Non-destructive control of complex semiconductor structures of radio electronic equipment with feedback circuits

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Abstract

The article analyzes the possibility of using non-destructive testing methods (namely thermal methods) to solve the main problems of technical diagnostics, such as: regulation of technical condition, fault localization and forecasting. Semiconductor radio-electronic equipment is selected as the object of control. It is fundamentally important to have in the object of control elements of feedback, which make it impossible to solve the problem of determining the technical condition using the methods of functional control. It is of the utmost importance that modern radio-electronic equipment is created using large integrated circuits, and defining a separate functional unit (separation of units) with changed parameters (with degradation of the state) is almost impossible.

Automatic control systems are present in electronic equipment both in the form of separate systems, and as a part of other functional knots and blocks as regulating devices. In the article, on the example of the scheme of phase auto-tuning of frequency, the possibility of solving technical diagnostics problems for the class of feedback systems (automatic control systems) is considered. Using the method of self-radiation (compatible with an autonomous automated diagnostic system) allows you to automatically determine the mode of operation of the elements that are part of the feedback circuits and thus the state of the entire circuit reentrancy (object of control).

The accumulation (increase) of voltage in the elements of the feedback circuits clearly indicates a deviation in the operation of the main system. This information, displayed by means of indications, allows reacting quickly to the current state of the object of control.

Key words: automatic control system, autonomous automated diagnostic system, object of control, feedback circuits, physical and chemical processes, radio-electronic component.

Introduction

The operation of any technical device is characterized by different physical quantities (temperature, pressure, speed). These values must be maintained at a given level or change according to a given law.

With the help of the automatic control system the problem of changing the physical quantity according to the required law is solved. A technical device in which automatic adjustment is performed is an object of regulation. Automatic control is a special case of automatic control.

The purpose of control in this case is to provide the necessary law of change of the regulated value (Kuzavkov V. V., 2015). The presence of feedback in the circuit design of the object of control does not allow the use of known methods to analyze the technical condition (Zherdiev M. K., 2013; Lienkov S.V., 2012).

In order to obtain diagnostic information in this case, it is necessary to exclude (open) the feedback circuits, which in some cases is impossible or dangerous.

When the feedback circuits are turned on, the results of determining the technical condition of the parameters of the output signal are ambiguous or distorted

The system, due to the feedback elements “tries to” pull the output signal to the “normal” level. In other words: the operation of the feedback system compensates for the change of parameters in the radio-electronic components of the object of control associated not only with the external operating conditions (temperature, humidity, etc.), but also with the physicochemical processes that occur in radio-electronic components during operation.

The procedure of control (determination) of the technical condition of both modern-day radio-electronic equipment and its individual functional units (radio-electronic equipment of varying complexity and large integrated circuits) are complicated.

To obtain reliable and objective information about the state of radio-electronic equipment, both during production and in operation and to determine its residual life, it is necessary to develop new (improved existing) methods, techniques, non-destructive testing, which would determine the actual technical condition individual radio-electronic components or all radio-electronic equipment without interfering with the circuit-technical solutions of the object of control, without violating its efficiency.

During the operation of radio-electronic equipment, a certain amount of heat is produced. Excessive heat indicates a problem and is a major symptom of preventive maintenance. Excessive heat indicates a problem and is a major feature of preventive maintenance. The reasons can be found both in the concentration of the main carriers and the presence of microvolumes of electrolytes, and in electrodiffusion (electromigration), corrosion and oxidation of metallization, the mechanism of degradation of metal films and the quality of internal contact joints that affect current.

Given that the temperature is a diagnostic parameter (Kuzavkov V.V., 2019), it is necessary to have automated software and hardware to solve the main problems of technical diagnostics.

Thus, the development (improvement) of non-destructive methods of temperature control of radio-electronic equipment (self-radiation method) to determine the actual technical condition (residual resource) of the control objects with feedback is an important and urgent task.

