Statistical synthesis and analysis of effective detecting element for heat-actuated devices of maximal type

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Abstract
Statistical synthesis and analysis of effective detecting element for heat-actuated devices of maximal type are made, a comparison of the efficiency of effective detecting element and existing ones is done.
Key words: EFFECTIVE DETECTING ELEMENT, HEAT-ACTUATED DEVICE OF MAXIMAL TYPE

Problem statement

In recent years the important place in ensuring fire safety of metallurgical production facilities is given to improve the efficiency of automatic detection and suppression of fires. In such systems, heat fire detectors are mainly used as the main sources of primary information about firing. In constructing the detecting elements for such fire detectors different physical effects and phenomena are used [1, 2]. It should be noted that heat-actuated devices of maximal type are more widely used among all types of thermal fire detectors. This is caused by their relatively low cost, ease of circuit design and structural design, as well as high operational reliability. Wherein in the first approximation [2], regardless of the physical effect or phenomenon or detecting elements of said detector units are aperiodic links of the first order, which inertial properties are determined by shape, dimensions and material properties of detecting element. Construction of detecting elements for heat-actuated devices is linked to the problem of determining the effective detecting elements ensuring a minimum standard error of volumetric average temperature to evaluate effectively the ambient temperature in difficult conditions of metallurgical production.

Analysis of recent research and publications

The papers [1, 2] are devoted to parametric optimization and identification of various types of effective detecting elements of heat-actuated devices. However, in these studies, the research is carried out within the framework of structural synthesis, based on the predetermined structure of the detecting elements at the determined heat effects. Structure synthesis of effective detecting element for the ambient temperature estimation was not considered and the random nature of heat was not taken into account. In contrast to the structural one the non-structural statistical synthesis makes it possible not only to determine the effective structure of detecting element among all possible structures of detecting elements based on random effects, but also their optimal settings for given random conditions. The results of this synthesis allow to evaluate the potential (limit) estimation of the ambient temperature by detecting elements of heat-actuated devices, to determine the degree of perfection of existing detecting elements for given random conditions, as well as to evaluate the suggestions and identify constructive ways to improve them. It should be noted that to solve the problem of statistical synthesis of effective detecting element there is a well-developed mathematical apparatus of the statistical theory of effective estimation.

Problem statement and its solution

The purpose of paper is a statistical analysis of the characteristics of current detecting elements of maximal heat-actuated devices, as well as statistical analysis and synthesis of effective detecting element in a random temperature jump from the source of fire and random temperature effects in the environment, specific to the actual conditions of operation of these detectors.

As the base the heat-actuated device of maximal type with thermoresistive detecting element will be considered. Structurally, this detector is determined by the series connection of detecting element, information retrieval sensor and threshold device. Balance resistive bridge is used as an information retrieval sensor, which is an instantaneous element with static transmission ratio k_d. Accordingly, the output voltage of information retrieval sensor

$$U_d = k_d \hat{a}1(t),$$

where $\hat{a}1(t)$ - the average volume temperature increment of thermoresistive detecting element of device when exposed to ambient temperature.

The maximal heat-actuated device must respond to a predetermined value of ambient temperature jump $a(t)$. It will be assumed that the value of the temperature jump, caused by source of fire, in the time interval $[0,T]$ of observation is a Gaussian random variable $a(t)=a_0$ with mean $m_a = m - T_o$ and variance D_a, where m – is the average value of ambient temperature, caused by source of fire, and the value T_o determines the initial average volume temperature of detecting element. In real conditions the appearance of specified ambient temperature jump is accompanied by random thermal effects $n(t)$, which are described by Gaussian process with zero mean and uniform spectral density $N/2$. With that said, the resulting temperature $y(t)$ at the outer edge of the surface of detecting element of heat-actuated device in the interval $t \in [0,T]$ can be described by process

$$y(t) = a(t) + n(t). \tag{1}$$

In this case, the average volume temperature $\hat{a}1(t)$ increment of thermoresistive detecting element of device when exposed to temperature (1) will be described by stationary equation

$$\tau\, d\hat{a}1(t)/dt + \hat{a}1(t) = y(t). \tag{2}$$

where τ - is the given magnitude of the time constant of existing detecting elements of heat-actuated devices. Due to the random nature of ambient temperature the average volume temperature increment of detecting element will be described by Gaussian law. For zero initial condition of equation (2) the dynamics of the average value of average volume temperature increment of detecting element

$$m_{\hat{a}1}(t) = m_a (1 - e^{-t/\tau})$$

and dispersion

$$D_{\hat{a}1}(t) = [D_a (1 - e^{-t/\tau}) + N(1 - e^{-t/\tau})/4\tau](1 - e^{-t/\tau}).$$

