UDC 537.52, 629.78

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AUTOMATIC MONITORING OF PARAMETERS OF ELECTRIC ROCKET PROPULSION SYSTEMS

Algorithms of automatic monitoring of the parameters of the electric rocket propulsion system are considered. The informative features of the subsystems of the electric rocket propulsion systems and the nature of their changes in the process of operation of the propulsion system are determined. The algorithms for detecting jump-like changes in informative features for different volumes of apriority information are presented.

Keywords: electric propulsion system, Hall thruster, measurements of the parameters, automatic control, algorithms of monitoring.

Electric rocket propulsion systems (ERPS) are increasingly used in the implementation of various space programs. The main advantage of the application of ERDU is a significant reduction in the mass of the propellant in comparison with chemical thrusters of low thrust. This is ensured by a significantly higher value of the specific impulse, by the possibility of multiple firings and by a long service life [1]. The ERPS consists of blocks and subsystems of various physical nature: an electric rocket thruster (ERT), a system for storing and supplying the propellant (SSSP), a power supply system (PSS) and an automatic control and monitoring system (ACS) that unites these systems into a single whole.

The most promising electric rocket engine is currently considered to be the Hall engine. In such an engine, the process of ionization of the propellant takes place in crossed electric and magnetic fields, and the acceleration of the formed ions is performed by a longitudinal electric field [3].

Electric rocket propulsion systems require complex control and monitoring algorithms. The need for the implementation of complex algorithms for controlling and monitoring the parameters of the ERPS subsystems is conditioned by the specifics of providing the electric energy of the spacecraft, ensuring the reliability of the ERPS operation during a long service life and the desire to cover a wider range of tasks being solved by the same ERPS.

Specificity of spacecraft's power supply is that, during long-term operation in space conditions, solar batteries, which until now are the main source of electric power for ERPS, are subject to considerable degradation, as a result of which, the electric power is significantly reduced. The automatic control and monitoring system of the ERPS should provide optimal modes of the ERPS in conditions of a significant change in the power of the primary power source.

As a result of the long-term autonomous functioning of the propulsion system, the parameters of its subsystems, in particular, the electric rocket engine, the system of storage and supply of the propellant and the power supply system, can be substantially changed, up to their failure. Therefore, the automatic control and monitoring system should ensure the maintenance of the optimum operating modes of the ERPS when the parameters are changed within certain limits, and in case of failures of individual elements, generate signals for the disconnection of the failed elements and connection of the backup ones.

The most informative parameter characterizing the normal operating mode of the Hall thruster is the magnitude of the discharge current (I_d), which characterizes the ionization processes in the accelerating channel of the engine. At that, information on the state of thruster operation and closed electron drift is contained both in the average value of the discharge current, and in the level and frequency ranges of the discharge current oscillations [10, 11].

The storage and supply systems of the propellant included in the ERPS can be built on various physical principles, but the gas systems for inert gases – xenon (Xe), argon (Ar) – have become most widespread at present. In the gas SSSP, informative parameters are: values of the pressure (P_i) in the working tracts of the system; information about the condition of the valves; the heating current of the thermo-throttle (I_{th}); temperature parameters (T_i) at various points of the SSSP [7].

The power supply system of the ERPS contains a number of controlled and uncontrolled power supply sources that provide electrical operation modes for individual subsystems of the ERPS. The normal functioning of a given source can be judged by the values of the voltage (V_i) and the current (I_i) and their correspondence to the required values [12, 13].

Thus, in electric rocket engines, it is possible to measure a vector of variables that characterize the current state of the engine, and similar vectors of variables can be measured for the system of storage and supply of the propellant, the power supply system and the automatic control unit of the ERPS.

The automatic monitoring unit for the parameters of the ERPS, which is an integral part of the automatic control unit, must provide the solution of the following tasks: gathering information about the current state of the subsystems; processing of the current information in order to identify emergency and abnormal situations; processing of the current information about the parameters of subsystems in order to forecast the occurrence of emergency situations, etc.