Material and methods

Modern objects of radio-electronic equipment are complex technical systems consisting of modules of different physical execution and purpose. Qualitative diagnostics of digital radio-electronic equipment units depend on the adequacy of the diagnostic model of the object of control and methods of diagnosis; as well as application of new method of non-destructive testing (Haidur H.I., 2015; Kuzavkov V. 2015).

Among the existing method of non-destructive (magnetic, electric, thermal, radio-wave, optical, radiation, acoustic) thermal one is the most informative and operational method, it helps in monitoring and evaluation of the technical condition of radio-electronic equipment. Interest in thermal methods of control is due to its versatility, high performance and safety of equipment maintenance (Vyshnivskyi V.V., Kuzavkov V.V., 2013).

Temperature, as a quantitative indicator of the internal energy of bodies, is a universal characteristic of objects and processes of the physical world, in which the generation, transformation, transmission, accumulation and utilization of energy in its various forms. The receipt (registration) of this information of the system and its corresponding processing allow defining and controlling the parameters of functional units control objects, which are difficult or impossible to measure directly (Hossorh Zh., 2005; Kuzavkov V.V., Romanenko M.M., 2018).

The main informative parameter of thermal control methods is the temperature difference between the defect-free and defective areas of the object. The temperature can be measured by contact and non-contact method. For the diagnosis of radio-electronic equipment, the most convenient is passive method of non-destructive. When using the passive method (it is called the method of self-radiation), heat flows of working objects are recorded, putting faults and defects in accordance with the places of increased heating (Haidur H.I., Kuzavkov V.V., 2015). Analysis of thermal processes (temperature fields, heat losses, etc.) allows you to get a variety of information about the state of objects and the flow of physical processes in different parts of the electrical circuit.

The purpose of the article is to substantiate the possibility of using the method of self-radiation for diagnosis radio-electronic objects with feedback circuits.

Results and discussion

When connected to feedback, the output signal of one element is fed to its input through the feedback elements. In fig. 1 shows the feedback connections. A comparison element is a device in which signals are summed. Depending on the sign of the feedback signal, there are positive and negative feedback (Kuzavkov V.V., 2015).

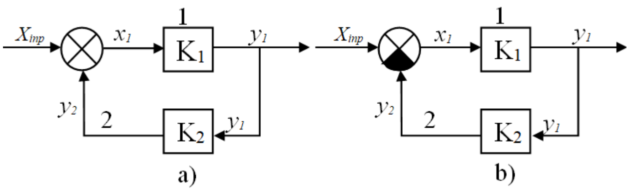

Fig. 1. Connection of elements with feedback circuits

In fig. 1, a – indicates a connection with positive feedback, b – with negative feedback. Element 1 is included in the forward circuit, element 2 is in the feedback circuit (i.e. item 1 is covered by the feedback).

One of the characteristics of a feedback system is the conversion factor. The input of element 1 receives an input signal$x_1 = x_{inp} \pm y_2$, where the plus sign corresponds to positive feedback, the minus sign - negative. The output signal of the element 1 is equal to the product of its input signal by the conversion factor:

$$y_1 = K_1 x_1 \pm K y_2 \qquad (1)$$

This signal is fed to the input of element 2, which is included in the feedback circuit. Accordingly, the output signal of element 2 can be obtained by multiplying the signal y_1 by the conversion factor of element 2:$y_2 = K_2 y_1$. Substituting the value of y_2 in the expression for y_1:

$$y_1 = K_1 x_{inp} \pm K_1 K_2 y_1 \qquad (2)$$

After the transformation we get:

$$y_1 \pm K_1 K_2 y_1 = K_1 x_{inp}, \text{ or}$$
$$y_1(1 \pm K_1 K_2) = K_1 x_{inp}$$

The total conversion factor is the ratio of the output signal to the input. In this case, the output is the signal y_1, and the input x_{inp}. Their relationship:

$$\frac{y_1}{x_{inp}} = \frac{K_1}{1 \pm K_1 K_2}.$$

In this expression, the minus sign corresponds to positive feedback, and plus to the negative.

Positive feedback is frequently used in the amplifying elements of automation. The positive feedback can be obtained with the help of relay system characteristics.