In steady state operation the mean and variance of average volume temperature increment of detecting element, described (2), will be determined by $m_{\hat{a}1}(\infty) = m_a$ and $D_{\hat{a}1}(\infty) = D_a + N/4\tau$ respectively. This means that the average value of the average volume temperature increment of detecting element tends to the average value of ambient temperature jump, and its dispersion - to the amount of temperature jump dispersion and spectral density of random effects, reduced 2τ times. Therefore, the dispersion component of average volume temperature increment of detecting element, resulting from the random environment thermal influence can only be affected by the selection of τ in steady state. At the same time in these conditions, all the ways to improve the performance of detecting elements based on reducing of their τ, will lead to increase in the dispersion of average volume temperature increment of detecting element, as well as cause a decline in the quality of fires detection by maximal heat-actuated devices.

Let us consider the synthesis of the effective detecting element of maximal heat-actuated device. The minimum of mean square error estimation of random temperature jump in random temperature effects will be considered as the criterion of detecting element effectiveness. In this formulation, the synthesis of effective detecting element can be considered as part of the particular problem solution of random process effective estimation, which does not change in the interval of observation in the presence of additive effects in the form of a random process.

Let a priori equation describing random ambient temperature jump $a(t)$ on the observation interval $[0,T]$ be determined in the form

$$da(t)/dt = 0,\ a(0) = a_0. \tag{3}$$

Then the observation equation for the synthesized detecting element will coincide with (1). According to [3], the structure and parameters of effective detecting element taking into account (3) and observation equation (1) can be described by the equation

$$d\hat{a}(t)/dt = K(t)[y(t) - \hat{a}(t)], \tag{4}$$

where $\hat{a}(t)$ - average volume temperature increment of detecting element, and the function $K(t) = 2D(t)/N$, where $\hat{a}(t)$ - current variance of optimum estimation error $\hat{a}(t)$. In this case, the equation for current variance estimation of the average volume temperature increment of detecting element is as follows:

$$dD(t)/dt = -2D^2(t)/N. \tag{5}$$

The solution of equation (5) will be described by the function

$$D(t) = D_a N(N + 2D_a t). \tag{6}$$

Equations (4) and (6) determine the structure and parameters of effective detecting element for conditions under consideration. The structure of the synthesized effective detecting element defined by (4) is shown in Fig. 1.

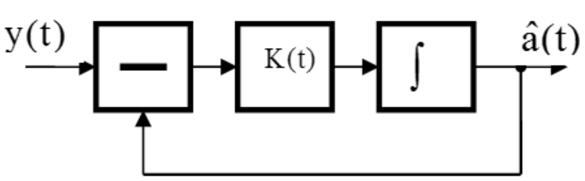

Figure 1. The structure of the effective detecting element of heat-actuated device

It turns out that for the conditions discussed above the synthesized effective detecting element must be unsteady and follow-up. However, its unsteadiness is described by transmission coefficient $K(t)$,which depends on time, spectral density of random thermal effects and ambient temperature jump dispersion, caused by source of firing. The dynamics of $K(t)$ for different ratios $q = D_a / N$, equal to 10^{-2}, 10^{-1} and 1 , is shown in Fig. 2. In a particular case when random temperature effects in the environment are not available or variance D_a is high, the ratio $K(t) = 1/t$. This means that in case $t \to \infty$ the ratio $K(t) \to 0$ and detecting element gradually stop responding to the ambient temperature, maintaining the unchanged value $\hat{a}(t)$ of average volume temperature element in the output of integrator (Fig. 1). Wherein the dispersion of average volume temperature of detecting element, following (6) tends to zero. Therefore, with the increase in time or observation interval the average volume temperature $\hat{a}(t)$ of effective detecting element can be arbitrarily close to the true value of the unknown and random ambient temperature increment caused by point of origin.

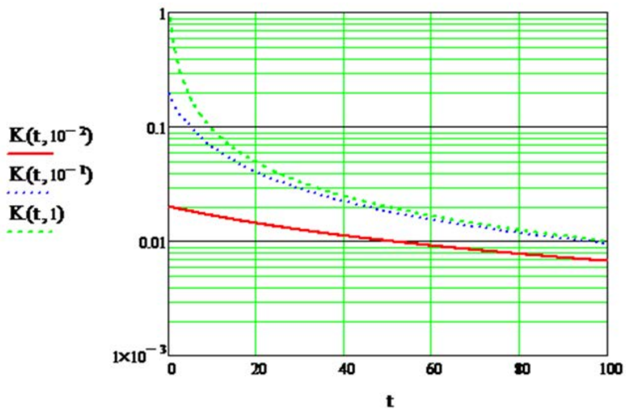

Figure 2. Dynamics of the effective detecting element transfer ratio

Besides the effective detecting element in the form of element with back action (Fig. 1) its realization is possible in the form of open-type element. On the basis of (4) effective detecting element in the form of open-type element can be defined by the equation:

$$d\hat{a}(t)/dt + K(t)\hat{a}(t) = K(t)y(t). \tag{7}$$

Introducing function $\tau_0(t) = 1/K(t)$, the equation (7) can be written in the form of non-stationary equation

$$\tau_0(t)d\hat{a}(t)/dt + \hat{a}(t) = y(t). \tag{8}$$

Equation (8) describes the effective detecting element in the form of structure similar to the structure of detecting elements of existing heat-actuated devices.

