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DIAGNOSTIC MODELS OF INOPERABLE STATES OF THE VORTEX ENERGY SEPARATOR DEVICE

*The **object** of study in the article is the vortex effect of temperature separation in a rotating gas flow, which is realized in small-sized vortex energy separators. The **subject matter** of this article is the process of forming diagnostic models of inoperable states of a vortex energy separator device as a rational control object when destabilizing influences appear. The **goal** is to develop an analytical approach to the formation of digital diagnostic models for rational control of cold and hot air flow temperatures that reflect the effects of direct signs of inoperable states of the vortex energy separator device that are inaccessible to measurement with indirect signs accessible to measurement. The **tasks** are to study the features of the process in the vortex energy separator device; to describe a rational control system of the vortex energy separator device; to analyze the experimental characteristics of the vortex energy separator device; to form linear mathematical models of the nominal mode of the vortex energy separator device; to develop linear diagnostic models that describe the inoperable states of the vortex energy separator as a rational control object; to form logical signs of diagnosing using diagnostic models. The **methods** used are the method of transfer functions, the method of the discrete states space, the method of diagnostic models, the method for forming production rules, the method of formation of two-digit predicate equations. The following **results** were obtained: linear mathematical models of functional elements and the entire device as a whole were formed for the nominal operation mode. Linear digital diagnostic models were developed for the inoperable states of the vortex energy separator device. Logical signs of diagnosis were formed on the basis of the diagnostic models. **Conclusions**. The scientific novelty lies in the formation of an analytical approach to the development of digital diagnostic models of inoperable states of the vortex energy separator device and two-digit predicate equations of indirect signs for a dichotomous diagnostic tree.*

Keywords: vortex energy separator device; rational control; destabilizing influences; linear mathematical models; digital diagnostic models; two-digit predicate equations.

Introduction

Increasing the environmental cleanliness of energy technologies is a trending direction of our time. One of these technologies is based on the use of the vortex effect for the phase separation of gases in a rotating flow. Devices realizing this effect are called vortex energy separators (VES).

VESs are widely used in air conditioning units due to the simplicity of technical implementation and maintenance, the absence of substances harmful to the environment, as well as lower production, operation and disposal costs compared to other types of units [1].

Deepening knowledge about the nature of the vortex effect has led to the possibility of using vortex devices in aviation. Thus, VESs are used in air conditioning systems in cabins and cabins of transport aircraft and are used in cooling systems for components of onboard radio-electronic equipment. In gas turbine engines, VES elements are implemented in the designs of vortex nozzles and profiled channels of hollow blades of turbine nozzles [2, 3].

In the well-known designs of such air conditioning units, single-mode wind turbines are used, the operation of which is carried out using the principle of control by a master action. The inevitable influence of destabilizing influences, such as changes in external operating conditions, compressed air parameters and internal factors due to changes in the technical characteristics of the vortex process, leads to a significant deterioration in the quality of object cooling.

Improving the quality of conditioning is possible through the use of the deviation control principle. At the same time, it is impossible to achieve a significant improvement in quality due to the instability of the process of vortex energy separation, as well as due to changes in the characteristics of drives and sensors of the VES device as an automatic control object.

A long study of the vortex effect has not led to the emergence of physical and mathematical models suitable for the problem of synthesis of an automatic control system. Due to the insufficient knowledge of the vortex effect, the study of the dynamic properties of specific VES and their inoperable states is carried out through

experimental studies and the formation of approximation mathematical models in the time and frequency domains [4].

It is possible to achieve a high quality of vortex energy separation using a new principle of control by diagnosis [5]. This principle is based on identifying the causes of the violation of the VES performance and the subsequent restoration of its normal functioning. For the formation of a diagnosis, mathematical models are used, called diagnostic ones, since they reflect the connection of the causes of a malfunction that are inaccessible to measurement with the consequences that are accessible to measurement.

The article presents the results of research on the formation of an analytical approach to the development of diagnostic models of inoperable states of the VES on the example of the breadboard device.

1. Vortex energy separator device

The functional diagram of VES is shown in Fig. 1.

The functional diagram is represented by a series connection of the following functional elements: a servo that controls the position of the cone valve, VE, temperature sensors for cold and hot air flows. When a control signal u is applied to the input of the servo, the position μ of the cone valve changes. Compressed air is supplied to the input of the VES with pressure P. As a result of vortex energy separation, two air flows are formed: cold with temperature θ_1 and hot with temperature θ_2, which are measured by the corresponding sensors with output voltages u_1 and u_2. Each functional element is affected by set of influences D_i, $i=\overline{1,4}$ that disrupt the performance of functional elements. A set of these destabilizing effects $D = D_1 \cup D_2 \cup D_3 \cup D_4$ disrupt the performance of the entire VES device.

Fig. 2 shows the design of the VES.

The operating principle of VES is as follows [6]. Compressed gas with pressure P enters the inlet of the nozzle device 1, which is a smoothly tapering channel of rectangular cross section, in which rotational motion is imparted to the air flow due to the spiral shape of the working surface 2. The most common form of the spiral

is the Archimedes spiral, which provides the smoothest change in the direction of the velocity vector. The swirling gas flow enters the energy separation chamber 3, moving along a helical trajectory in the near-wall region to the straightening crosspiece 4 and then to the cone valve 5. Passing through the crosspiece, the flow loses the circumferential velocity component, as a result of which the pressure slightly increases. The flow area of the cone valve is insufficient to pass the entire mass of gas, so part of the flow begins to move in the opposite direction from the valve in the axial region of the energy separation chamber and is discharged through the aperture 6.
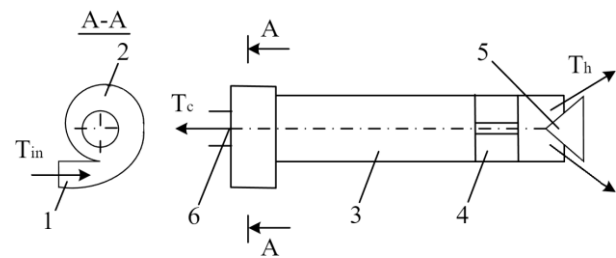
Fig. 2. Design of VES: 1 – nozzle device; 2 – twisting device; 3 – energy separation chamber; 4 – crosspiece; 5 – cone valve; 6 – diaphragm

Between the vortex flows moving in the opposite direction, energy is exchanged, as a result of which the peripheral layers are heated, and the paraxial ones are cooled. Thus, the temperature of the air leaving the energy separation chamber through the cone valve is higher than the temperature of the air supplied to the VES. Accordingly, the flow leaving through the diaphragm of the gas has a lower temperature than the air at the inlet of the VES.

For the first time, the effect of vortex energy separation was discovered by the French engineer Joseph Ranque in 1920s while studying the operation of cyclones. In the 1940s, as a result of a study to improve the efficiency of the thermal separation of gases, the German physicist Robert Hilsch obtained new experimental results. In honor of these outstanding researchers, the vortex effect began to be called the
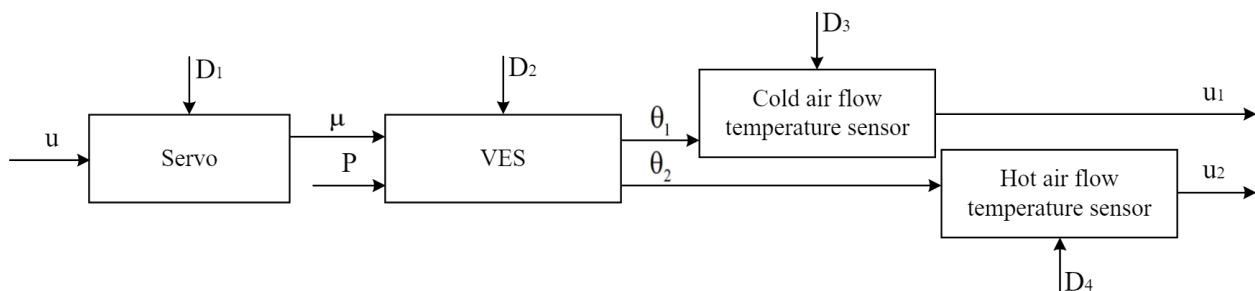
Fig. 1. Functional diagram of the VES device

Ranque-Hilsch effect. From the moment of discovery of the vortex effect, its intensive study begins with the aim of technical implementation in various technologies [7–9].

The significant non-linearity of the static characteristics of the VES device, the distribution of parameters and their non-stationarity in steady state and transient conditions necessitate the use of adaptive control of the state of the rotating air flow in order to ensure the quality indicators and environmental cleanliness of the energy gas separation technology required for various technical applications.

2. Rational control

Rational control is one of the approaches to adaptive control of objects with uncertainty (Kulik, 2016). Rational control is based on the assumption of the destabilizing influences uncertainty that violate the operability of control object. Destabilizing influences are various uncontrolled disturbing influences, noise, interference, defects, malfunctions and failures. The uncertainty of destabilizing effects is due to the uncertainty of the moment of destabilization occurrence, the constructive part of the object where it appeared, the type of destabilization to which it belongs, as well as the unknown specific value. A set of destabilizing influences has a finite value. The elements of that set are specific physical kinds of destabilizing influences.