The operation of automatic control system is based on the principle of negative feedback. In the comparison element, the mismatch signal *y(t)* is formed as a result of the influence of the signal and the input signal *g(t).* (fig. 2). It is due to the negative feedback that the adjustable value is automatically maintained at a given level. After all, due to the negative feedback, the deviation *y(t)* from *g(t)* is constantly determined and a regulatory influence is produced (according to this deviation). A sensor is included in the automatic control system feedback circuit. Amplifiers and automation actuators are included in the direct circuit. If, the conversion factors of all elements included in the direct circuit are denoted by the conversion factor K_{conv} and for the K_s sensor, the total conversion factor automatic control system K_{ACS}:

$$K_{ACS} = \frac{K_{conv}}{1 + K_{conv} K_s}.$$

Analysis of expressions (1,2) shows that the signal level at the input of the feedback elements depends on the transmission coefficients not only of the feedback circuits, but also on the transmission coefficients of the main circuit. That is, changing the parameters and characteristics of the elements in the main circuit (for any reason) leads to significant changes in the mode of operation of the feedback elements, respectively, to significant changes in the temperature of these elements. This fact (reflecting the state of the main system on the mode of operation of the feedback path elements) allows to use the method of self-radiation (hereinafter – the method) (Vyshnivskyi V.V., Kuzavkov V.V., 2013) to solve problems of diagnosing feedback systems without breaking (without opening) feedback circuits by purposefully contactless control of feedback elements.

The essence of the method of diagnosing electronic units is that as diagnostic parameters are used parameters of signals in the infrared range of waves that occur during the operation of control objects.

It should be noted that of particular interest is the infrared range of 8–14 μm, which completely coincides with the widest window of transparency of the atmosphere. The range of infrared waves 3–5,5 and 7–14 μm is the basis of thermal non-destructive testing (corresponds to the emissivity of control objects in the temperature range from -50 to +500°C). A complete description of the proposed method is given in (Kuzavkov V.V., 2015).

The functional diagram of the automatic control system control by deviation is shown in Fig 2. (Kuzavkov V.V., 2015).

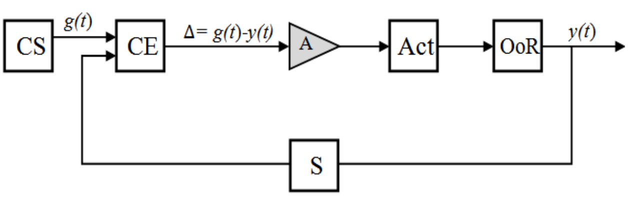

Fig. 2. Functional diagram of the automatic control system: *y(t)* is the function of the change in time of the variable that is regulated; *g(t)* is the law of the variable that is regulated.

The essence of the principle of deviation control is that the adjustable value *y(t)* is measured using the sensor (S) and enters the comparison element (CE). The other input of the CE receives the control signal *g(t)* from the control sensor (CS). In CE, the values of *g(t)* and *y(t)* are compared (i.e., *g(t)* is subtracted from *y(t)*). At the output of the CE a signal is formed, which is equal to the deviation of the adjustable value from the specified:

$$\Delta = g(t) - y(t).$$

This signal is fed through the amplifier (A) to the actuator (Act), which affects the object of control. This effect will change until the adjustable value *y(t)* becomes equal to the given *g(t).*

The object of regulation is constantly affected by various influences (load of the object, external factors, and internal processes in semiconductor structures). These effects tend to change the value of *y(t).* The task of automatic control system is to determine the deviation *y(t)* from *g(t)* and to form a control signal that seeks to reduce the deviation to zero. As a result, it is not possible to determine the actual technical condition of the object of control and the parameters of the output signal.

Thus, the only real opportunity to obtain information about the current technical condition of the object of control with elements of feedback is to control the functioning of the feedback elements, because any processes that occur in radio-electronic equipment are accompanied by the release of internal body energy, which is in thermodynamic equilibrium proportional to the temperature of the object. As a result, the surfaces of the feedback elements acquire a specific temperature distribution (Kuzavkov V.V., 2015).

