UDC 681.5.08: 004.942 (045)

G. E. Sokolov

BUILDING A COMPUTER MODEL OF AN OPTOELECTRONIC FIRE SMOKE ALARM DETECTOR

Department of Aviation Radio-Electronic Complexes, National Aviation University, Kyiv, Ukraine
E-mail: gennadii_sokolov@mail.ru

Abstract**—***The work deals with modeling an optoelectronic fire smoke alarm detector at the functional diagram level by means of MATLAB tools. The developed model makes it possible to estimate the ability of a logic unit to distinguish between fire signals and noise.*

Index Terms**—**Modeling of systems; optoelectronics; fire alarm detector; MATLAB.

I. INTRODUCTION. SETTING THE PROBLEM

Modeling of systems at the functional diagram level is widely used in the practice of design [1]. In this work modeling of an optoelectronic fire smoke alarm detector has been carried out at the functional level by means of MATLAB tools. Such detectors are widely used in fire alarm systems. The purpose of creating a model is theoretical research of the influence of signal processing parameters in the fire smoke alarm detector on smoke detection efficiency in atmospheric noise environment.

II. DEVELOPMENT OF A COMPUTER MODEL OF THE FIRE SMOKE LINEAR OPTOELECTRONIC DETECTOR

The development of a computer model of the fire smoke linear optoelectronic detector is carried out during the following stages [2]:

1. Choosing the prototype detector.
2. Analyzing the structural diagram of the prototype detector and analyzing the signal processing in the structural units of the diagram.
3. Constructing a simplified block diagram of the specified model of the detector.
4. Constructing a functional model of the detector.
5. Constructing a mathematical model of signal processing in the detector.
6. Designing a block diagram of the computer program implementing the mathematical model.
7. Writing and debugging the program in the chosen programming language.
8. Testing the program.

As a prototype detector we take an active infrared security and fire alarm detector “Kvant-1”, which is analyzed below. The detector “Kvant-1” reacts to smoke in operation. The device triggers an alarm when smoke enhancing the optical density of the environment by 10 % appears in its operating area within 3 seconds.

The operation principle of the device is based on scattering and absorption of the infrared energy emitted by the smoke and on registering its part that has reached the receiver.

The operation of the device is illustrated by the block diagram shown in Fig. 1. The generator *3* produces a pulse current that powers the transmitter *2*, whereby its radiation becomes intensity modulated. This radiation is formed as a narrow beam (by the lens of the emitter) and sent to the reflector *1* installed on a wall of the room. Part of the scattered energy reaches the surface of the photodetector *4*, which converts it into an electric pulse signal amplified in the preamplifier *5* and then fed to the amplifier *7*. The output signal of the amplifier *7* is supplied to the synchronous detector *8*, which demodulates it, and then via the integrator *9* it gets to the alarm signal generator *10.* The synchronous detector *8* is controlled by sync pulses arriving from the generator *3*.

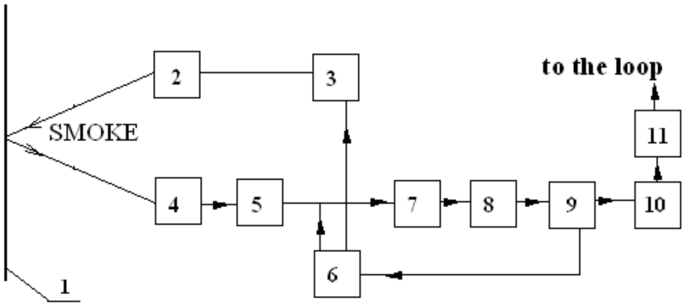

Fig. 1. Block-diagram of the detector “Kvant-1”: *1* is Reflecting surface; *2* is Emitter; *3* is Generator; *4* is Photodetector; *5* is Preamplifier; 6 is Automatic gain control unit; *7* is Amplifier; *8* is Detector; *9* is Integrator; *10* is Alarm signal generator; *11* is Alarm unit

The appearance of smoke within the operating area of the device causes amplitude modulation of the output pulses of the amplifier. The pulse envelope derived by the synchronous detector *8* comes to the alarm signal generator *10* via the integrator *9*. The alarm signal generator produces a signal with duration more than *2* seconds and applies it to the alarm unit *11* that opens the contacts of a slave relay.