With regard to the problem of automatic control of the VES, the rational control system, shown in Fig. 3, consists of two interconnected subsystems. The first subsystem is a rational control object (RCO), the second one is a rational control device (RCD), interconnected by signal links.

RCO includes a control object, VES, to which compressed air is supplied with pressure P, a servo that changes the position $\mu(t)$ of the cone valve in the energy separation chamber and temperature sensors for cold $\theta_1(t)$ and hot $\theta_2(t)$ air flows. RCO is affected by a set of uncontrolled destabilizing effects D.

The second subsystem, RCD, consists of diagnostic and control modules. In the diagnostics module, based on the control signal $u(kT_0)$ and the signals of the temperature sensors $u_1(kT_0)$ and $u_2(kT_0)$ a functional state diagnosis of RCO is formed as the estimates of the characteristics of destabilizing effects $\hat{D}$. In the control module, control impacts $u_c(kT_0)$ and $u_o(kT_0)$ are formed, recovering the operation of RCO based on the results of its diagnosis.

The key in the presented functional diagram is the diagnostics module. The purpose of this module is to form the diagnosis of RCO. This requires detecting the current destabilizing effect, localizing and identifying its place, type and kind, in other words, diagnosing the RCO. For the formation of diagnostic procedures, diagnostic models are used that analytically connect the cause of the malfunction of RCO with the consequence of its appearance in signals $u_1(kT_0)$ and $u_2(kT_0)$. Diagnostic models are developed as a result of processing the experimental characteristics of the VES device.

3. Experimental characteristics of the VES device

A series of experimental studies was carried out on a prototype VES device with the following geometric dimensions: diameter of the working part $D_{wp} = 5.8$ mm; length of the working part $L_{wp} = 20 \cdot D_{wp}$; control valve position range $\Delta\mu_{wp} = 2$ mm; diaphragm diameter $D_d = 2.5$ mm. External conditions are the compressed air pressure P = 0.5…0.7 MPa; ambient temperature T = 292 K.

As a result of the experimental study, the static characteristics of the VES device shown in Fig. 4 were obtained, reflecting the dependence of the temperature of the cold θ_1 and hot θ_2 air flows on the valve movement μ for three values of compressed air pressure: ■ – 0.5 MPa, ● – 0.6 MPa and ▲ – 0.7 MPa.

It is obvious that the static characteristics are continuous and non-linear, therefore, they can be fragmentarily approximated by linear dependencies. In order to determine the structure and parameters of the VES device, experimental logarithmic amplitude-frequency characteristics of the VES were obtained for two values of the operation point $\mu_{10} = 0.5$ mm and $\mu_{20} = 1.25$ mm
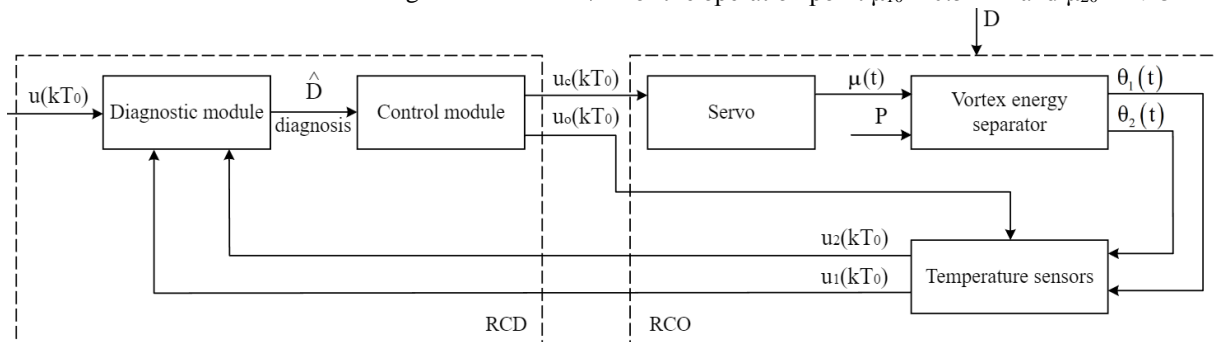

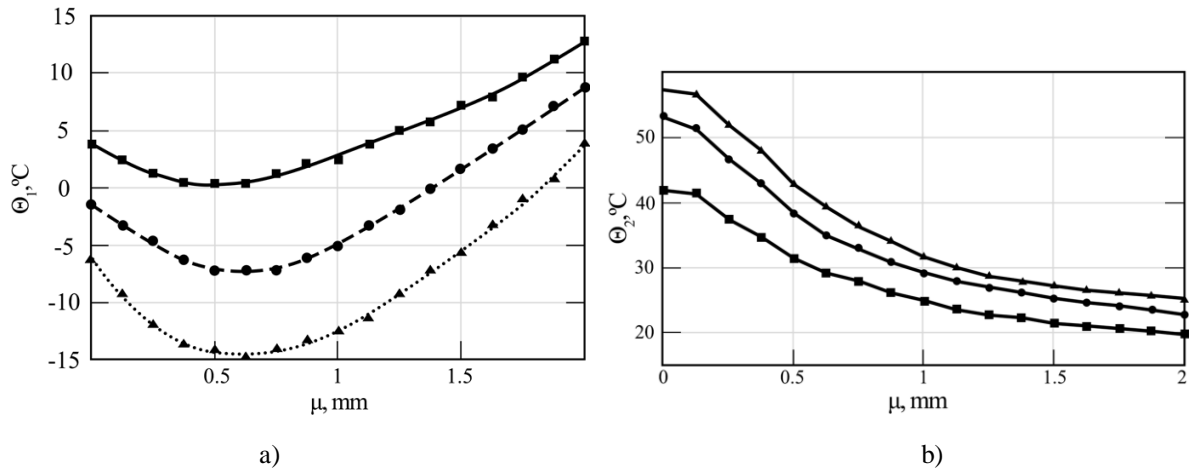Fig. 3. Functional diagram of the rational control system

Fig. 4. Graphs of the static characteristics of VES for the cold (a) and hot (b) air flows

for compressed air pressures: ● – 0.6 MPa and ▲ – 0.7 MPa. The frequency characteristics are presented in Fig. 5.

As follows from the obtained graphs, they can be approximated by linear dependencies to obtain mathematical models in the form of transfer functions.

In order to evaluate the inertial properties and quality indicators of the VES device, discrete transient responses were experimentally obtained for two values of the operation points $\mu_{10} = 0.5$ mm and $\mu_{20} = 1.25$ mm for compressed air pressures of 0.6 MPa and 0.7 MPa. The transient characteristics are shown in Fig. 6.

As a result of processing the experimental data of the VES prototype device, adequate mathematical models were obtained in a linear approximation for both cold air flow and hot air flow depending on the valve displacement for various pressure values [10–12].

Thus, it was found that the energy separation transformation processes in the VES prototype device can be represented for different operating points and at different values of compressed air pressure by first-order linear mathematical models both in the form of differential equations and in the form of transfer functions.

4. Mathematical models of nominal mode

Transformation properties of RCO (Fig. 3) in the nominal mode, that is, in the absence of destabilizing effects from the set D, can be reflected in a linear approximation using the block diagram shown in Fig. 7.

The transfer function of the servo is described by an integrator

$$W_1(s) = \frac{M(s)}{U_c(s)} = \frac{\kappa_1}{s}. \qquad (1)$$

Transfer functions of VES for cold air flow

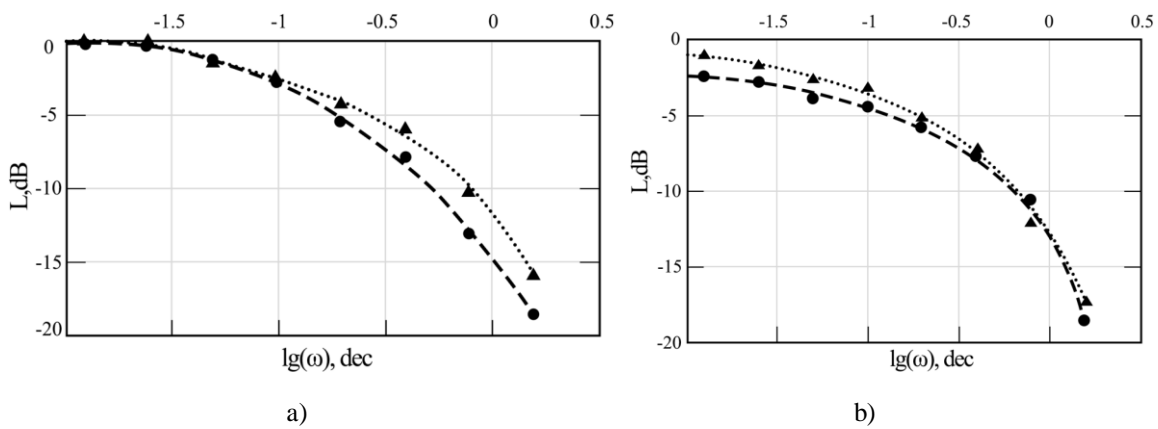$$W_2(s) = \frac{\Theta_1(s)}{M(s)} = \frac{\kappa_2}{T_2 s + 1} \qquad (2)$$