The study of ways of changing the current through the object of control (temperature object of control) is to construct the dependence of the physical quantity on time (Kuzavkov V. Zabezpechennia, 2015).

In electronic equipment, the basis of the method is Joule's law (Kuzavkov V.V., 2015):

$$P = I^2 R.$$

The increase in the amount of heat from a single radio-electronic component is possible due to many reasons. For semiconductor structures, the increase in temperature is a consequence of aging (physicochemical processes depending on the operating time). Excessive heat (different from the average) indicates the presence of deviations in the actual technical condition (areas with low values may indicate the presence of a break (open circuit).

The correction of the change in temperature value in relation to the normal value of the current through the object of control is determined by the expression:

$$\Delta T_r = \Delta T_m \left(\frac{I_m}{I_n}\right)^2,$$

where is T_r the temperature rise, T_m – measured temperature rise, I_n – normal current, I_m – measured current.

In many cases, complex circuits can be built on the basis of individual functional units. In turn, individual functional units are replaced by programmable logic integrated circuits – an ultra-large integrated circuit that accommodates on the chip universal user-configured functional converters and programmable connections between them [8]. Thus, on the area of the semiconductor crystal 100–200 sq. mm can be located a complex piece of hardware, the technical condition which is actually impossible to control (in terms of technical diagnostics) (Kuzavkov V.V., 2019).

The change of the infrared field of the radio-electronic components in the process of operation should be used to determine the actual technical condition of the object of control. To do this, the measuring device – the infrared radiation recorder is placed on the normal above the object of control. A signal with certain parameters is generated at the output of the recorder. The presence and parameters of the signal on the recorder serve as information about the fact of operation and condition of the object of control. Based on the comparison of the parameters of the reference and received signals, a decision is made on the technical condition of the control objects.

It should be noted that the technical means of analog-to-digital conversion can provide any number of temperature levels and high measurement accuracy to display the state of radio-electronic equipment. In this case, the function of thermal control can be made an internal function of the control objects, providing it at the design stage. As a generalized control parameter, the value of the temperature of the housing object of control, should be used, strictly binding the geometric measurement point of the diagnostic parameter to the internal structure of the object of control (to the location of the feedback elements). In the radio-electronic equipment of the next generation constructed on elements "system on a crystal" (SoC), the effective organization of diagnostics as the temperature sensor can be placed in (on) a semiconductor crystal is possible. This will eliminate the inertia of measurements, simplify the design and schematic solution, and increase the reliability of control data.

An example of a widespread in the communication object of control with feedback is a circuit of phase lock loop (PLL), which includes: a generator voltage control (GVC), phase detector (PD), filter (F) and amplifier (A) (fig. 3) (Kuzavkov V.V., 2015).

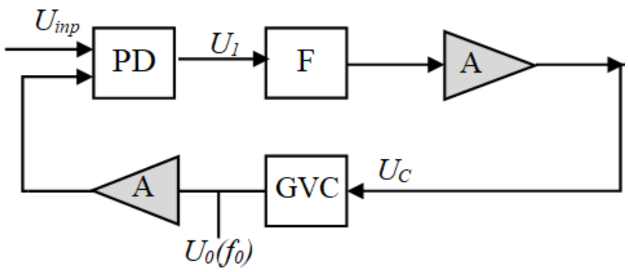

Fig. 3. Structural diagram of phase lock loop

The error detector (phase detector – PD) compares the phases of the signal of the reference generator U_0 and the input signal U_{inp} and produces a voltage U_1, the magnitude of which depends on the phase difference of these signals. If this difference is equal to φ radians, then the output voltage of the PD will be determined by the expression:

$$U_1 = K\varphi(\varphi - \frac{\pi}{2}),$$

where is K_φ the transmission factor "phase – voltage PD" (V/rad).

The output voltage of the PD is passed through the filter and their harmonics. The voltage from the F output is amplified and used as a control voltage for the control voltage generator U_C. Its value is:

$$U_C = K_\varphi A\left(\varphi - \frac{\pi}{2}\right),$$

where is A the amplification factor.

