Classification analysis of analytical and probabilistic methods for predicting the state of complex systems

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Abstract. The paper considers a class of analytical forecasting methods, a class of probabilistic methods, and methods of artificial neural networks for solving the problem of predicting the state of complex systems on board an aircraft, such as: mathematical simulation, operator method, one-dimensional time series forecasting method, potential function method, zone method, and generalized point method.

1. Introduction

The development of the domestic and global aviation industry is characterized by a constant rate of increasing the number and complexity of functions performed by individual systems on board the aircraft. Increasingly, such systems are aviation complexes that are complex systems. The complexity of systems generally leads to an increase in service life and requires the introduction of predictive models that allow continuous and periodic monitoring of the state of systems, forming a forecast of the state of systems based on parametric or statistical information [1, 2].

The paper considers analytical methods of forecasting, probabilistic and statistical classification methods for solving the problem of predicting the state of complex systems on board an aircraft, such as: simulation, operator method, method of predicting one-dimensional time series, method of potential functions, method of zones and method of generalized point.

Among the class of analytical methods for predicting the state of complex systems, there are a number of methods that can solve the problem of determining the flow of a process over a future period of time in a specific dimension. Among these methods: simulation—the method based on a machine experiment that allows you to predict the course of processes, set the timing of system control; operator method—allows you to describe a large class of processes, but has limitations on accuracy; the method of forecasting one-dimensional time series, which has the ability to impose additional conditions that increase the accuracy of the forecast, is based on the mathematical apparatus of the theory of interpolation.

In general, these methods are aimed at obtaining an analytical expression to describe the mathematical model of the process under study, but they have their drawbacks: they do not take into account the random component of the impact on performance and require a voluminous amount of initial information about changes in parameters.
When considering forecasting based on statistical classification, it is necessary to pay attention to the zone method and the generalized point method, which allow you to quickly make predictions, but are not applicable to complex systems and do not take into account the random component. There is also a method of potential functions—a method of training in pattern recognition, based on the approximation of the decision function by decomposing it into a series according to a known system of functions.

These methods provide the possibility of adaptation and self-learning, using both probabilistic and deterministic models, but these methods need to sample data for an object of the same type as the object whose indicators need to be predicted. If the methods of statistical classification are chosen, the forecasting task is reduced to the methods of object and image recognition and the use of neural networks [3].

2. Classification of methods

2.1. Analytical methods

The family of methods of simulation is based on the creation of models of the system, mathematical dependencies that allow you to calculate the future state of the object. Such methods should include structural models, such as classification trees. One of the conditions for using simulation is the initial presence of mathematically described dependencies of the studied parameters of the system under consideration. You can also build a model of system aging. If you have information about the aging of the system, you can determine the time of maintenance. With the help of such methods, it is possible to obtain high accuracy of forecasting with a sufficient amount of a priori data about the processes of the system. The disadvantages of this method include a considerable amount of calculations and the lack of the ability to take into account random external and internal effects.

The gradient method consists in extrapolating the health function in the gradient direction. This method is considered optimal in the sense that it allows you to evaluate the performance of the system in the direction of the most rapid achievement of the maximum permissible values. Forecasting is performed in two stages. On the first one, the components of the gradient vector are calculated, on the second one, extrapolation is performed in the calculated direction.

In some cases, the operator method or the generalized parameter method makes sense, the essence of which is that a number of observed parameters describing the system is reduced to a one-dimensional function, then this function is considered as an artificial parameter that displays the overall performance of the system. However, two tasks need to be solved next: determining the relative values of the a priori parameters and, in fact, constructing a mathematical model for the generalized parameter. All primary parameters should be reduced to a single number system, i.e. normalized. This allows us to obtain a number of dimensionless quantities that characterize the state of the system and correctly use them as a function of a generalized parameter.