Fig. 5. Graphs of experimental logarithmic amplitude-frequency characteristics of VES
for operation point $\mu_{10} = 0.5$ mm (a) and operation point $\mu_{20} = 1.25$ mm (b)
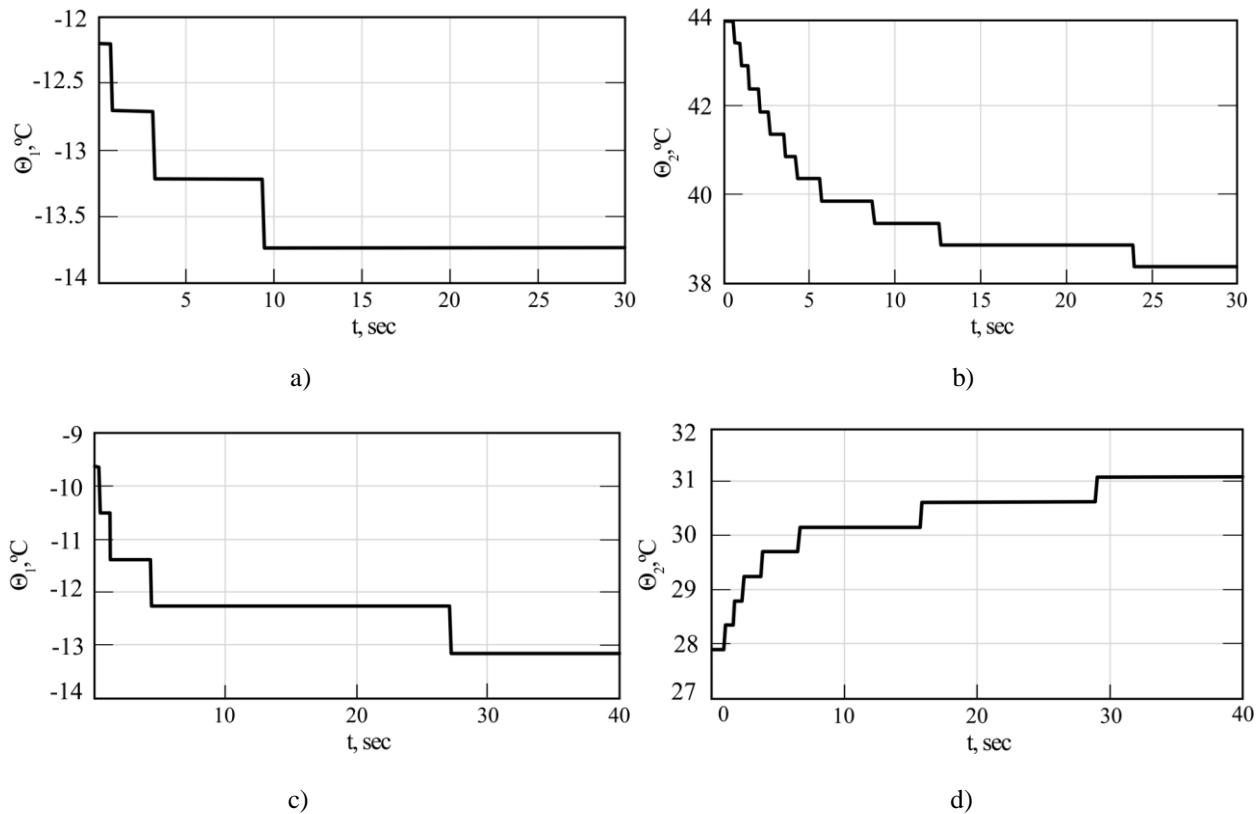
a)

b)

c)

d)

Fig. 6. Transient characteristics of VES:
a – operation point $\mu_{10} = 0.5$ mm for cold air flow; b – operation point $\mu_{10} = 0.5$ mm for hot air flow;
c – operation point $\mu_{20} = 1.25$ mm for cold air flow; d – operation point $\mu_{20} = 1.25$ mm for hot air flow
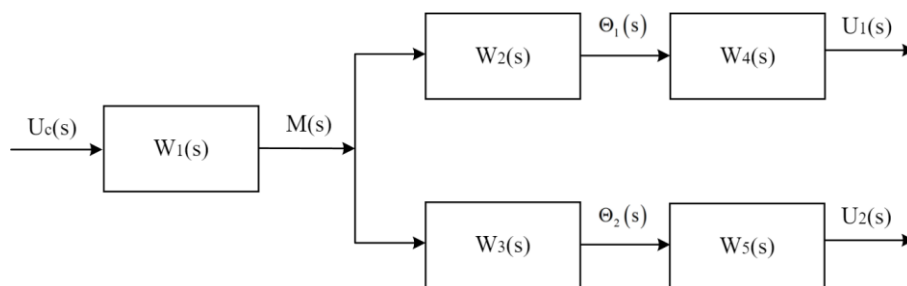
Fig. 7. Block diagram of RCO

and hot air flow

$$W_3(s) = \frac{\Theta_2(s)}{M(s)} = \frac{\kappa_3}{T_3 s + 1}. \qquad (3)$$

Transfer functions of the temperature sensors

$$W_4(s) = \frac{U_1(s)}{\Theta_1(s)} = \frac{\kappa_4}{T_4 s + 1}; \quad W_5(s) = \frac{U_2(s)}{\Theta_2(s)} = \frac{\kappa_5}{T_5 s + 1}. \qquad (4)$$

Then the transfer functions for the cold and hot air flows channels are described as

$$W_c(s) = \frac{U_1(s)}{U_c(s)} = W_1(s) \cdot W_2(s) \cdot W_4(s) =$$
$$= \frac{\kappa_1 \kappa_2 \kappa_4}{T_2 T_4 s^3 + (T_2 + T_4) s^2 + s}; \qquad (5)$$

$$W_h(s) = \frac{U_2(s)}{U_c(s)} = W_1(s) \cdot W_3(s) \cdot W_5(s) =$$
$$= \frac{\kappa_1 \kappa_3 \kappa_5}{T_3 T_5 s^3 + (T_3 + T_5) s^2 + s} \qquad (6)$$

respectively.

In the state space, the RCO in the nominal mode is described by the following system of equations

$$
\begin{bmatrix} \dot{x}_1(t) \\ \dot{x}_2(t) \\ \dot{x}_3(t) \\ \dot{x}_4(t) \\ \dot{x}_5(t) \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ \dfrac{\kappa_2}{T_2} & -\dfrac{1}{T_2} & 0 & 0 & 0 \\ 0 & \dfrac{\kappa_4}{T_4} & -\dfrac{1}{T_4} & 0 & 0 \\ \dfrac{\kappa_3}{T_3} & 0 & 0 & -\dfrac{1}{T_3} & 0 \\ 0 & 0 & 0 & \dfrac{\kappa_5}{T_5} & -\dfrac{1}{T_5} \end{bmatrix} \cdot \begin{bmatrix} x_1(t) \\ x_2(t) \\ x_3(t) \\ x_4(t) \\ x_5(t) \end{bmatrix} + \begin{bmatrix} \kappa_1 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \cdot u_c(t); \quad \begin{bmatrix} x_1(0) \\ x_2(0) \\ x_3(0) \\ x_4(0) \\ x_5(0) \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix};
$$

$$
(7)
$$

$$
\begin{bmatrix} u_1(t) \\ u_2(t) \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} x_1(t) \\ x_2(t) \\ x_3(t) \\ x_4(t) \\ x_5(t) \end{bmatrix}.
$$

In order to describe RCO in a discrete state space, one can use the Euler formula, according to which

$$
\dot{x}(kT_0) \approx \frac{x\big[(k+1)T_0\big] - x(kT_0)}{T_0}, \qquad (8)
$$

where k = 0, 1, 2, … is a sample time, T_0 is a quantization period.

Applying equation (8) to equation (7), the following system of finite difference equations are obtained

$$
\begin{bmatrix} x_1\big[(k+1)T_0\big] \\ x_2\big[(k+1)T_0\big] \\ x_3\big[(k+1)T_0\big] \\ x_4\big[(k+1)T_0\big] \\ x_5\big[(k+1)T_0\big] \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ \dfrac{\kappa_2 T_0}{T_2} & 1-\dfrac{T_0}{T_2} & 0 & 0 & 0 \\ 0 & \dfrac{\kappa_4 T_0}{T_4} & 1-\dfrac{T_0}{T_4} & 0 & 0 \\ \dfrac{\kappa_3 T_0}{T_3} & 0 & 0 & 1-\dfrac{T_0}{T_3} & 0 \\ 0 & 0 & 0 & \dfrac{\kappa_5 T_0}{T_5} & 1-\dfrac{T_0}{T_5} \end{bmatrix} \cdot \begin{bmatrix} x_1(kT_0) \\ x_2(kT_0) \\ x_3(kT_0) \\ x_4(kT_0) \\ x_5(kT_0) \end{bmatrix} + \begin{bmatrix} \kappa_1 T_0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \cdot u_c(kT_0); \quad \begin{bmatrix} x_1(0) \\ x_2(0) \\ x_3(0) \\ x_4(0) \\ x_5(0) \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix};
$$

$$
(9)
$$

$$
\begin{bmatrix} u_1(kT_0) \\ u_2(kT_0) \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} x_1(kT_0) \\ x_2(kT_0) \\ x_3(kT_0) \\ x_4(kT_0) \\ x_5(kT_0) \end{bmatrix}.
$$

This system of equations can be represented in a more compact form

$$
x(k+1) = A \cdot x(k) + b \cdot u(k); \; x(0) = x_0;
$$
$$
u(k) = C \cdot x(k), \qquad (10)
$$

where x(k) is the state vector, dim[x(k)] = 5, A, b and C are the matrices of the corresponding dimensions, u(k) is the output vector, dim[u(k)] = 2.