The device has the automatic gain control unit (AGC) *6* that controls the gain when the signal goes from the preamp at low levels and the magnitude of its power radiation at high levels. To do this, the control signal is taken from the integrator *9*. The magnitude of the control signal is proportional to the voltage at the output of the synchronous detector *8*. Both AGC loops operate synchronously and change the gain of the signal path, but this kind of arrangement increases the AGC dynamic range.

It is important to note that the most important signal processing element determining the noise immunity of the detector is the AGC unit. The infrared beam propagates from the emitter *2* to the photodetector *4* in changing air dustiness and pollution, which leads to significant changes in the optical density of the air. Consequently, the input signal of the receiver is significantly reduced, which may be erroneously taken as a fire start.

The signal processing algorithm included in the detector “Kvant-1” that separates the signal from the noise is based on the experimentally revealed regularity: optical density variations of the air due to its dustiness and pollution and changes in gas composition are significantly slower than they are in the case of smoke when a fire starts. The AGC unit, having a slow reaction, slowly restores the output level of the amplifier that has changed due to the noise, but misses a signal reduction pulse caused by rapid smokiness. Signal level reduction by 10 % within *3* seconds should be perceived by the detector as “Alarm”. Slower variations should not be perceived as “Alarm”.

Analyzing the efficiency of the detector with varying optical density of the air and with different parameters of AGC is the aim of our modeling.

The block-diagram of the proposed model of the detector has been simplified in order to facilitate the modeling process. For this purpose it is necessary:

a) to keep the basic units of the model that determine the operation of the detector and its noise immunity;

b) to get rid of the units playing minor roles, such as units *10* and *11* just matching the detector output signal formats and its receiving hardware.

A simplified block-diagram is shown in Fig. 2.

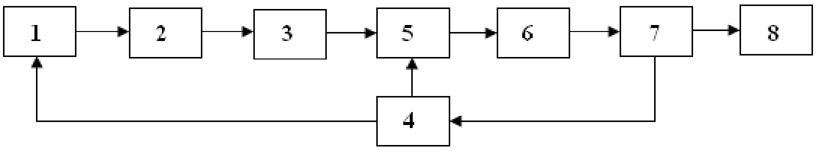

Fig. 2. A simplified block-diagram of the detector model: *1* is Generator; *2* is Optical path; *3* is Preamplifier; 4 is Automatic gain control unit; *5* is Amplifier; 6 is Detector; 7 is Integrator; 8 is Resolver

The simplifications made for the block-diagram of Fig. 2 as compared to the block-diagram of Fig. 1 can be justified as follows.

The emitter, the smoke-filled space, the reflector and the detector make up the optical path. Here the emitter makes electric-to-optic signal conversion and the photodetector makes optic-to-electric signal conversion. Thus, at the input and output of unit *2* there are electric signals, and the operation of the optical path can be described by means of a transfer function.

The AGC is assumed to be linear, which, in effect, makes it possible to describe its operation by means of just one loop during simulation. As it takes place, AGC regulates the transfer factor of the signal path from unit *1* to unit *5*. Then the voltage transfer ratio of the AGC unit (unit *4*) can be introduced as

$$K_{AGC} = K_{AGC\_\mathrm{Generator}} \times K_{AGC\_\mathrm{Amplifier}},$$

which can be considered the AGC factor of a single loop (e.g, amplifier loop).

The resolver makes a decision about the presence or absence of a fire. Its simplest form is a threshold device. The question of where the decision is passed is not considered in the simulation.

The main method of constructing a functional diagram is representation of a single unit of the simplified block-diagram by its voltage transfer ratio:

$$K_U = \frac{U_{OUT}}{U_{IN}}.$$

The voltage transfer ratio of the amplifier (unit *5*):

$$K_U = K_0 \times K_{AGC},$$

where K_0 is a constant determined by hardware; K_{AGC} is voltage transfer ratio of the AGC unit (unit *4*).

The second important point in the construction of the functional diagram is discreteness of signal processing. A time interval T is chosen in which a decision about the presence or absence of fire is made (a sharp drop in the transfer factor of the optical path). This interval is divided into subintervals ΔT during which the voltage transfer ratio of the amplifier and the voltage transfer ratio of the AGC unit are constant and vary from one subinterval to the next.

The output signal of the detector (unit *6*) is formed as a DC component of its input signal averaged over a subinterval ΔT:

$$U_{OUT.DET} = K \times \int_{L\Delta T}^{(L+1)\Delta T} U_{IN.DET.} dt,$$

where the constant K is chosen so that

$$U_{OUT.DET} = 1,$$

the value of the transfer factor of the optical path being the initial one.

