattern in the change of their distribution law as the observation interval (i-index) is changing.

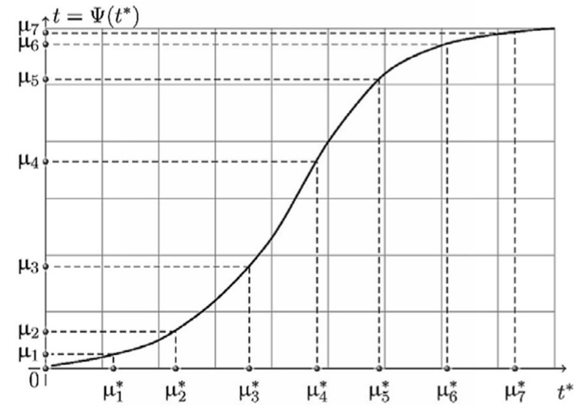

Fig. 1. Homogeneous-into-inhomogeneous flow transition.

Normalizing flow function model

We shall consider a mathematical model [2,6–8] that takes into account the event flow inhomogeneity and makes it possible to determine the reliability indicators of components provided the probabilistic characteristics of the process are time variable. In this model, the real inhomogeneous event of failures is the reflection of a homogeneous flow of events based on the monotone transformation, $\Psi(x)$, referred to as the NFF.

The inhomogeneity of the flow of failures is given by the $\Psi(x)$-function, the role of which is described below. The normalizing flow function establishes a link between the hypothetical homogeneous flow of failures and the unreal flow. Using the inverse transformation of the real flow, it is possible to obtain an approximately similar flow of events. The real flow may contain thickening (thinning) points: when the number of events in a certain time interval is much greater (accordingly smaller) than the number of events in the adjoining intervals of an approximate duration.

Fig. 1 shows a transformation of a homogeneous flow of events into a random flow using the Ψ (t^*)-function. The events in the homogeneous and inhomogeneous event flows are reflected on the X-axis and the Y-axis, respectively.

With such behavior of the failure flow, variation with time will take place, from one cycle to another cycle of the time-to-failure distribution law. A cycle is understood as the operation of the system component under investigation from the time it starts to operate (or is installed after repair) to a failure, with a new cycle of the component operation starting after each repair and the installation into the system.

We shall proceed to a formal description of the normalizing flow function model in essence.

Let us consider a flow of events in which an event is supposed to mean either a failure of a certain component (0-index) or its renewal (1-index) (see Fig. 2). The operating time to failure (ξ^0) and the renewal time (ξ^1) are random values. Let $\xi^0{}_i$ and $\xi^1{}_i$ be independent. We shall assume that $\xi^1{}_i=0$, that is the renewal takes place instantaneously; besides, we shall omit the superscript in the failure times, that is $\xi^0{}_i=\xi_i$.