In the discrete space of states, descriptions of the conversion properties of RCO can be represented using the block diagram shown in Fig. 8.
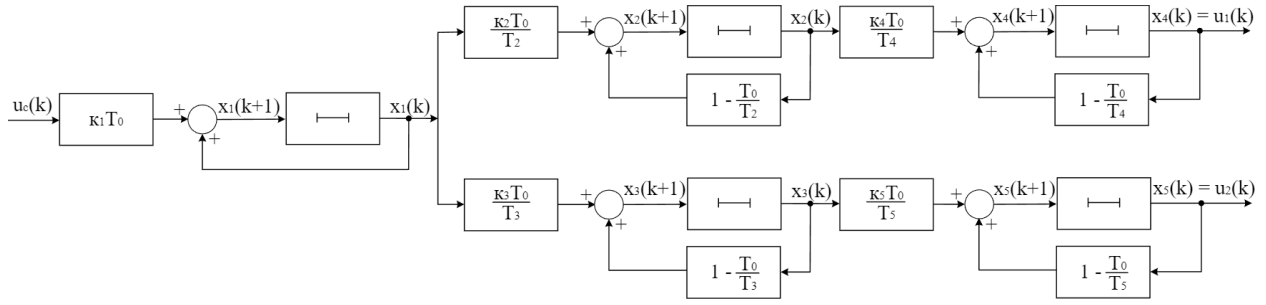
Fig. 8. Block diagram of RCO in the discrete state space

In the scheme, when describing the arguments of variables, the quantization cycle T_0 is omitted.

The presented block diagram makes it possible to qualitatively evaluate such properties of RCO as controllability and observability, without using the analytical criteria of R. Kalman.

A necessary property for diagnosing is diagnosability. Diagnosability is understood as a property that consists in the possibility of unambiguously establishing the cause of an inoperable state. The block diagram (Fig. 8) makes it possible to evaluate this property without resorting to analytical criteria for structural and signal diagnosability [5].

The presented mathematical models of the linear approximation of RCO in the nominal mode of its operation allow us to proceed to the formation of diagnostic models that reflect the influence of destabilizing effects on the signals available for measurement.

5. Diagnostic models of inoperable states

When developing the diagnostic module (Fig. 3), diagnostic models are used. Digital diagnostic models reflect the relationship of indirect signs of diagnosis with direct signs in the form of finite-difference equations. Diagnostic models are used to describe the inoperable states of the VES device and are designed to solve the following diagnostic tasks:

1) detection of inoperable states;
2) localization of an inoperable functional element;
3) determination of the type of destabilization;
4) determination of the kind of destabilizing effect that caused the device to fail;
5) formation of a dichotomous diagnostic tree.

Destabilizing influences from the set D are the impacts that lead the functional elements to its inoperable. Under the operable state of VES device is understood such a state in which the value of all parameters characterizing the ability to perform the specified functions meets the requirements of the technical specifications. Any deviations from the specified functions indicate an inoperable condition. The reason for the deviations is destabilizing influences. As a result of the analysis of the influence of the destabilizing effects of the VES device on its performance, it was found that both external factors (pressure, temperature, humidity) and internal factors (malfunction, failures, failures) lead to a change in the position of the operation points of functional elements on static characteristics and an increase in inertial properties. Further, the features of the formation of diagnostic models for each task of diagnosing a VES device will be considered.

Servo. The task of detecting inoperable states is to establish the fact of occurrence of deviations in the operation of RCO device from the required nominal mode. Destabilizing influences from the set D leads to the appearance of a perturbed motion of the energy separation process and can be described by the vector-matrix equation

$$\tilde{x}(k+1) = \tilde{A} \cdot \tilde{x}(k) + A \cdot \tilde{x}_0 + \tilde{b} \cdot u(k); \ x(0) = 0; \qquad (11)$$
$$\tilde{u}(k) = \tilde{C} \cdot \tilde{x}(k),$$

where $\tilde{x}(k)$ is a disturbed state vector, $\tilde{u}(kT_0)$ is a disturbed measurements vector, $\tilde{A}$, $\tilde{b}$ and $\tilde{C}$ are the matrices of the parameters of the inoperable VES state, $\tilde{x}_0$ is an operation point drift vector of the VES.

In order to determine the deviation in the operation of the device, it is necessary to subtract the equation describing the operable state (10) from equation (11), and as a result, obtain

$$\Delta x(k+1) = \Delta A \cdot \tilde{x}(k) + A \cdot \tilde{x}_0 + \Delta b \cdot u(k); \qquad (12)$$
$$\Delta x(0) = 0; \ \Delta u(k) = \Delta C \cdot \tilde{x}(k),$$

where ΔA, Δb и ΔC are the matrices of the deviations of parameters from its nominal values.

Equation (12) is the equation of the diagnostic model relating the deviation of the measurement vector $\Delta u(k)$ with the deviations of the parameters ΔA, Δb, ΔC and $\tilde{x}_0$. The two-digit predicate equation

$$z_0 = S_2 \left\{ \left| \Delta u(k) \right| \geq \delta_0 \right\}, \ k = \overline{k_1, k_2}, \ p, \qquad (13)$$

where z_0 is a boolean variable, S_2 is a two-digit predicate symbol, δ_0 is tolerance for deviation, p is a confidence coefficient for the fulfillment of the argument condition on the diagnosing interval $[k_1, k_2]$. If the absolute value of measurement deviation becomes equal to or exceeds the tolerance value δ_0, then $z_0 = 1$ means that the VES device is inoperative. Otherwise, $z_0 = 0$, which means that the VES device is operational.

The nominal operating mode is described by the following recursive equation, based on Fig. 8,

$$x_1(k+1) = x_1(k) + \kappa_1 T_0 u(k). \qquad (14)$$

Destabilizing influences lead to a change in the gain $\tilde{\kappa}_1$ and the appearance of zero-drift u_{10}. Then the equation of the perturbed motion of the servo will be

$$\tilde{x}_1(k+1) = \tilde{x}_1(k) + \tilde{\kappa}_1 T_0 u(k) + u_{10}. \qquad (15)$$

In order to localize the inoperable state of the servo, a diagnostic model is used, described by the equation obtained by subtraction of the operable state equation (14) from equation (15):

$$\Delta x_1(k+1) = \Delta x_1(k) + \Delta \kappa_1 T_0 u(k) + u_{10}. \qquad (16)$$

The down and up states are set using a boolean variable whose value is determined by a two-digit predicate equation

$$z_1 = S_2 \left\{ \left| \Delta x_1(k) \right| \geq \delta_1 \right\}, \ k = \overline{k_1, k_2}, \ p. \qquad (17)$$

When the condition of the argument is met, $z_1 = 1$, which means that the servo is inoperable. If $z_1 = 0$, then the servo is operational.

Using the assumptions about the one-time and independence of destabilizing effects on the diagnosing interval, the influence of the change and zero-drift x_{10} on the deviation of the output signal $\tilde{x}_1(k)$ can be analyzed separately. Assuming that there has been a change in the gain, the disturbed motion equation will be

$$\tilde{x}_1(k+1) = \tilde{x}_1(k) + \tilde{\kappa}_1 T_0 u(k). \qquad (18)$$

If subtract the equation describing the nominal mode of operation (11) from equation (18), then

$$\Delta x_1(k+1) = \Delta x_1(k) + \Delta \kappa_1 T_0 u(k), \qquad (19)$$

where $\Delta x_1(k) = \tilde{x}_1(k) - x_1(k)$,

$$\Delta \kappa_1(k) = \tilde{\kappa}_1(k) - \kappa_1(k).$$

The resulting equation describes the relation between the direct sign of diagnosing $\Delta \kappa_1$ and indirect sign $\Delta x_1(k)$ and is a diagnostic model of the inoperable state of the servo when the gain is destabilized.

The inoperable state caused by zero-drift is described by an appropriate diagnostic model

$$\Delta x_1(k+1) = \Delta x_1(k) + u_{10}. \qquad (20)$$

The presented diagnostic models are used to determine the type of destabilization, in other words, it is possible to establish the cause of destabilization: by changing the gain $\Delta \kappa_1$ or the appearance of zero-drift u_{10}. As a result of the assumption that direct signs are quasi-stationary on the diagnosing interval, based on equation (19), the following equation can be obtained

$$\frac{\Delta x_1(k+1) - \Delta x_1(k)}{T_0 u(k)} \approx \frac{\Delta x_1(k+2) - \Delta x_1(k+1)}{T_0 u(k+1)}. \qquad (21)$$

From this relation, the argument of a two-digit predicate equation is

$$z_2 = S_2 \left\{ \left| \Delta x_1(k+2) u(k) - \Delta x_1(k+1) \left[u(k+1) + u(k) \right] + \right. \right.$$
$$\left. \left. + \Delta x_1(k) u(k+1) \right| \geq \delta_2 \right\}, \ k = \overline{k_1, k_2}, \ p. \qquad (22)$$

The logical variable takes the value $z_2 = 1$ if the servo malfunctions due to a change in the gain κ_1. If $z_2 = 0$, then the malfunction of the servo occurred as a result of the appearance of a zero-drift u_{10}.