The transfer factor of unit 7 (integrator) is

$$K_{INT} = 1 - EXP(-t/\tau),$$

where τ is time constant of the integrator. The dependence of the transfer factor of the integrator on time is given in Fig. 3. This figure also shows the approximation of this function by a step function. Here the transfer factor of the integrator can be represented as:

$$K_{INT} = \begin{cases} 0, & \text{if} \quad t < \tau; \\ 1, & \text{if} \quad t > \tau. \end{cases}$$

This is the transfer factor of the delay line for a time τ. By virtue of the adopted principles of functional diagram formation, the delay time is multiple of ΔT.

The voltage transfer ratio of the unit AGC is formed according to the relationship:

$$K_{AGC} = 1/(U_{OUT.DET.} \times K_{INT.}).$$

It is easy to see that for the initial and constant transfer factor of the optical path

$$K_{AGC} = 1.$$

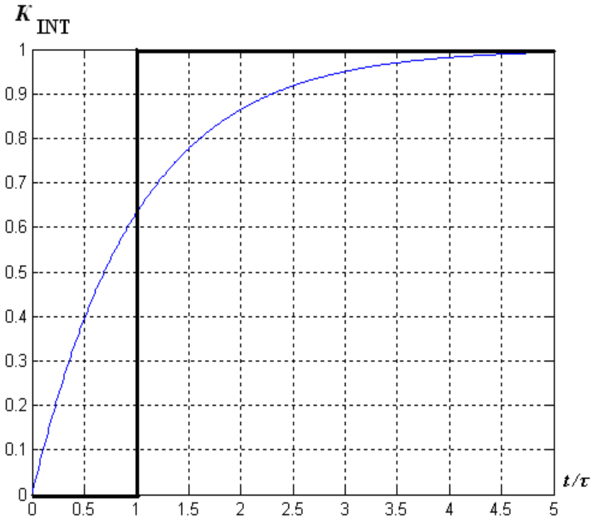

Fig. 3. Approximation of the transfer factor of the integrator

It means that the transfer factor of the amplifier is also constant, and the constant voltage at the integrator output is equal to 1.

The resolver (unit *8*) at the same time makes an unambiguous conclusion about the absence of fire.

Now if the transfer factor of the optical transmission path drops, the input signal of the resolver reduces to a certain minimum and then grows again to 1 due to AGC. If in the interval T the input signal of the resolver is less than the threshold level, the resolver (unit *8*) makes the conclusion about the beginning of a fire.

Based on the foregoing, the functional diagram of the detector model can be represented as shown in Fig. 4.

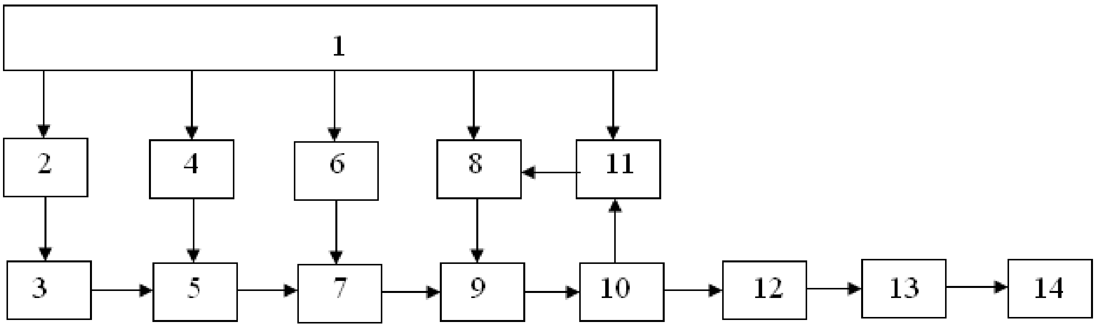

Fig. 4. The functional diagram of the detector model

The elements of the model are:

- shaper of initial data for modeling;
- shaper of time points at which numerical simulation is made;
- generator signal shaper;
- shaper of the transfer factor of the optical path for all points of time;
- shaper of the output signal of the optical path;
- preamp gain shaper;
- shaper of the preamplifier output;
- amplifier gain shaper (AGC unit);
- amplifier output shaper;
- detection unit;
- integrator;
- memory device;
- resolver (threshold unit);
- screen showing the solution of the resolver.

Constructing a mathematical model of signal processing in the detector.