Table 1 lists the main controlled parameters of the subsystems of the ERDU and the nature of their possible changes. An analysis of the nature of the possible change in the monitored parameters of the subsystems of the ERPS shows that, in the automatic monitoring unit of the ERDU along with the tolerance monitoring algorithms checking whether the monitored parameters are in a given tolerance ranges, algorithms for detecting a sudden change, as well as a slow drift of the monitored parameters should be implemented, for making decisions as for prevention of emergency and abnormal situations in individual subsystems and in ERPS as a whole.

Mathematical formulation of the problem of automatic monitoring of parameters of the ERPS. To automatically monitor the parameters of the subsystems of the ERPS, measurements of various informative characteristics that characterize the functioning and operability of the propulsion system are used. The model of such measurements can be a sequence of random variables – one-dimensional random signals X(1), X(2), X(3), ..., X(k) or a sequence of random vectors [X(1)], [X(2)], ..., [X (k)], a multidimensional discrete random signal, where $[X(k)] = [X1(k), X2(k), ..., Xm(k)]^T$; T is the sign of transposition. Properties of discrete signals and their use for solving forecasting and control problems are considered in [2]. Obviously, the measured signals contain information on the state of the subsystems of the ERPS, and can be used for solving the tasks of monitoring.

Table 1

Informative characteristics of subsystems of the ERPS and the nature of their change

ERPS unit	Monitored parameters	Typical anomalies
Hall thruster: - stationary plasma thruster; - thruster with the anode layer	Average discharge current (I_d). Amplitude (A_i) and frequency (ω_i) of oscillations of voltage (V_d) and current (I_d) of discharge.	Abrupt change, slow drift. Abrupt change, slow drift.
System of storage and supply of gaseous propellant	Pressure in the tubing of the SSSP (P_i). Information on the state of the valves. Current of heating of the thermo-throttle (I_{th}).	Slow drift. “Open – Shut”. Abrupt change, slow drift.
Electric power supply sources	Values of voltage (V_i) and current (I_i) of the sources of power supply, increase of the amplitude of pulsation (ΔV, ΔI).	Abrupt change, slow drift.

The problem of automatic monitoring of the ERPS can be formulated as follows. In normal operation, the characteristics of the discrete signals do not change, and values of their parameters are within the set limits. An indication of the alarm is the change in the properties of the discrete signals.

The detection of these changes and evaluation of their parameters is the main task of signal processing [8, 9]. Despite the variety of the nature of the change in the controlled signals, several typical models of such changes can be distinguished.

The most characteristic for the information features of the operation of ERPS subsystems are rapid changes (jumps) in the mean value of the signal, the measurement errors of which are independent normally distributed random variables with zero mathematical expectation and known variance. In a particular case, jump direction (up or down) can be known. In the jump-like form, variance, parameters of the distribution laws, the laws themselves and spectral (correlational) properties of the signals can vary. In this case, the task of processing the measurements of the parameters of the ERPS consists of detecting changes, identifying them, determining the moment of detection and estimating the parameters. Based on these data, models of changes can be constructed to solve the tasks of monitoring, forecasting and controlling.

At present, the theory of detecting and recognizing pulsed signals against a background of interference in communication, radiolocation, and radio navigation systems has been well developed [5, 6]. These signals, as a rule, are known up to their parameters. The unknowns are the amplitude, phase or frequency. The problem is reduced to calculating the ratio of the likelihood functions and comparing it with the threshold, the value of which is chosen by the Neumann-Pearson criterion from the condition that the number of false alarms should not exceed a given value.

In the problems of monitoring under consideration, it is not always possible to calculate the likelihood ratio, since often neither the signal type nor its parameters are known, and in some cases the characteristics of the perturbations acting on the subsystems of the ERPS are unknown. The problem of detecting and assessing the changes in the properties of stochastic signals and dynamical systems has now become an intensively developing direction of mathematical statistics.

In [8], a review of research in this field is given, algorithms for sequential analysis, maximum likelihood, on the basis of nonparametric methods and their application in seismology, speech segmentation, geophysical signal analysis and electrocardiograms are considered. These and other methods of mathematical statistics can be used to detect jumps and trends, identify piecewise constants, piecewise linear and quadratic functions, and evaluate their parameters in the tasks of processing measurements in the means and systems of monitoring and technical diagnostics of various objects, including ERPS. In the case of only qualitative a priori information on the expected changes in signals (increase, decrease), nonparametric methods for estimating the homogeneity of samples of measurements using the omega-squared criterion, based on Fisher's F distribution, restoring the laws themselves and evaluating their parameters are effective [4, 5, 6].