Similarly, the two-digit predicate equation is formed based on the diagnostic model (20). Then

$$z_3 = S_2 \left\{ \left| \Delta x_1(k+2) - 2\Delta x_1(k+1) + \Delta x_1(k) \right| \geq \delta_3 \right\};$$
$$k = \overline{k_1, k_2}, \ p. \qquad (23)$$

If $z_3 = 1$, then the malfunction of the servo occurred as a result of the appearance of a zero-drift u_{10}. If $z_3 = 0$ the violation is caused by a change in the gain κ_1.

Predicate equations are used in the formation of a dichotomous search tree for the causes of a violation of the VES device performance.

For deep diagnostics of the servo for the purpose of subsequent recovery of performance, it is necessary to know the values of destabilization. From the diagnostic model (19), one can obtain an equation for the for-

mation of the estimated value of the change in the gain in the form

$$\Delta\kappa_1(k) = \frac{\Delta x_1(k+1) - \Delta x_1(k)}{T_0 u(k)}, \quad (24)$$

where $\Delta\kappa_1(k)$ is a per sample gain deviation value of servo. In order to obtain the estimated value, the procedure of arithmetic mean averaging is used

$$\Delta\hat{\kappa}_1 = \frac{1}{m}\sum_{k=1}^{m}\Delta\kappa_1(k). \quad (25)$$

In a similar way, the estimated zero-drift value is determined

$$u_{10}(k) = \Delta x_1(k+1) - \Delta x_1(k);$$
$$\hat{u}_{10} = \frac{1}{m}\sum_{k=1}^{m}u_{10}(k). \quad (26)$$

In order to use the above algorithms, it is necessary to access the variable $x_1(k)$, which follows from the device diagnosability condition, which is obvious from the block diagram (Fig. 8). Therefore, for diagnosability, the valve position sensor $\mu(t)$ is required, since $x_1(t) = \mu(t)$. The output signal of the sensor $u_\mu(k)$ must be brought to the state variable in such a way

$$\frac{u_\mu(k)}{\kappa_\mu} = x_1(k), \quad (27)$$

where κ_μ is a gain of displacement sensor.

The presented diagnostic models of the servo (12), (16), (19) and (20) make it possible to analytically solve the problems of detection, localization, establishing the type and kind of destabilizing effects.

VES. In the nominal mode, the conversion processes are described by two recurrent equations:

$$x_2(k+1) = \left(1 - \frac{T_0}{T_2}\right)x_2(k) + \frac{\kappa_2 T_0}{T_2}x_1(k); \quad (28)$$

$$x_3(k+1) = \left(1 - \frac{T_0}{T_3}\right)x_3(k) + \frac{\kappa_3 T_0}{T_3}x_1(k). \quad (29)$$

Further, the formation of diagnostic models based on equation (28) will be considered. The destabilizing effects of VES in the channel for measuring the cold air flow leads to a change in the gain $\tilde{\kappa}_2$, time constant $\tilde{T}_2$ and the drift of operation point θ_{10}. The equations of

perturbed motion of the transformation process will take the form

$$\tilde{x}_2(k+1) = \left(1 - \frac{T_0}{\tilde{T}_2}\right)\tilde{x}_2(k) +$$
$$+ \frac{\tilde{\kappa}_2 T_0}{\tilde{T}_2}x_1(k) + \left(1 - \frac{T_0}{\tilde{T}_2}\right)\theta_{10}. \quad (30)$$

In order to localize the inoperable state of the VES when using measurements of the cold air flow temperature sensor, a diagnostic model is used, described by the equation

$$\Delta x_2(k+1) = \left[\frac{T_0}{T_2^2}x_2(k) - \frac{\kappa_2 T_0}{T_2^2}x_1(k)\right]\Delta T_2 +$$
$$+ \frac{\Delta\kappa_2 T_0}{T_2}x_1(k) + \left(1 - \frac{T_0}{T_2}\right)\theta_{10}. \quad (31)$$

This equation describes the analytical relation of signal deviation Δx_2 and deviation of parameters $\Delta\kappa_2$, ΔT_2 and θ_{10} reflecting the inoperable state of the VES. The fact of an inoperable state is determined using a two-digit predicate equation

$$z_4 = S_2\left\{\left|\Delta x_2(k)\right| \geq \delta_4\right\}, \ k = \overline{k_1, k_2}, \ p. \quad (32)$$

The inoperable state of the VES corresponds to $z_4 = 1$, and workable corresponds to $z_4 = 0$.

As follows from the graphs of static characteristics (Fig. 4), a change in pressure leads to the drift of operation point of the VES. When the operation point is shifted, the parameters change $\tilde{\kappa}_2$ and θ_{10}, therefore, the equation of perturbed motion has the form

$$\tilde{x}_2(k+1) = \left(1 - \frac{T_0}{T_2}\right)\tilde{x}_2(k) +$$
$$+ \frac{\tilde{\kappa}_2 T_0}{T_2}x_1(k) + \left(1 - \frac{T_0}{T_2}\right)\theta_{10}. \quad (33)$$

By subtracting equation (28) from equation (33), the diagnostic model of VES is determined when the operation point is shifted

$$\Delta x_2(k+1) = \left(1 - \frac{T_0}{T_2}\right)\Delta x_2(k) +$$
$$+ \frac{\Delta\kappa_2 T_0}{T_2}x_1(k) + \left(1 - \frac{T_0}{T_2}\right)\theta_{10}. \quad (34)$$

Applying this diagnostic model to the next discrete, one can obtain point values of direct signs $\Delta\kappa_2$ and θ_{10}:

$$\Delta\kappa_2(k+2) = \frac{\Delta x_2(k+2) - \left(2 - \frac{T_0}{T_2}\right)\Delta x_2(k+1)}{\frac{T_0}{T_2}\left[x_1(k+1) - x_1(k)\right]} + \\ + \frac{\left(1 - \frac{T_0}{T_2}\right)\Delta x_2(k)}{\frac{T_0}{T_2}\left[x_1(k+1) - x_1(k)\right]}; \quad (35)$$

$$\theta_{10}(k+2) = \frac{\Delta x_2(k+2) - \left(1 - \frac{T_0}{T_2}\right)\Delta x_2(k+1)}{\left(1 - \frac{T_0}{T_2}\right)\left[x_1(k) - x_1(k+1)\right]} + \\ + \frac{\left(1 - \frac{T_0}{T_2}\right)\Delta x_2(k)}{\left(1 - \frac{T_0}{T_2}\right)\left[x_1(k) - x_1(k+1)\right]}. \quad (36)$$

Using the least squares method, the average values $\Delta\hat{\kappa}_2$ and $\hat{\theta}_{10}$ can be calculated.

Under destabilizing influences that change the inertial properties of the VES, the equation of the perturbed motion of the transformation process takes the form

$$\tilde{x}_2(k+1) = \left(1 - \frac{T_0}{\tilde{T}_2}\right)\tilde{x}_2(k) + \frac{\kappa_2 T_0}{\tilde{T}_2}x_1(k). \quad (37)$$

Then the diagnostic model for such a case

$$\Delta x_2(k+1) = \left[\frac{T_0}{T_2^2}x_2(k) - \frac{\kappa_2 T_0}{T_2^2}x_1(k)\right]\Delta T_2. \quad (38)$$

This diagnostic model is used to determine the type of destabilization associated with a change in the inertial properties of the VES. So, from the relation

$$\frac{\Delta x_2(k+1)}{\frac{T_0}{T_2^2}\left[x_2(k) - \kappa_2 x_1(k)\right]} \approx \\ \approx \frac{\Delta x_2(k+2)}{\frac{T_0}{T_2^2}\left[x_2(k+1) - \kappa_2 x_1(k+1)\right]} \quad (39)$$

the two-digit predicate argument

$$z_5 = S_2\left\{\left|\Delta x_2(k+2)\left[x_2(k) - \kappa_2 x_1(k)\right] - \\ -\Delta x_2(k+1)\left[x_2(k+1) - \kappa_2 x_1(k+1)\right]\right| \geq \delta_5\right\}; \quad (40)$$

$$k = \overline{k_1, k_2}, \; p$$

is formed.

The boolean variable will take on the value $z_5 = 1$ if the predicate equation argument condition is met. If $z_5 = 0$, then this means that the condition is not fulfilled and, consequently, the type of destabilization under consideration is absent.

In order to determine the magnitude of the change in inertial properties, the following equation is used

$$\Delta T_2(k+2) = \frac{T_2^2 \Delta x_2(k+1)}{T_0\left[x_2(k) - \kappa_2 x_1(k)\right]}. \quad (41)$$

Estimated value is determined using the root-mean-square averaging procedure

$$\Delta\hat{T}_2 = \frac{1}{m}\sum_{k=1}^{m}\Delta T_2(k). \quad (42)$$

The diagnostic model uses the variable $\Delta x_2(k+1) = \tilde{x}_2(k+1) - x_2(k)$. The value of the variable $\tilde{x}_2$ can be obtained using the equations for the cold air flow temperature sensor nominal mode.