Setting the initial digital parameters for modeling:

$T = 10$ sec is simulation time;

$\Delta T = 0.25$ sec is a unit interval of simulation;

$dt = 1$mks. – time interval between simulation moments;

$T1 = 460$ ms. is generator signal period;

$Q = 23$ is generator signal on-off time ratio;

U_0 is generator signal amplitude;

$M = 1$ is this parameter defines the delay of the integrator: $(M + 1)\Delta T$ sec;

$R1 = 0.8$; $R2 = 0.2$; $R1 + R2 = 1$; these parameters define the characteristics of the AGC unit;

$P = 0.8$ is this parameter defines the threshold of the threshold device.

Setting the time parameters for digital simulation:

$$dt = 10^{-6};\quad t = 0,\ dt,\ 2dt,\ 3dt, \ldots ,\ T.$$

$$N = T/\Delta T.$$

Calculating the output voltage of the generator:

$$U_{GEN} = U_0 \begin{cases} 1, & \text{if}\quad 0 + T1\cdot n < t < T1/Q + T1\cdot n, \\ 0, & \text{if}\quad T1/Q + T1\cdot n < t < T1 + T1\cdot n, \end{cases} \qquad \text{where}\quad 0 < n < N.$$

Calculating the transfer factor of the optical path.

The transfer factor of the optical path is taken normalized, i.e. $K \le 1$.

The transfer factor of the optical path is defined by an arbitrary function of time, for example:

$$K_{OPT}(t) = A1 + A2\exp(-0.5t);\quad 0 < t < T,\ \text{where}\quad A1,\ A2\ \text{are const.}$$

Calculating the signal at the output of the optical path:

$$U_{OPT} = U_{GEN}(t)K_{OPT}(t).$$

Setting the preamplifier gain:

$$K_{PREAMP} = Q.$$

Calculating the preamplifier output:

$$U_{PREAMP} = U_{OPT}K_{PREAMP}.$$

Setting the initial gain of the amplifier:

$$K_{AGC}(1) = 1.$$

Calculating the amplifier output at the first unit modeling interval ΔT:

$$U_{AMP} = U_{PREAMP}K_{AGC}(1). \qquad (1)$$

Calculating the detector output at the ith unit modeling interval ΔT:

$$U_{OUT.DET} = K\int_{i\Delta T}^{(i+1)\Delta T} U_{AMP.}dt,$$

where

$$K = 1/\Delta T.$$

Storing the output signal of the detector at the ith unit modeling interval in an array $L[i]$:

$$L[i] = U_{OUT.DET}(i).$$

Calculating the corrected value of the amplifier gain:

$$K_{AGC} = \begin{cases} 1, & \text{if}\quad i \le M; \\ R1 + R2/L[i-M], & \text{if}\quad i > M. \end{cases}$$

Substituting $K_{AGC}(i)$ for $K_{AGC}(1)$ in (1), we repeat the calculation until simulation has been done over the entire modeling interval:

$$0 \le t \le T,\ \text{or}\quad 1 \le I \le N.$$

The array $L[i]$ contains a function describing the detector output variation with time over the entire simulation interval. If at least one element of the array is less than a threshold value P, it is a sign of a fire. Therefore, the minimum value in the array $L[i]$ is compared with the threshold P.

If min $\{L[i]\} > P$, the display shows “Standby”; if min $\{L[i]\} < P$, the display shows “Fire”.

Designing a block-diagram of the computer program implementing the mathematical model.

Figure 5 shows the block-diagram of a computer program. The dotted line represents the part responsible for signal processing. This part is made as a Script-file.