In [8] it was suggested that the detector be considered optimal if, for a fixed average time between false alarms, the delay in detection is minimal. In systems for automatic monitoring of technical systems, the most important task is to detect changes. Therefore, unlike the algorithms proposed in [8], algorithms based on the Neumann-Pearson criterion are examined here: the maximum probability of detection for a given probability of false alarm, and the delay time is regarded as a controlled constraint. This means that the probability of detection can be adjusted by changing the delay time if the information is processed in real time.

Mathematical formulation of the problem of detecting jumps in normal measurements. We consider a discrete sequence of measurements of a certain parameter $X_1, X_2, ..., X_k$, where $X_k = a + \Delta X_k$, and ΔX_k is the measurement error. And it is known that the error distribution law is normal with zero expectation and variance σ^2. The parameter a can assume two values, a_1 and a_2, wherein the change occurs abruptly in time unknown in advance $\Delta t \cdot K_1$.

It is necessary, having such a priori information, to propose a measurement processing algorithm for detecting a jump and estimating the moment of its appearance – K_1^*. After detection (decision on the presence of a jump), measurements are stopped. Obviously, the decision made at $K_1^* < K_1$ is erroneous (false), and the decision at $K_1^* > K_1$ is delayed; and the error in determining the jump time is $\Delta t(K_1^*-K_1)$.

The following qualitative requirements for the detection algorithm seem to be obvious:

1) the probability of making a wrong decision P_{op} in the time interval $0 \le t < \Delta t K_1$ should be sufficiently small;

2) the detection lag time $\Delta t(K_1^* - K_1)$ must not exceed the specified value – t_3.

The above requirements are contradictory, this fact should be taken into account when justifying the measurement processing algorithm. In the problem under consideration, the decisions must be taken successively at each step as the measurements are taken. The problem of recognizing two objects A_1 and A_2 [4] is well known. If the vector of recognition indicators $[X]^T = [X_1, X_2, ..., X_k]$ is measured, and the conditional laws of probability distribution of the random vector $W([X]/A_1)$ and $W([X]/A_2)$ are known, then the decision rule based on the criterion of the minimum of the mean risk (the average cost of errors) is formulated as follows:

1) from measurements [X], it is necessary to calculate the value of the likelihood ratio

$$l([X]) = W([X]/A_2)/W([X]/A_1);$$

2) determine the threshold of comparison

$$l_0 = \frac{P_1 C_{12}}{P_2 C_{21}},$$

where P_1, P_2 are the a priori probabilities of the appearance of objects A_1 и A_2;

C_{12} and C_{21} are the cost of recognition errors to take the first object for the second and second for the first;

3) if the inequality $l([X]) \ge l_0$ holds, then the decision is object A_2; if $l([X]) < l_0$, then the decision is object A_1.

When using such an algorithm, the mathematical expectation of the cost of errors (mean risk) is

$$M[C] = P_1 P_{12} C_{12} + P_2 P_{21} C_{21},$$

where P_{12} and P_{21} are probabilities of making wrong decisions.

If the probabilities P_1 and $P_2 = 1 - P_1$ are not known, then the comparison threshold can be chosen by assuming the cost of errors C_{12} and C_{21} inversely proportional to the probabilities of their appearance P_1 and P_2. In this case, always $l_0 = 1$.

The second way to select the threshold is by the Neumann-Pearson criterion: it is necessary to specify one of the error probabilities (for example P_{12}) and determine the threshold value l_0.

It is convenient to make the decision by calculating the log likelihood ratio. In this case, if $Z = \ln l([X])$, then the decision rule for detection of object A_2 is as follows:

1) by the criterion of average risk, $Z \ge 0$;

2) by the Neumann-Pearson criterion, $Z \ge Z_0$.