A method for predicting one-dimensional and multidimensional time series. A family of methods, the main principle of which is to extrapolate the values of a quantity or quantities from already known data, that is, to calculate the values of functions beyond the boundaries of a number of known values. The input data here is a time series of system parameters in dynamics—a set of observations of certain numerical characteristics over time for a certain period.

This group includes methods of extrapolation from the exponential average and from the moving average. Such methods are most often used for short-term forecasting.

In practice, one-dimensional time series forecasting is more often used. To implement this method, the predicted process is represented as a time series. In this case, the prediction result is obtained in the form of a single number. Sometimes predicting a multidimensional process can be reduced to this case. In addition, there are a number of tasks where it is necessary to predict individual time functions (parameters). The problem statement is as follows: based
on the known values of the parameter $\xi(t_i)$, $t_i \in T_1$, where $T_1$ is the last period of operation of the object, calculate the value of the parameter during the upcoming operation $T_2$. The domain $T_1$, where the change in $\xi(t)$ is known, is used to determine the unknown coefficients of the mathematical model that are optimal for solving the specific problem under consideration, i.e., generally speaking, for training the model. To do this, it seems appropriate to apply the theory of interpolation.

Obviously, the accuracy of the prediction result directly depends on the accuracy of determining the unknown coefficients. To improve accuracy in specific tasks, it is also necessary to introduce additional conditions that are determined by various external influences. The choice and construction of an analytical expression for forecasting is one of the main issues that fundamentally affects the final result. As such expressions, we usually choose polynomials of various degrees, elementary time functions, etc., but using a separate polynomial or polynomial as the desired expression turns out to be impractical, since its predictive capabilities are narrowed. We need a formula of such a structure that would contain polynomials of different degrees with different adaptation coefficients. Its construction is a non-trivial task that requires a specific approach for each specific case.

In [4] propose an original method for predicting time series based on principal component analysis, which takes into account the spectral composition of the predicted process. The disadvantages of the time series forecasting method include the fact that it is a method for predicting one-dimensional processes. The processes studied in practice are most often multidimensional, and it is not always possible to reduce them to one-dimensional ones.

The exponential smoothing method is a method in which the prediction of values is calculated by the average values of the current period and the average value observed in the previous period. The weights of observations are also taken into account: the recent values of the parameters have more weight than the more recent ones. However, the model should be extended with two components: with a stable trend and with a periodic component, for example, the Holt exponential smoothing model with trend correction-with double smoothing.

It should be borne in mind that increasing the forecast time increases the degree of uncertainty of the system operation processes. For this reason, statistical extrapolation methods are most often used.

2.2. Probabilistic methods
One of the probabilistic forecasting methods is the statistical gradient method. The use of the statistical gradient method involves a statistical assessment of the regularity of the approximation of the values of the state function to the permissible boundaries. It should be noted that the state function at a fixed time is a multidimensional vector, and the number of its coordinates corresponds to the number of independent parameters of the state function.

The idea of the method is as follows. At time $t_n$, from the $k$ coordinates of the state vector, groups by $l$ are randomly selected and the corresponding increments of coordinates $\gamma_1 \ldots \gamma_l$ are determined, where $i_s$ are unit random vectors, $\gamma = t_n - t_{n-1}$, after which the increment of the entire state function is calculated over the time interval $\gamma$ after that, the vector sum $i_s \Delta Q_s$ is compiled for $s \in 1 \ldots l$, where $\Delta Q_s$ is the increment of the state function (operability). In a sense, this vector sum is an analogue of the gradient for a linear space (in the limit when $l \to \infty$, this is the gradient of the performance function). Thus, the found direction of the vector sum $i_s \Delta Q_s$ at finite $l$ is a statistical estimate of the gradient direction that should be chosen for prediction. The considered gradient method is a special case of the statistical gradient method for $l = k$ and non-random vectors $i$ [5].