In this case the main difference of effective detecting element is in the unsteadiness of time constant $\tau_0(t)$. This means that the time constant $\tau(t)=\tau$ is a fixed time for current detective elements. It is clear that the effective detecting element (8) and current detecting element (2), wherein the time constant is fixed, will have different characteristics.

To compare the effective and current detecting elements, let us obtain the equation for dispersion $D_T(t,\tau)$ of the random temperature jump estimation error, caused by the source of firing at the specified time constant of current detecting elements. Let us introduce the value for specified error $T(t)=a(t)-\hat{a}1(t)$. Let us subtract the equation (2) from equation (3), substituting the expression $y(t)$ from (1) in it. Then we will obtain a linear differential equation for the estimation error of random temperature jump

$$\tau dT(t)/dt + T(t) = -n(t). \quad (9)$$

In the right part (9) is Gaussian process with the correlation function $\delta(t-t_1)N/2$. For $D_T(0,\tau)=0$ dispersion dynamics of estimation of random temperature jump will be determined by

$$D_T(t,\tau)=N(1-e^{-2t/\tau})/4\tau. \quad (10)$$

In accordance with requirements of EN-54 standard for heat-actuated devices the value τ for detecting elements amounts to the value τ 1=20 c and τ 2=60 c Dependencies of error variance for existing $D_T(t,\tau)$ and effective $D(t)$ detecting element on normalized time t/τ for the ambient temperature jump monitoring conditions, characterized by predetermined ratio $q=D_a/N$, are shown in Fig. 3.

From the analysis of submitted dependences it follows that in these circumstances the existing detecting elements of heat-actuated devices in the time interval, exceeding (3-10) τ significantly lose to effective detecting element. At the same time similar values of estimation error variance occur at fixed time moments $t1 \approx 2\tau 1$ and $t2 \approx 6\tau 2$ for the respective time constants of current detecting elements. With increase in the ratio $q=D_a/N$ the efficiency of effective detecting elements over existing detecting elements becomes essential. The use of existing (non-effective) detecting elements leads to a decrease in performance of heat-actuated devices, as well as the occurrence of fluctuations in output voltage of data acquisition sensor that can impair the quality indicators of fires detection. The value of detection quality indicators deterioration is inversely proportional to the ratio $q=D_a/N$ characterizing the detection conditions of firing source.

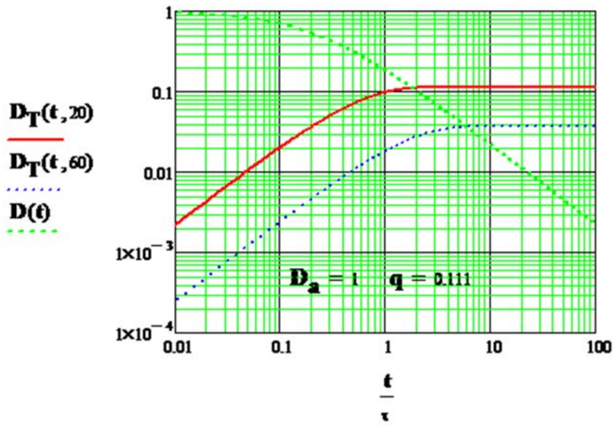

Figure 3. Dependencies of the temperature estimation error variance for the current and the effective detecting element

Dynamics of average volume temperature for effective detecting element and current detecting elements with values τ 1=20 c and τ 2=60 c is illustrated in Fig. 4 and Fig. 5, respectively. Modeling was carried out by numerical integration of the corresponding differential equations for the random temperature jump $\lambda_0=a_0$, and the values $a_g=a(g\Delta t)$ and $a1_g=\hat{a}1(g\Delta t)$ describe the average volume temperature of effective and current element, respectively, for the values $a_0=a1_0=2$, where $g=1,2,3,......$; $\Delta t=0{,}1c$ - integration step.

From the analysis of these dependencies it follows that the dynamics of average volume temperature of existing (non-effective) detecting element in a significant random temperature effects in the environment $q=0{,}033$ is characterized by the transition process, which duration is approximately five time constants (for the appropriate detecting element), and accompanied by the growth of fluctuations of average volume temperature of element to the level of steady mode.