In the case under consideration, for independent measurements, the conditional distribution laws of the sample $[X_k] = [X_1, X_2, ..., X_k]$ will be written in the form

$$W([X_k]/A_{1,2}) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\frac{1}{2\sigma^2}\sum_{i=1}^{k}(X_i - a_{1,2})^2\right]. \quad (1)$$

For a log-likelihood ratio, we obtain an expression of the form

$$Z(k) = \frac{a_2 - a_1}{\sigma^2}\left[\sum_{i=1}^{k} X_i - \frac{k(a_2 + a_1)}{2}\right]. \quad (2)$$

The sequence Z (k), k = 1, 2, ... is a discrete normal random signal whose mathematical expectation before the jump ($k < K_1$), as follows from (2), is equal to

$$\mathrm{M}[Z(k/0)] = M_1(k) = -\frac{(a_2 - a_1)^2}{2\sigma^2} k, 1 \le k < K_1.$$

The difference $a_2 - a_1 = \Delta a$ is the magnitude of the jump. The ratio $\Delta a^2/\sigma^2 = q^2$ is equal to the ratio of the jump power to the power of the measuring noise. Therefore, we can write

$$M_1(k) = - q^2 k/2\ ,\ \ 1 \le k < K_1\ . \tag{3}$$

The mathematical expectation Z(k) after the jump ($k \ge K_1$) can be written in the form

$$M[Z\ (k/c)] = M_2(k) = M_1(K_1-1) + q^2(k-K_1+1)/2\ .$$

As a result, we obtain

$$M_2(k) = q^2(k-2K_1+2)/2\ . \tag{4}$$

The variance of Z(k) does not depend on the presence of a jump and is

$$D[Z\ (k)] = (a_2-a_1)^2 k/\sigma^2 = q^2 k\ . \tag{5}$$

The probability of making a decision at time Δtk can be defined as the probability of satisfying the inequality $Z(k) \ge 0$

$$P_p(k) = \int_0^\infty W(Z(k))dZ(k).$$

Using (3), (4) and (5), we obtain

$$P_p(k) = \begin{cases} 1-\Phi(q\sqrt{k}/2), 1 \le k < K_1, \\ \Phi\left(\dfrac{q(k-2K_1+2)}{2\sqrt{k}}\right), K_1 \le k < \infty. \end{cases} \tag{6}$$

Analysis of expression (6) shows that the probability of making wrong decisions (segment $1 \le k < K_1$) continuously decreases and reaches a minimum at $k=K_1-1$.Then a slow increase in the probability of finding a jump ($k \ge K_1$) begins .At the point $k=2(K_1-1)$, the detection probability is 0.5, and the delay is $t_3=\Delta t\ (K_1-1)$. It is quite obvious that the considered algorithm is not suitable for practical use, since for $k \to \infty$ $t_3(k) \to \infty$, although in this case $P_p(k) \to 1$.

To reduce the delay, it is necessary to discard (forget) some of the old measurements. This procedure can be performed using an n-dimensional movable window that, out of the sequence X(k), selects the sequence X(k-n), X(k-n+1), X(k-n+2), ..., X(k-1). In this case, the log likelihood ratio can be written in the form

$$Z(k) = \frac{a_2 - a_1}{\sigma^2}\left[\sum_{i=1}^{n} X(k-i) - \frac{n(a_2+a_1)}{2}\right]. \tag{7}$$

If the inequality Z (k)> 0 holds on the segment at the point k ($n \le k \le K_1$), then such an event is called a false alarm [136] and its probability is equal to

$$P_{ЛТ} = \int_0^\infty W(Z/0)dZ = \frac{1}{\sqrt{2\pi D}}\int_0^\infty e^{-\frac{(Z-M_1)^2}{2D}} dZ = 1-\Phi\left(\frac{q\sqrt{n}}{2}\right). \tag{8}$$

In order for the jump to be detected, the following condition must be fulfilled: there should not be any false alarms in the segment $1 < k \le K_1-1$. The probability of this event (the absence of false detection) is

$$1-P_{ЛО} = (1-P_{ЛТ})^{K_1-1} = \left[\Phi\left(\frac{q\sqrt{n}}{2}\right)\right]^{K_1-1}.$$

Thus, in order to satisfy the requirements of a high probability of detecting a jump of a given intensity (q), it is necessary to increase the window size and reduce the probability of false alarm.