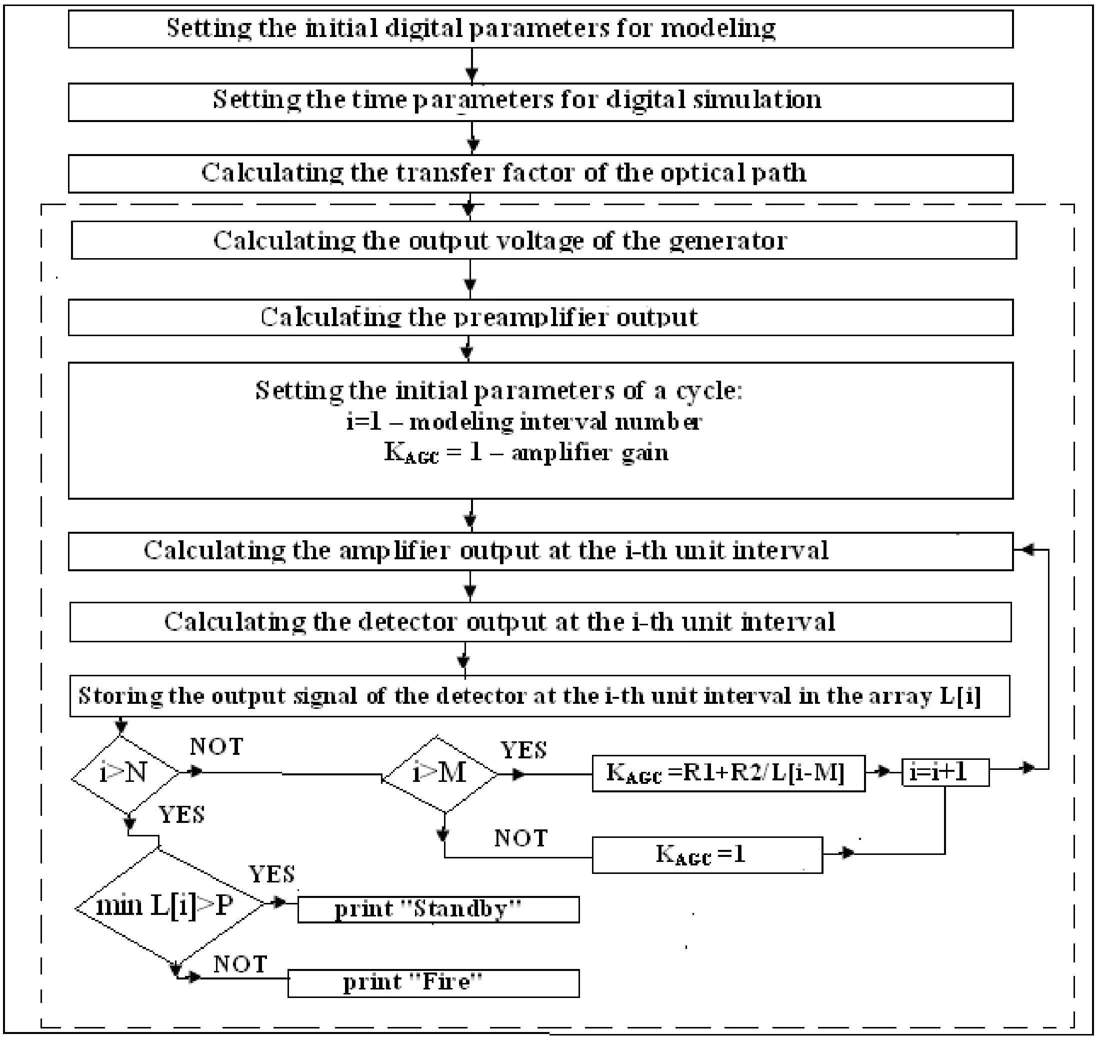

Fig. 5. Block-diagram of the computer program

In accordance with the above developed block-diagram of the computer program, a computer program has been written and debugged in the MATLAB environment.

```
T1 = 460∗10^-6; Q = 23; T = 10; dt = 10^-6;
U0 = 1; M = 1; R1 = 0.7; R2 = 0.3; P = 0.7;
t = 0: dt: T;
K = 0.5 + 0.5·exp(-t);
IR2.
```

In this case IR2 effects the execution of the following operators which are made as a Script-file.

Script-file **IR2**

```
y=U0*(0.5+0.5*square(2*pi*t/T1,100/Q));
Y=y.*K*Q*;Y1=Y;
L=zeros(1,40);L1=zeros(1,40);
i=1;
while i<=40
n1=1+0.25*(i-1)*10^6; n2=0.25*i*10^6;
w=trapz(t(n1:n2),Y(n1:n2))/0.25;
w1=trapz(t(n1:n2),Y1(n1:n2))/0.25;
L(i)=w;L1(i)=w1;
 z(n1:n2)=Y(n1:n2);
if i>M
Y=Y*(R1+R2/L(i-M));
end
i=i+1;
end
 B=min(L);
 if B<P
disp('Standby ')
```

```
else disp('Fire')
end
k1=L./L1;t1=0.25:0.25:10;
```

After the program has run, the screen shows a decision:

Standby

With the help of the operator *plot*:

```
plot (t1, L, t1, L1, t1, k1), grid
```

you can display the basic functions associated with the operation of the detector:

– transfer factor of the optical path;
– amplifier gain (regulated by AGC);
– detector output written to a storage device.