Next, the features of the formation of diagnostic models of VES will be considered, based on equation (29). Various destabilizing effects lead to a change in the gain $\tilde{\kappa}_3$, time constant $\tilde{T}_3$ and the appearance of drift of the operation point θ_{20}. Therefore, the equations of the perturbed transformation process will be

$$\tilde{x}_3(k+1) = \left(1 - \frac{T_0}{\tilde{T}_3}\right)\tilde{x}_3(k) + \frac{\kappa_3 T_0}{\tilde{T}_3}x_1(k) + \left(1 - \frac{T_0}{\tilde{T}_3}\right)\theta_{20}. \quad (43)$$

The parameters of equations (37) and (38) are interconnected, since they describe the process of generating cold and hot air flows at the outlet of the VES. Therefore, the deviation from the workable state in one air flow. In this regard, it is possible to localize the inoperable state of the VES using the diagnostic model (31) and the predicate equation (32).

Destabilizations leading to a change in parameters $\tilde{\kappa}_3$ and θ_{20}, affect the output signal of the VES as follows

$$\tilde{x}_3(k+1) = \left(1 - \frac{T_0}{T_3}\right)\tilde{x}_3(k) + \frac{\tilde{\kappa}_3 T_0}{T_3}x_1(k) + \left(1 - \frac{T_0}{T_3}\right)\theta_{20}. \quad (44)$$

Then the diagnostic model of VES with a drift of the operation point has the form

$$\Delta x_3(k+1) = \left(1 - \frac{T_0}{T_3}\right)\Delta x_3(k) + $$
$$+ \frac{\Delta \kappa_3 T_0}{T_3} x_1(k) + \left(1 - \frac{T_0}{T_3}\right)\theta_{20}. \tag{45}$$

Using this equation, the per sample value of the parameters can be calculated

$$\Delta \kappa_3(k+2) = \frac{\Delta x_3(k+2) - \left(2 - \frac{T_0}{T_3}\right)\Delta x_3(k+1)}{\frac{T_0}{T_3}\left[x_1(k+1) - x_1(k)\right]} + $$
$$+ \frac{\left(1 - \frac{T_0}{T_3}\right)\Delta x_3(k)}{\frac{T_0}{T_3}\left[x_1(k+1) - x_1(k)\right]}; \tag{46}$$

$$\theta_{20}(k+3) = \frac{\Delta x_3(k+2) - \left(1 - \frac{T_0}{T_3}\right)\Delta x_3(k+1)}{\left(1 - \frac{T_0}{T_3}\right)\left[x_1(k) - x_1(k+1)\right]} + $$
$$+ \frac{\left(1 - \frac{T_0}{T_3}\right)\Delta x_3(k)}{\left(1 - \frac{T_0}{T_3}\right)\left[x_1(k) - x_1(k+1)\right]}. \tag{47}$$

Using the least squares method, having formed an excess system of equations for various quantization cycles, one can obtain the corresponding estimates of parameter changes $\tilde{\kappa}_3$ and θ_{20}.

The change in the inertial properties of the VES for the channel for measuring the hot air flow is described by the equation

$$\tilde{x}_3(k+1) = \left(1 - \frac{T_0}{\tilde{T}_3}\right)\tilde{x}_3(k) + \frac{\kappa_3 T_0}{\tilde{T}_3} x_1(k). \tag{48}$$

The diagnostic model for the case under consideration has the form

$$\Delta x_3(k+1) = \left[\frac{T_0}{T_3{}^2} x_3(k) - \frac{\kappa_3 T_0}{T_3{}^2} x_1(k)\right]\Delta T_3. \tag{49}$$

This diagnostic model is used to determine the type of destabilization by using the relation

$$\frac{\Delta x_3(k+1)}{\frac{T_0}{T_3{}^2}\left[x_3(k) - \kappa_3 x_1(k)\right]} \approx$$
$$\approx \frac{\Delta x_3(k+2)}{\frac{T_0}{T_3{}^2}\left[x_3(k+1) - \kappa_3 x_1(k+1)\right]} \tag{50}$$

with the help of which a logical variable is formed

$$z_6 = S_2\left\{\left|\Delta x_3(k+2)\left[x_3(k) - \kappa_3 x_1(k)\right] - \right.\right.$$
$$\left.\left. -\Delta x_3(k+1)\left[x_3(k+1) - \kappa_3 x_1(k+1)\right]\right| \geq \delta_6\right\}; \tag{51}$$
$$k = \overline{k_1, k_2}, \, p.$$

If $z_4 = 1$, the type of destabilization is set, which led to a change in the inertial properties of the VES in the channel for measuring the hot air flow. If $z_4 = 0$, then this means that there is no change in the inertial properties of the VES.

The per sample value of the change in inertial properties, based on equation (41), is calculated by the equation

$$\Delta T_3(k+2) = \frac{T_3{}^2 \Delta x_3(k+1)}{T_0\left[x_3(k) - \kappa_3 x_1(k)\right]}. \tag{52}$$

Estimated value is determined as the result of root-mean-square averaging

$$\Delta \hat{T}_3 = \frac{1}{m}\sum_{k=1}^{m}\Delta T_3(k). \tag{53}$$

The diagnostic model uses the variable $\Delta x_3(k+1) = \tilde{x}_3(k+1) - x_3(k)$. The value of the variable $\tilde{x}_3$ can be obtained using the equations for the hot air temperature sensor nominal mode.

The presented diagnostic models of VES are used in the formation of nodes of the dichotomous search tree for the reasons for the inoperable state of VES.

Temperature sensors. The cold air flow temperature sensor in accordance with the block diagram (Fig. 8) is described by the following equation

$$x_4(k+1) = \left(1 - \frac{T_0}{T_4}\right)x_4(k) + \frac{\kappa_4 T_0}{T_4} x_2(k). \tag{54}$$

Various destabilizing effects lead to a malfunction and manifest themselves in the form of a change in the parameters $\tilde{\kappa}_4$ and $\tilde{T}_4$, as well as a drift of the operation point u_{10}.

Perturbed motion equation for the sensor

$$\tilde{x}_4\left(k{+}1\right) = \left(1 - \frac{T_0}{\tilde{T}_4}\right)\tilde{x}_4\left(k\right) + \frac{\tilde{\kappa}_4 T_0}{\tilde{T}_4}x_2\left(k\right) + \left(1 - \frac{T_0}{\tilde{T}_4}\right)u_{10}. \quad (55)$$

The diagnostic model is described by the equation

$$\Delta x_4\left(k{+}1\right) = \left[x_4\left(k\right) - \kappa_4 x_2\left(k\right)\right]\frac{T_0}{T_4^{\,2}}\Delta T_4 +$$
$$+ \frac{\Delta \kappa_4 T_0}{T_4}x_2\left(k\right) + \left(1 - \frac{T_0}{T_4}\right)u_{10}, \quad (56)$$

reflecting relation deviation of sensor output $\Delta x_4\left(k{+}1\right)$ with deviation of parameters $\Delta \kappa_4$, ΔT_4 and u_{10}. The cold air flow temperature sensor inoperative state is established by a two-digit predicate equation

$$z_7 = \left\{\left|\Delta x_4\left(k\right)\right| \geq \delta_7\right\}, \; k = \overline{k_1, k_2}, \; p. \quad (57)$$

When the condition of the argument is met p times on the diagnosing interval $\left[k_1, k_2\right]$ $z_7 = 1$, which means the inoperative state of this sensor. Otherwise, $z_7 = 0$ indicates its workable state.

The assumption of a one-time and independent change of parameters in the diagnosing interval allows us to consider diagnostic models for each parameter separately.

The change in the gain $\tilde{\kappa}_4$ leads to a deviation from the reference behavior and is described by the equation

$$\Delta x_4\left(k{+}1\right) = \left(1 - \frac{T_0}{T_4}\right)\Delta x_4\left(k\right) + \frac{\Delta \kappa_4 T_0}{T_4}x_2\left(k\right) \quad (58)$$

that describes a diagnostic model that reflects the analytical relation of a direct sign $\Delta \kappa_4$ with an indirect sign of diagnosis $\Delta x_4\left(k\right)$. With the help of this model, it is possible to establish the presence of a direct sign that is not available for measurement, using an indirect sign that is available for measurement. Based on the condition of quasi-stationarity, the following relation is determined

$$\frac{\Delta x_4\left(k{+}1\right) - \left(1 - \dfrac{T_0}{T_4}\right)\Delta x_4\left(k\right)}{\dfrac{T_0}{T_4}x_2\left(k\right)} \approx$$

$$\approx \frac{\Delta x_4\left(k{+}2\right) - \left(1 - \dfrac{T_0}{T_4}\right)\Delta x_4\left(k{+}1\right)}{\dfrac{T_0}{T_4}x_2\left(k{+}1\right)}. \quad (59)$$

From this relation, a two-digit predicate equation is formed

$$z_8 = S_2\left\{\left|\left[\Delta x_4\left(k{+}2\right) - \left(1 - \frac{T_0}{T_4}\right)\Delta x_4\left(k{+}1\right)\right]\Delta x_2\left(k\right) - \right.\right.$$
$$\left.\left. - \left[\Delta x_4\left(k{+}1\right) - \left(1 - \frac{T_0}{T_4}\right)\Delta x_4\left(k\right)\right]\Delta x_2\left(k{+}1\right)\right| \geq \delta_8\right\}; \quad (60)$$
$$k = \overline{k_1, k_2}, \; p.$$

If the predicate argument condition is met, then $z_8 = 1$, which means that the sensor has a deviation of the gain $\Delta \kappa_4$. If $z_8 = 0$ coefficient deviation is absent.