In real conditions, the problem of detecting jumps differs from the idealized model and, above all, in the content of a priori information about the monitored process.

The following variants of the initial data options are possible:

1) in normal measurements, the initial value a_1 is known, the jump value $\Delta a = a_2 - a_1$ is unknown, the variance of the measurement noise is either known or unknown;

2) in normal measurements, a_1 and a_2 are unknown, the variance of the measurement noise is either known or unknown;

3) in normal measurements, a jump in the power of the measurement noise is expected;

4) the laws of distribution of measurements are unknown, the form of the law and its parameters can change abruptly;

5) it is expected that at an unknown time the controlled process becomes non-stationary (for example, its mathematical expectation or variance begins to change).

It is necessary, in conditions of a priori uncertainty of the initial data, to propose and investigate the algorithms for processing the measurements and the decision rules for detecting jumps, estimating their intensity and the errors in determining the time of appearance (the delay time). Basing on these data, the task of predicting the state of the monitored object and detecting emergency situations can be solved.

Conclusions. The problem of automatic monitoring of variables characterizing the current state of an electric rocket propulsion system based on a Hall engine is formulated. The informative signs of the subsystems of the ERPS and the nature of their changes during the operation of the propulsion system are determined. The mathematical problem of detection of abrupt changes of informative signs of electric propulsion is formulated. Algorithms are presented for detecting jumplike changes in informative signs with different amounts of a priori information. The proposed algorithms can be used in the development of real electric rocket propulsion systems.

List of references

1. **Архипов А.С.** Стационарные плазменные двигатели Морозова / Архипов А.С., Ким В.П., Сидоренко Е.К. // М.: МАИ, 2012. 292 с.

2. **Бокс Дж.** Анализ временных рядов, прогноз и управление / Бокс Дж., Дженкинс Г. // М.: Мир, 1974.

3. **Бугрова А. И.** Плазменные ускорители и ионные инжекторы / Бугрова А.И., Ким В.П. // под общ. ред. Н.П. Козлова, А.И. Морозова. М.: Наука, 1984. 272 с.

4. **Дуда Р.** Распознавание образов и анализ сцен /Дуда Р., Харт П. //. - М.: Мир, 1976

5. **Левин Б.Р.** Теоретические основы статистической радиотехники. Книга 2. - М.: Сов. радио, 1975.

6. **Левин Б.Р.** Теоретические основы статистической радиотехники. Книга 3. - М.: Сов. радио, 1976.

7. **Ломакин В.Д.** Результаты математического моделирования системы подачи как исполнительного устройства для ЭРД /Ломакин В.Д., Быков С.Е., Петренко А.Н. // В кн.: Труды II Всесоюзной научно-технической конференции “Современные проблемы двигателей и энергетических установок летательных аппаратов”. - М.: МАИ, 1980. - С.133.

8. Обнаружение изменения свойств сигналов и динамических систем: Под ред. М. Бассавиль, А. Банвениста, - М.: Мир, 1989.

9. Технические средства диагностирования: Справочник/В.В. Клюев и др.; Под общ. ред. В.В. Клюева. - М.: Машиностроение, 1989.

10. **Petrenko O.N**. Results of Research of Steady Work Modes of Stationary Plasma Thrusters”, Processing of the 47th International Astronautical Congress, IAF-96-S.3.03, Beijing, China, 7-11 October, 1996.

11. **Petrenko O.N**. “Problem of Automatic Control and Parameters Monitor System Designing for the Electrical Propulsion Engine Modules”, Processing of the Fourth Ukraine-Russia-China Symposium on Space Science and Technology, Vol. 1, P. 349-351, September 12 -17, 1996, Kiev, Ukraine.

12. **Petrenko O.N**. “The Problem of Control and Monitor Units Development for the Electrical Propulsion Modules” /Petrenko O.N., Prisniakov V.F.//, Processing of the First IAA Symposium on Realistic Near-term Advanced Scientific Space Missions, June 25-27, 1996, Torino, Italy.