III. STUDING THE FIRE SMOKE LINEAR OPTOELECTRONIC DETECTOR BASED ON THE DEVELOPED COMPUTER MODEL

The fire smoke linear optoelectronic detector works as a tracking system monitoring the optical attenuation of the environment. The effectiveness of this tracking system determines the main characteristics of the detector.

If the system is too slow to respond to changes in environment attenuation, the decision that a fire is present is made for any gradual increase in attenuation – from changes in the composition of the gaseous medium, from the total dustiness of the premise, etc. In this case, false alarm probability is unacceptably large.

If the system is too quick to respond to changes in environment attenuation, then, in the case of a fire, the AGC system immediately restores the resolver input level. The decision that a fire is present is not made in this case, and the undetection probability is unacceptably high.

The tracking system quality is determined by:

– the integrator time constant (M – integrator time delay);
– the correction coefficients ($R1$ and $R2$) of the AGC unit gain.

We estimate the effect of these parameters on the tracking system quality for a typical case of smoke when a fire takes place. The transfer factor of the optical path is modeled by the function:

$$K_{OPT} = 0.5 + 0.5\exp(-t).$$

Study the effect of the integrator time delay (M) for constant values of the correction coefficients $R1 = 0.8$, $R2 = 0.2$.

Figure 6 shows: the transfer factor of the optical path (line *1*); the gain of the amplifier, the adjustable AGC (line *3*); the detector output (line *2*) stored in the memory unit for the system with the time delay of the integrator $\tau = 0.5$ sec ($M = 0$).

Figure 7 shows: the transfer factor of the optical path; the gain of the amplifier, the adjustable AGC; the output signal of the detector stored in the memory unit for the system with the time delay of the integrator $\tau = 2.5$ sec ($M = 4$).

We can see that an increased delay in the integrator increases the dip in the output signal curve, but at the same time it decreases the stability of the tracking system.

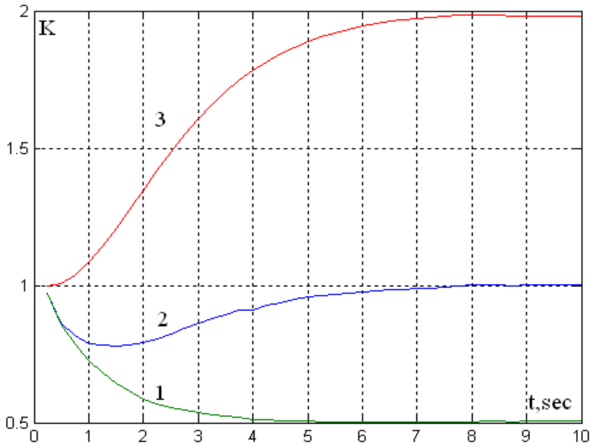

Fig. 6. Detector curves for $M = 0$, $R1 = 0.8$, $R2 = 0.2$

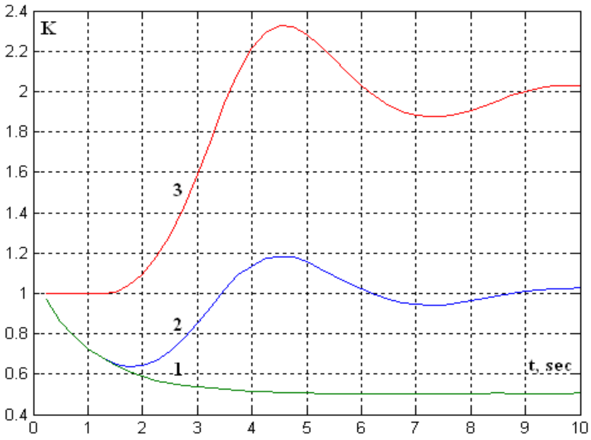

Fig. 7. Detector curves for $M = 4$, $R1 = 0.8$, $R2 = 0.2$

Consider the effect of the correction coefficients $R1$ and $R2$ for a constant time delay of the integrator (M).

Figure 8 shows: the transfer factor of the optical path; the gain of the amplifier, the adjustable AGC; the detector output stored in the memory unit for the system with the time delay of the integrator $M = 1$ and the correction coefficients $R1 = 0.5$, $R2 = 0.5$.