Prediction using the Bayes criterion. The method is based on the use of the Bayes formula, i.e. the method is based on the probability theory, which determines the probability of the occurrence of an event. Most often, a generalized formula is considered, and the recognition
of an event occurs based on a number of parameters—signs. The application of the method is reduced to the following steps:

- identify key features—parameters that affect the performance of the system;
- determine the probability of finding the system in each of the three states: without power, in normal operation, and with failure;
- determine the probability of failure at a certain time interval during normal operation;
- determine the values of the signs-parameters, when they are reached, the “failure” event occurs and the probability of reaching these values.

In this case, it is necessary to take into account a comprehensive study of the parameters:

- build a diagnostic matrix in which to give the categories of signs in different cases. This matrix includes a priori probability indicators;
- it may be necessary to adjust the probability of the signs;
- choose the decision rule and make a decision about the diagnosis;
- calculate the probability of an erroneous decision and the confidence probability of a correct decision.

The Bayes method allows you to accurately determine the probability of an event with certain signs. However, the use of Bayes theory has one important drawback for solving the problem of predicting failures on board an aircraft: the probabilities of rare events, such as a system failure or a CSE block, have high errors [6].

Method of coordinate-based self-learning. The forecasting accuracy can be improved by introducing self-learning into the forecasting process. Self-learning in probabilistic forecasting is manifested in the adaptation of the probabilistic characteristics of an object, as a result of which preference is given to certain directions. As information accumulates, the assessment of the direction of the greatest change in the object’s performance is gradually optimized, which, obviously, should be chosen as the direction of forecasting. Accordingly, in the course of information accumulation, the variance of these estimates should decrease, i.e., the learning process should determine the direction of forecasting, but on the other hand, the learning algorithm should include the possibility of recalculation if the situation has changed or the training was inaccurate. This principle is implemented in the coordinate-wise self-learning method [7]. The algorithm of its work is as follows. Let the probability of choosing the prediction direction along the s-th coordinate is a function of some memory parameter along the s-th coordinate at the n-th control step. This function should always be monotonic and non-decreasing. The learning algorithm is implemented by appropriately changing the memory parameter at each next step, in such a way that if the performed prediction step led to a result that was unsatisfactory for some physical or simply a priori reasons, that is, it was made in an unfavorable direction, then the probability of choosing this direction on the next step decreases. Such a forecasting algorithm has a certain inertia, since the direction of forecasting in most cases cannot change significantly in one step.

Forecasting using regression equations. The forecasting problem can be solved using an autoregressive model [8, 9]. Methods of the theory of statistical regression make it possible to predict one or several values \(y_1, y_2, \ldots, y_q\) based on information about the parameters of the object \(x_1, x_2, \ldots, x_k\). The sought value can represent a certain generalized criterion of the state, or, in a particular case, the future value of the parameter \(Y\). The task is to determine such a mathematical model \(Y = f(x_1, x_2, \ldots, x_k)\), knowing which it is possible to judge with some certainty about the change of the desired value \(Y\) depending on the parameters \(x\).

At the moment, there is another class of methods—the creation of artificial neural networks (ANN). These methods are convenient because there is the ability to train neural networks to
recognize images and predict one-dimensional and multidimensional time series. At least three layers of neurons are involved in the prediction: the input, output, and hidden—the inner layer. At the moment, the current models are the autoregressive model: ARIMA moving average autoregression, GARCH autoregressive conditional heteroskedasticity, and the ARDLM model of autoregression and distributed lag [5, 6, 10].

3. Conclusion
To solve the problem of predicting the state of complex systems, each of the methods under consideration does not fully cover the problem of predicting the state of complex systems. All methods require a large amount of a priori data.

The most appropriate way is to use the method of predicting one-dimensional and multidimensional time series using INS. This direction is quite promising. There are a number of positive qualities of using the INS, including scaling to different systems and no loss of performance with incomplete a priori data. Among the disadvantages, we can clearly distinguish the need for a large amount of initial information.

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