The maximum voltage at the output of the PD takes place at $\varphi = \pi$ and $\varphi = 0$ – it is determined by the expression:

$$U_{1(\max)} = \pm K_{\varphi}\frac{\pi}{2}.$$

Accordingly, the maximum possible control voltage is equal to:

$$U_{C(\max)} = \pm K_{\varphi}K_{u}\frac{\pi}{2}. \qquad (3)$$

Using the expression (3) it is possible to determine the value of temperature – control voltage and, accordingly, the operating conditions of the object of control (PD) of the whole radio-electronic equipment without opening the control circuit.

The source of energy in a multilayer semiconductor structure is a heated crystal. The crystal temperature *T* is determined according to the diagnostic model of the p-n junction. For the method, which is based on the analysis of the volt-ampere characteristics of the semiconductor junction (Haidur H.I., Kuzavkov V.V., 2015), the temperature depends on the current through the p-n junction and the physicochemical properties of the semiconductor:

$$\mathrm{T} = \frac{\mathrm{U} - \varphi_{z0}}{\frac{\mathrm{k}}{\mathrm{q}}\ln\frac{\mathrm{I}}{\mathrm{I}_{00}} - \varepsilon_s},$$

where is k the Boltzmann constant; T – temperature; q – electron charge; I_{00} – value that does not depend on temperature; φ_{z0} – width of the forbidden zone at zero temperature; ε_s – temperature sensitivity.

In the expanded form, taking into account the concentration of the main charge carriers in the semiconductor structure (Haidur H.I., Kuzavkov V.V., 2015):

$$T = \frac{U-\varphi_{z0}}{\frac{k}{q}ln\left(\frac{-\frac{2qD_n}{Ln}S_n'\cosh\frac{W}{Ln}n_1+\frac{2qD_n}{Ln}S_n'cth\frac{W}{Ln}n_2}{I_{00}}\right)-\varepsilon_s}, \qquad (4)$$

where is W the width of the diffusion region; L_n – the length of the diffusion displacement of electrons; S_n' – area of the semiconductor; D_n – concentration ratio of the main carriers; n_1, n_2 – carriers of different types.

The power of the heated crystal after a certain period of time is transmitted to the surface of the radio-electronic component where the registration of the diagnostic parameter is done. The heating temperature of the radio-electronic component surface under continuous exposure is determined by the expression [6]:

$$T = T_0 + PR_t\left(1 - e^{\frac{t}{mCR_t}}\right),$$

where P – electric power that causes heating of the elements; R_t – thermal resistance of the radio-electronic component surface; t – time of influence; m, C – physical parameters of radio-electronic components (mass and specific heat).

Taking into account expressions (3) and (4), the maximum heating temperature of the elements in the feedback circuit (the maximum possible control voltage of the PLL circuit) under continuous exposure will be:

$$T = T_0 + \left(K_{\varphi}K_u\pi\right)^2\frac{R_t}{4R}\left(1 - e^{\frac{t}{mCR_t}}\right).$$

Therefore, the relationship between surface temperature and control voltage will allow obtaining the calculated values of the diagnostic parameter. The comparison of the calculated values and the measured ones allows making a decision about the actual technical condition of the control objects taking into account the operating time (as well as the aging process of the semiconductor structure).

The application of the self-radiation method is possible due to the advent of high-speed matrix receivers of large-format infrared signal and the use of computer-measured information processing systems.

Conclusions

The article substantiates the possibility of using the method of self-radiation to diagnose radio-electronic objects with feedback elements. Solving diagnostic tasks for automatic control system (feedback systems) by existing methods is difficult or impossible without breaking the feedback circuits. Heat emitted by feedback elements for any reason (and due to physicochemical processes in semiconductor radio-electronic components during operation) creates a thermal imprint and can be recorded and processed in real time.

The advantages of the method are:

there is no need to use output contacts and control points;

there is no influence of the device of diagnostics on “own” reliability of object of control;

reduction of time for solving problems of technical diagnostics.

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