Figure 9 shows: the transfer factor of the optical path; the gain of the amplifier, the adjustable AGC; the detector output stored in the memory unit for the system with the time delay of the integrator $M = 3$ and the correction coefficients $R1 = 0.5$, $R2 = 0.5$.

Comparing Fig. 6 to Fig. 8 and Fig. 7 to Fig. 9 we can conclude that with decreasing $R1$ and increasing $R2$ the operation of the detector varies only slightly for a short delay in the integrator. The time of transition to a steady state does not change critically. But for a long time delay in the integrator, the transition to a steady state increases sharply and becomes unacceptably long. In this case self-excitation of the detector is possible (Fig. 9).

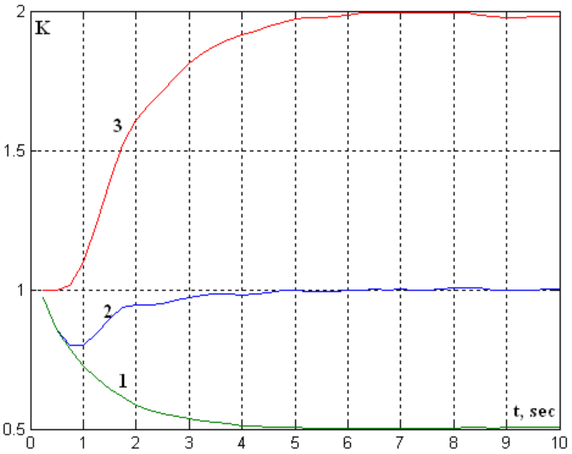

Fig. 8. Detector curves for *M*=1, *R*1=0.5, *R*2=0.5

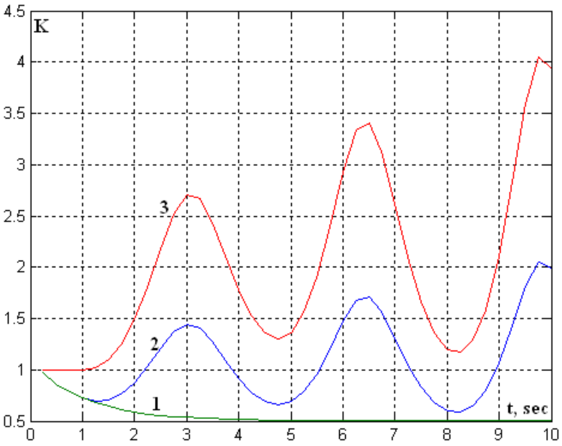

Fig. 9. Detector curves for *M*=3, *R*1=0.5, *R*2=0.5

IV. STUDYING THE EFFECT OF INTERFERENCE ON THE OPERATION OF THE FIRE SMOKE LINEAR OPTOELECTRONIC DETECTOR

False alarm of the detector may be caused by two main types of interference:

– weather conditions causing very slow changes in environment attenuation;

– birds crossing the detector beam and causing a short-term and rapid change in beam attenuation.

Figure 10 represents a very slow change in environment attenuation (line*1*)

$$K_{OPT} = 0.5 + 0.5\exp(-0.5t).$$

and the output signal of the detection unit of the detector that responds to this change (line *2*). This figure also shows a change in the smoky environment attenuation (line *3*) and the output signal of the detection unit according to Fig. 6 (line *2*). The parameters of the detector are: $M = 0$, $R1 = 0.8$, $R2 = 0.2$. We can see that the right choice of the threshold evaluation (e.g. $P = 0.80$) provides reliable separation of these two signals.

Figure 11 shows a short-term change in environment attenuation (line *1*) and the output signal of the detection unit of the detector responding to this change (line *2*). The parameters of the detector are the same. We can see that a simple threshold evaluation does not allow separating this interference and avoiding false alarms. However, we can also see that an additional evaluation of threshold exceedance time solves this problem.