From equation (58), an expression is determined for calculating per sample values of the deviation of the gain

$$\Delta \kappa_4\left(k{+}2\right) = \frac{\Delta x_4\left(k{+}1\right) - \left(1 - \dfrac{T_0}{T_4}\right)\Delta x_4\left(k\right)}{\dfrac{T_0}{T_4}x_2\left(k\right)}. \quad (61)$$

The estimated value of change of the gain is a root-mean-square averaging

$$\Delta \hat{\kappa}_4 = \frac{1}{m}\sum_{k=1}^{m}\Delta \kappa_4\left(k\right). \quad (62)$$

The values of variable $x_2\left(k\right)$ are obtained as a result of solving the equation for the servo and the VES. In other words, this is the output of the reference model, which converts the control signal $u(k)$ into the output signal of the VES in the nominal mode $x_2(k)$.

A change in the time constant leads to a deviation in the output signal of the cold air temperature sensor $\Delta x_4\left(k\right)$, which is described by the equation

$$\Delta x_4\left(k{+}1\right) = \left[\frac{T_0}{T_4^{\,2}}x_4\left(k\right) - \frac{\kappa_4 T_0}{T_4}x_2\left(k\right)\right]\Delta T_4, \quad (63)$$

which is a diagnostic model that reflects the relation of the direct diagnostic sign ΔT_4, which is unmeasurable, with the indirect sign $\Delta x_4\left(k\right)$, which is measurable. With this diagnostic model, a two-digit predicate equa-

tion is formed to establish the type, that is, the change in the time constant,

$$z_9 = S_2 \left\{ \left| \Delta x_4\left(k+2\right)\left[x_4\left(k\right) - \kappa_4 x_2\left(k\right)\right] - \right. \right.$$
$$\left. \left. -\Delta x_4\left(k+1\right)\left[\Delta x_4\left(k+1\right) - \kappa_4 x_2\left(k+1\right)\right]\right| \geq \delta_9 \right\}; \quad (64)$$
$$k = \overline{k_1, k_2}, \text{ p.}$$

If $z_9 = 1$, then it means that there is a time constant deviation T_4. If $z_9 = 0$, then the time constant deviation is absent.

Equation (59) gives an expression for the calculation of the deviation

$$\Delta T_4\left(k+2\right) = \frac{T_4{}^2 \Delta x_4\left(k+1\right)}{T_0\left[x_4\left(k\right) - \kappa_4 x_2\left(k\right)\right]}, \quad (65)$$

then the estimated average value of the deviation

$$\Delta \hat{T}_4 = \frac{1}{m} \sum_{k=1}^{m} \Delta T_4\left(k\right). \quad (66)$$

The variable $x_2(k)$ is an output signal of the corresponding reference model.

The occurrence of a drift in the operation point u_{10} leads to a deviation in the output signal of the sensor, which is described by the equation

$$\Delta x_4\left(k+1\right) = \left(1 - \frac{T_0}{T_4}\right)\Delta x_4\left(k\right) + \left(1 - \frac{T_0}{T_4}\right)u_{10}. \quad (67)$$

The presence of that drift is established with the help of predicate equation using the values of the deviation signal

$$z_{10} = S_2 \left\{ \left| \Delta x_4\left(k+2\right) - \left(2 - \frac{T_0}{T_4}\right)\Delta x_4\left(k+1\right) + \right. \right.$$
$$\left. \left. + \left(1 - \frac{T_0}{T_4}\right)\Delta x_4\left(k\right)\right| \geq \delta_{10} \right\}; \quad (68)$$
$$k = \overline{k_1, k_2}, \text{ p.}$$

Then, if $z_{10} = 1$, the drift of operation point is present. If $z_{10} = 0$ the drift is absent.

The per sample value of the drift is calculated using the equation

$$u_{10}\left(k+2\right) = \frac{\Delta x_4\left(k+1\right) - \left(1 - \dfrac{T_0}{T_4}\right)\Delta x_4\left(k\right)}{1 - \dfrac{T_0}{T_4}} \quad (69)$$

and the average estimated value of the drift

$$\hat{u}_{10} = \frac{1}{m} \sum_{k=1}^{m} u_{10}\left(k\right). \quad (70)$$

The presented diagnostic models of the cold air flow temperature sensor are used, as shown, in the formation of logical variable nodes of the dichotomous diagnostic tree.

Diagnostic models of the hot air temperature sensor are formed based on the equation

$$x_5\left(k+1\right) = \left(1 - \frac{T_0}{T_5}\right)x_5\left(k\right) + \frac{\kappa_5 T_0}{T_5}x_3\left(k\right) \quad (71)$$

that describe the nominal mode of the temperature conversion process $\theta_2(k)$ into voltage $u_2(k)$. Inoperable states are described by the perturbed motion equation

$$\tilde{x}_5\left(k+1\right) = \left(1 - \frac{T_0}{\tilde{T}_5}\right)\tilde{x}_5\left(k\right) + \frac{\tilde{\kappa}_5 T_0}{\tilde{T}_5}x_3\left(k\right) + \left(1 - \frac{T_0}{\tilde{T}_5}\right)u_{20}, (72)$$

where $\tilde{\kappa}_5$, $\tilde{T}_5$ and u_{20} are the parameters reflecting sensor destabilization.

The deviation of the perturbed motion relative to the nominal (71) is described by the following equation

$$\Delta x_5\left(k+1\right) = \left[x_5\left(k\right) - \kappa_5 x_3\left(k\right)\right]\frac{T_0}{T_5{}^2}\Delta T_5 +$$
$$+ \frac{\Delta \kappa_5 T_0}{T_5}x_3\left(k\right) + \left(1 - \frac{T_0}{T_5}\right)u_{20}, \quad (73)$$

which is a diagnostic model used in solving the localization problem. Thus, the two-digit predicate equation

$$z_{11} = \left\{ \left| \Delta x_5\left(k\right)\right| \geq \delta_{11} \right\}, \ k = \overline{k_1, k_2}, \text{ p} \quad (74)$$

allows you to distinguish between an inoperable state, if $z_{11} = 1$, and workable state, if $z_{11} = 0$.

Assumption of independence of change in direct signs of the inoperable state $\Delta \kappa_5$, ΔT_5 and u_{20} allows to consider diagnostic models for each direct sign.

The appearance of deviation of the inertial property of the sensor ΔT_5 leads to a deviation of its output signal in accordance with the equation

$$\Delta x_5\left(k+1\right) = \frac{T_0}{T_5{}^2}\left[x_5\left(k\right) - \kappa_5 x_3\left(k\right)\right]\Delta T_5. \quad (75)$$

This equation is a diagnostic model that relates the deviation of the direct sign ΔT_5, unmeasurable, with the indirect sign $\Delta x_5(k+1)$, measurable. This model allows

us to form an argument of a two-digit predicate equation to establish the type of destabilization

$$z_{12} = S_2 \left\{ \left| \Delta x_5(k+2) \left[x_5(k) - \kappa_5 x_3(k) \right] - \right. \right.$$
$$\left. \left. - \Delta x_5(k+1) \left[\Delta x_5(k+1) - \kappa_5 x_3(k+1) \right] \right| \geq \delta_{12} \right\}; \quad (76)$$
$$k = \overline{k_1, k_2}, \ p.$$

If $z_{12} = 1$, then it means that there is a deviation in the time constant ΔT_5. Otherwise, $z_{12} = 0$ means the absence of this deviation.

Changing the gain $\tilde{\kappa}_5$ causes changes in the output signal of the sensor $\tilde{x}_5(k)$ and in terms of deviations from the nominal equation is described as follows

$$\Delta x_5(k+1) = \left(1 - \frac{T_0}{T_5} \right) \Delta x_5(k) + \frac{\Delta \kappa_5 T_0}{T_5} x_3(k). \quad (77)$$

Establishing the type of this parameter deviation is carried out by means of a two-digit predicate equation

$$z_{13} = S_2 \left\{ \left| \left[\Delta x_5(k+2) - \left(1 - \frac{T_0}{T_5} \right) \Delta x_5(k+1) \right] \Delta x_3(k) - \right. \right.$$
$$\left. \left. - \left[\Delta x_5(k+1) - \left(1 - \frac{T_0}{T_5} \right) \Delta x_5(k) \right] \Delta x_3(k+1) \right| \geq \delta_{13} \right\}; \quad (78)$$
$$k = \overline{k_1, k_2}, \ p.$$

If $z_{13} = 1$ there is an appearance in the deviation sensor of the gain $\Delta \kappa_5$. If $z_{13} = 0$ this deviation is absent.