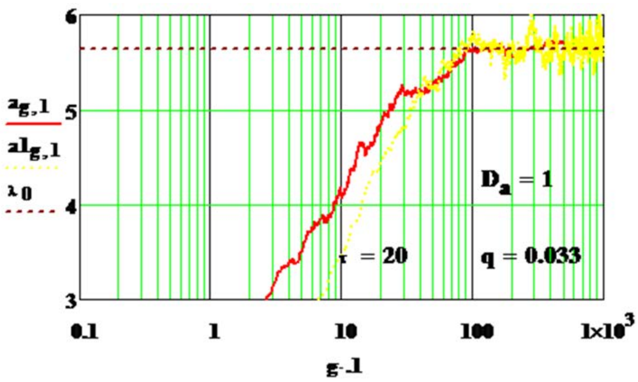

Figure 4. Dynamics of the average volume temperature of effective and existing detecting element (time constant 20sec)

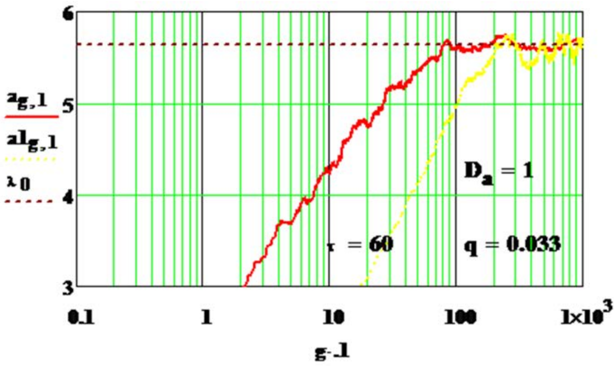

Figure 5. Dynamics of the average volume temperature of effective and existing detecting element (time constant 60sec)

The dynamics of the average volume temperature of effective detecting element under similar conditions is characterized by a slight improvement in the transition process, but significantly lower fluctuations level at steady mode compared to the fluctuations of steady mode for an existing (non-effective) detecting element.

Unlike existing detecting elements the average volume temperature fluctuations for effective detecting element at steady-state tend to zero, providing the potential accuracy under the condition $t \to \infty$ of the unknown random ambient temperature jump estimation (zero error). Using the existing (non-effective) detecting elements in heat-actuated devices, with the value of time constant, equal to 60 s, the dynamics of their average volume temperature slows down, but there will be a reduction in the average volume temperature fluctuations level in the steady mode (Fig. 5). In general, the performance of effective detecting element over the existing (non-effective) detecting elements increases more significant, when the value $q = D_a / N$ is larger (Fig. 6).

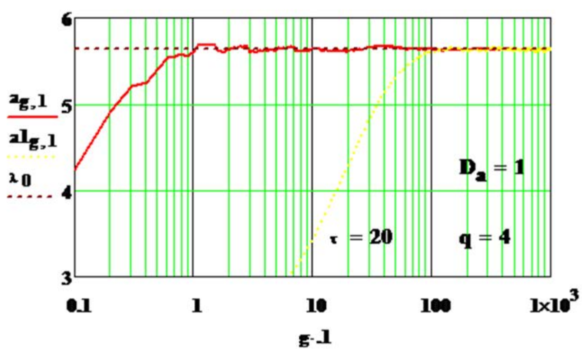

Figure 6. Dynamics of the average volume temperature of effective and existing detecting element at the value $q = 4$

It should be noted that the mentioned above properties and characteristics of the effective and existing (non-effective) detecting element of heat-actuated devices are characteristic for the conditions determined by the constancy of the random temperature jump in observation interval at random temperature effects in the environment. Therefore, to extend the full results obtained here to the case of arbitrary nature of the ambient temperature increment changes by firing source in the observation interval at random temperature effects is impossible.

Conclusions

A statistical analysis of the existing detecting elements of the heat-actuated devices of maximal type is made and the problems of statistical analysis and synthesis of effective detecting element in the case of constant ambient temperature jump in time at random temperature effects described by Gaussian process with zero mean and a predetermined uniform spectral density are solved. It is shown that the effective detecting element of maximal heat-actuated device must be follow-up, and can also be implemented as a corresponding detecting element of open type with time constant variable. It was found that the existing detecting elements for the random ambient temperature jump used in heat-actuated devices of maximal type, are similar to the effective detecting elements in structure. A comparative analysis of the effective and existing detecting elements of heat-actuated devices with presence of random temperature effects is made. It is shown that detecting elements of existing heat-actuated devices have a sufficient accuracy and operating speed, which can serve as one of the main and fundamental causes for their effectiveness reduction in real metallurgical industry, characterized by different random temperature effects in the environment.

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