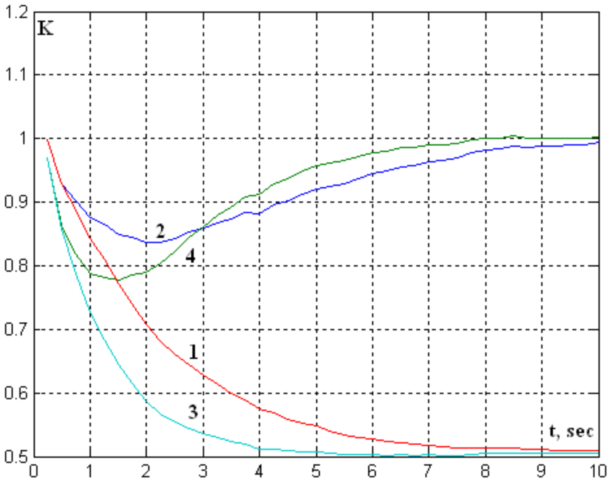

Fig. 10. Detector curves in the case of meteorological changes of the environment

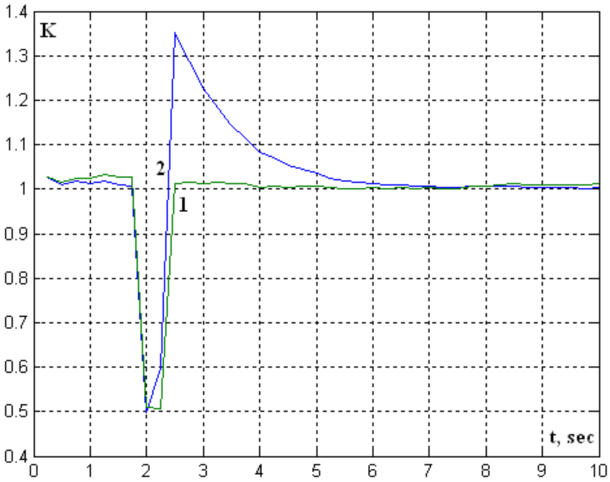

Fig. 11. Detector curves in the case of beam crossing by a bird

V. CONCLUSIONS

The developed model makes it possible to estimate the reliability of separating fire signals from interference/noise signals and determine signal parameters that cause false alarms.

The model also allows us to evaluate the quality of the signal processing algorithm used in this detector. It may be helpful both for developers of IR fire detectors in improving processing algorithms and for students in studying the principles of this type of detectors**.**

VI. REFERENCES

[1] Borisov, Y. P.; Tsvetnov, V. V. Mathematical modeling of radio systems and devices. Moscow, Radio and communication. 1985. 176 p. (in Russian).

[2] Sokolov, G. Ye. “A procedure of building a computer model of an optoelectronic measuring system.” *Electronic and Control Systems*. N 4(34), 2012. pp. 123–129.

Received 22 January 2014.

Sokolov Gennadii. Candidate of Physics and Mathematics Sciences. Associate Professor.
Department of Aviation Electronic Systems NAU, Kyiv, Ukraine.
Education: Moscow State Lomonosov University, Moscow, USSR (1976).
Direction of scientific activity: equipment security systems.
Number of publications: 63.
E-mail: gennadii_sokolov@mail.ru

Г. Є. Соколов. Побудова компьютерної моделі оптично-електронного пожежного димового сповіщувача

Проведено моделювання на рівні функціональної схеми оптично-електронного пасивного охоронного сповіщувача за допомогою Matlab. Розроблена модель дозволяє оцінити надійність розділення сигналів від пожежі та від завад у логічному блоці.

Ключові слова: моделювання систем; оптоелектроніка; охоронні сповіщувачі; Matlab.

Соколов Геннадій Євгенович. Кандидат фіз.-мат. наук. Доцент.
Кафедра авіаційних радіоелектронних комплексів, Національний авіаційний університет, Київ, Україна.
Освіта: Московський державний університет ім. М. В.Ломоносова, Москва, СРСР (1976).
Напрям наукової діяльності: апаратура систем безпеки.
Кількість публікацій: 63.
E-mail: gennadii_sokolov@mail.ru

Г. Е. Соколов. Построение компьютерной модели оптико-электронного пожарного дымового извещателя

Проведено моделирование на уровне функциональной схемы оптико-электронного пожарного дымового извещателя средствами Matlab. Разработанная модель позволяет оценить надежность разделения логическим блоком сигналов от пожара и сигналов от помех.

Ключевые слова: моделирование систем; оптоэлектроника; охранные извещатели; Matlab.

Соколов Геннадий Евгеньевич. Кандидат физ.-мат. наук. Доцент.
Кафедра авиационных радиоэлектронных комплексов, Национальный авиационный университет, Киев, Украина.
Образование: Московский государственный университет им. М. В.Ломоносова, Москва, СССР (1976).
Направление научной деятельности: аппаратура систем безопасности.
Количество публикаций: 63.
E-mail: gennadii_sokolov@mail.ru