The drift of the sensor operation point by u_{20} leads to a deviation of the output signal in accordance with the equation

$$\Delta x_5(k+1) = \left(1 - \frac{T_0}{T_5} \right) \Delta x_5(k) + \left(1 - \frac{T_0}{T_5} \right) u_{20}, \quad (79)$$

which is a diagnostic model for the direct sign of diagnosis, which is not available for measurement.

It is possible to establish the presence of the drift of operation point by the available measurement of the output signal using the diagnostic model (79) and the two-digit predicate equation

$$z_{14} = S_2 \left\{ \left| \Delta x_5(k+2) - \left(2 - \frac{T_0}{T_5} \right) \Delta x_5(k+1) + \right. \right.$$
$$\left. \left. + \left(1 - \frac{T_0}{T_5} \right) \Delta x_5(k) \right| \geq \delta_{14} \right\}; \ k = \overline{k_1, k_2}, \ p. \quad (80)$$

If the conditions of the argument of the predicate equation are satisfied, then $z_{14} = 1$, which indicates the

occurrence of the drift if operation point of the hot air flow sensor. If $z_{14} = 0$, then the operation point drift is absent.

The above diagnostic models are used to obtain estimated values of direct signs of diagnosis. So, from equation (75), the equation is determined for the calculation of the deviation value

$$\Delta T_5(k+2) = \frac{T_5^2 \Delta x_5(k+1)}{T_0 \left[x_5(k) - \kappa_5 x_3(k) \right]}, \quad (81)$$

then the estimated average value of the deviation

$$\Delta \hat{T}_5 = \frac{1}{m} \sum_{k=1}^{m} \Delta T_5(k). \quad (82)$$

Then from equation (77) the formula for the calculation of the deviation of the gain is determined

$$\Delta \kappa_5(k+2) = \frac{\Delta x_5(k+1) - \left(1 - \frac{T_0}{T_5} \right) \Delta x_5(k)}{\frac{T_0}{T_5} x_3(k)}. \quad (83)$$

The estimated value of change of the gain is a root-mean-square averaging

$$\Delta \hat{\kappa}_5 = \frac{1}{m} \sum_{k=1}^{m} \Delta \kappa_5(k). \quad (84)$$

The drift of operation point from equation (79) is defined as

$$u_{20}(k+2) = \frac{\Delta x_5(k+1) - \left(1 - \frac{T_0}{T_5} \right) \Delta x_5(k)}{1 - \frac{T_0}{T_5}} \quad (85)$$

and the estimated value

$$\hat{u}_{20} = \frac{1}{m} \sum_{k=1}^{m} u_{20}(k). \quad (86)$$

For a complete diagnosis of the VES device, knowledge is required not only of the estimated values of the direct signs of diagnosis, but also of the kinds of destabilization. As a rule, in practice it is enough to know two kinds of destabilizations. The first one is when the deviation of the direct sign can be compensated by means of signal adjustment. The second, when the deviation of the direct sign cannot be compensated, is the non-compensated kind, which is parried by means

of algorithmic or hardware reconfiguration. Two-digit equations are used to determine these kinds. So, for example, to determine the kinds of changes in the inertial properties of the hot air flow sensor, a two-digit predicate equation is used

$$z_{15} = S_2 \left\{ \Delta \hat{T}_5 \geq \Delta \overline{T}_5 \right\}, \qquad (87)$$

where $\Delta \overline{T}_5$ is threshold value of a kind. $z_{15} = 1$ indicates an uncompensated deviation of the time constant T_5, and $z_{15} = 0$ indicates the kind of deviation to be compensated.

Boolean variables z_i, obtained when solving problems of diagnosing using diagnostic models, make it possible to form a procedure for searching for the reasons for the inoperable state of the VES device in the form of a dichotomous tree. The dichotomous tree, in fact, is a structured production knowledge base of emergency situations with the rules of inference about the causes, that is, about the diagnosis. The diagnostic module (Fig. 3) implements a dichotomous diagnostic tree, and the obtained diagnosis $\hat{D}$ enters the control module, in which the corresponding control signals are generated $u_c(kT_0)$ and $u_o(kT_0)$ which allow to recover the operability of the VES device and, thereby, to carry out rational control under conditions of destabilizing influences.

Conclusions

Conducted theoretical and experimental studies on the application of the control principle by diagnosis of the VES device made it possible to form a number of linear discrete mathematical models of inoperable states are the digital diagnostic models. They make it possible to proceed to the analytical solution of the problems of microprocessor diagnostics of the VES device and to form machine-implemented procedures for microprocessor diagnostics with depth up to the type of destabilizing effect in real time. The diagnosis obtained serves as the basis for the development of algorithms for rational control of the VES device performance in emergency situations caused by various destabilizing effects.

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ДІАГНОСТИЧНІ МОДЕЛІ НЕПРАЦЕЗДАТНИХ СТАНІВ ПРИСТРОЮ ВИХРОВОГО ЕНЕРГОРОЗДІЛЬНИКА

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Об'єктом дослідження у статті є вихровий ефект температурного поділу у потоці газу, що обертається, який реалізується у малогабаритних вихрових енергороздільниках. **Предметом** вивчення в статті є процес формування діагностичних моделей непрацездатних станів пристрою вихрового енергороздільника як раціонального об'єкта управління при появі дестабілізуючих впливів. **Метою** є розробка аналітичного підходу до формування цифрових діагностичних моделей раціонального управління температурою потоків холодного та гарячого повітря, що відображають вплив недоступних вимірюванням прямих ознак непрацездатних станів пристрою вихрового енергороздільника з непрямими ознаками, що доступні вимірюванням. **Задачі**: дослідити особливості процесу у пристрої вихрового енергороздільника; провести аналіз експериментальних характеристик пристрою вихрового енергороздільника; описати раціональну систему управління вихровим енергороздільником; провести аналіз експериментальних характеристик пристрою вихрового роздільника; сформувати лінійні математичні моделі номінального режиму роботи пристрою вихрового енергороздільника; розробити лінійні діагностичні моделі, що описують непрацездатні стани вихрового енергороздільника як раціонального об'єкта управління; сформувати логічні ознаки діагностування за допомогою діагностичних моделей. Використовуваними **методами** є: метод передавальних функцій, метод простору дискретних станів, метод діагностичних моделей, метод формування продукційних правил, метод формування двозначних предикатних рівнянь. Отримано наступні **результати**: сформовані лінійні математичні моделі функціональних елементів та всього пристрою загалом для номінального режиму функціонування. Розроблено лінійні цифрові діагностичні моделі для непрацездатних станів вихрового енергороздільника. Сформовано логічні ознаки діагностування на основі діагностичних моделей. **Висновки**. Наукова новизна полягає у формуванні аналітичного підходу до розробки цифрових діагностичних моделей непрацездатних станів пристрою вихрового енергороздільника та двозначних предикатних рівнянь непрямих ознак для дихотомічного дерева діагностування.

Ключові слова: пристрій вихрового енергороздільника; раціональне управління; дестабілізуючі впливи; лінійні математичні моделі; цифрові діагностичні моделі; двозначні предикатні рівняння.

ДИАГНОСТИЧЕСКИЕ МОДЕЛИ НЕРАБОТОСПОСОБНЫХ СОСТОЯНИЙ УСТРОЙСТВА ВИХРЕВОГО ЭНЕРГОРАЗДЕЛИТЕЛЯ

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Объектом исследования в статье является вихревой эффект температурного разделения во вращающемся потоке газа, который реализуется в малогабаритных вихревых энергоразделителях. **Предметом** изучения в статье является процесс формирования диагностических моделей неработоспособных состояний устройства вихревого энергоразделителя как рационального объекта управления при появлении дестабилизирующих воздействий. **Целью** является разработка аналитического подхода к формированию цифровых диагностических моделей рационального управления температурой потоков холодного и горячего воздуха, отражающих влияния недоступных измерению прямых признаков неработоспособных состояний устройства вихревого энергоразделителя с косвенными признаками, доступными измерению. **Задачи**: исследовать особенности процесса в устройстве вихревого энергоразделителя; описать рациональную систему управления устройством вихревого энергоразделителя; провести анализ экспериментальных характеристик устройства вихревого энергоразделителя; сформировать линейные математические модели номинального режима работы устройства вихревого энергоразделителя; разработать линейные диагностические модели, описывающие неработоспособные состояния вихревого энергоразделителя как рационального объекта управления; сформировать логические признаки диагностирования с использованием диагностических моделей. Используемыми **методами** являются: метод передаточных функций, метод пространства дискретных состояний, метод диагностических моделей, метод формирования продукционных правил, метод формирования двузначных предикатных уравнений. Получены следующие **результаты**: сформированы линейные математические модели функциональных элементов и всего устройства в целом для номинального режима функционирования. Разработаны линейные цифровые диагностические модели для неработоспособных состояний устройства вихревого энергоразделителя. Сформированы логические признаки диагностирования на основе диагностических моделей. **Выводы**. Научная новизна заключается в формировании аналитического подхода к разработке цифровых диагностических моделей неработоспособных состояний устройства вихревого энергоразделителя и двузначных предикатных уравнений косвенных признаков для дихотомического дерева диагностирования.

Ключевые слова: устройство вихревого энергоразделителя; рациональное управление; дестабилизирующие воздействия; линейные математические модели; цифровые диагностические модели; двузначные предикатные уравнения.

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