Reduction of error and expansion of spatial range of measurement of the electrical field strength sensor

S V Biryukov¹, S S Kolmogorova¹, A S Kolmogorov and A V Tyukin²

¹Omsk State Technical University, 11, Mira ave., Omsk, 644050, Russia
²Siberian State Automobile and Highway University, Omsk, Russia

sbiryukov154@mail.ru

Abstract. The article is directed to improving the metrological characteristics of the previously investigated multi-element planar electro-induction sensor of the components of the electric field intensity vector. For this purpose, its mathematical model is made and analytic expression is obtained for error taking into account design parameters of sensor responsible for its error in nonuniform field and spatial range of measurement. Using mathematical model, geometric dimensions of sensitive elements of sensor are optimized in terms of minimum error and maximum of spatial measurement range. This allowed the following technical results to be obtained. At optimal parameter $b = h/L$ ($h$ - spacing between edges of sensor and electrode, $L$ - linear dimension of sensor) of sensor error from field nonuniformity does not go out beyond 3% in all spatial range $0 \leq a \leq 0.2$ ($a = L/d$, $d$ - distance to field source). Thus, the sensor can be used for measuring at distances from the source of the field $d$ equal to five linear dimensions $L$ ($d \approx 5L$).

1. Introduction

The conditions surrounding in the household and in the production of the electric equipment, the gametes and the organizer create unfavorable conditions for vital activity of a person. Under these conditions, a person twenty-four hours per day practically without protective means should be under the influence of electromagnetic fields, to a greater degree of electric fields. External electric fields are not felt by a person. However, the long residence time under the conditions of the action of the electric fields affects the self-feeling and ultimately on the health of the human. Therefore, for normal vital activity of a human, it is necessary for most of the time to find it in areas with reduced electric field strength. One solution to the above problem may be the method of finding the areas of the life space with reduced intensity of the electromagnetic field, in which a longer part of the time will be a person.

In order to solve the indicated problem, means for monitoring and measuring the intensity of the electric field are necessary, which makes it possible to use them under household conditions.

The existing whole number of measurement and measurement means, electric fields, is intended for use in industrial conditions and is not convenient in household conditions due to its significant mass-dimensional characteristics. Therefore, electric field strength sensors having a small mass and dimensions are needed to create the household measurement and control means. The manufacture of such sensors is possible using nanotechnologies that ensure their integration into modern gares, for example smart phones, calculators and others.
The first attempt by authors [4] to create small-sized electric field strength sensors has led to positive results. While sensors developed by the authors had high metrological characteristics (up to 2% error), however, the spatial range of measurement $a$ determined by the distance to the source of field $d$ was small and was $a = Md = 0.15$, where $M$ is the linear dimension of the sensor.

This work is directed to further investigation of the multi-electrode sensor of the components of the Field Strength vector, made in the form of a square plate, which provides for measurement of intensity in a wider spatial range than the precursor [4], and having guaranteed metrological characteristics. In conclusion of operation [4] it has been noted that the metrological characteristics of the sensor can be improved by solving the problem of optimizing the dimensions of the sensitive elements of the sensor. In this regard, in this regard, further studies will be conducted in this direction.

2. Formulation of the problem

In this article, for additional tests of the flat multielement sensor of the components of the intensity of the electric field are carried out in order to detect the geometric parameters of the sensor affecting its error and the spatial range of the measurement and perform their optimization. This results in the following problems:

1) create a structural model of a multi-element planar sensor of the component vector components of an electric field intensity vector;
2) set parameters of sensitive elements of sensor responsible for its error in nonuniform electric field;
3) optimization of sensor sensitive elements in terms of minimum of error and maximum of spatial measurement range;
4) estimate error of sensor with optimal sensitive elements in nonuniform electric fields.

3. Theory

The theoretical basis and method of construction of a planar three-coordinate sensor have been described in detail in [4]. It follows from the operation of [4] that it is necessary to use, for building a planar three-coordinate sensor, a method of three secant mutually perpendicular planes, and for providing symmetry of the sensor and equality of sensitivities along each coordinate axis, it is expedient to use as the basis of the sensor of the body of regular geometric shapes (sphere [5, 6], cube [7, 8], cylinder [9], disk [10, 11], square plate [12]).

In accordance with the stated objectives, further studies will be directed to creating a sensor with optimal design parameters. In the basis of construction of such a sensor it is expedient to put the conductive plate in the shape of a square and to form eight conducting sensitive elements of the sensor four on two bases of the conductive plate by the method of the three secant planes. In order to carry out the optimization of the sensitive elements of the multi-element sensor, its design model is made with an indication of its geometric parameters, is presented in fig. 1.
The sensor includes a conductive square plate 1, four pairs of conductive sensing elements, of which four elements 2 to 5 are arranged on one base of the plate and four elements 6 and 9 on the other base thereof. Sensitive elements are spaced apart from edge of plate by distance $h$, and from each other by distance $2h$ and are isolated from each other and base of plate having thickness of $2\tau$. The sensor elements are conductors of high resistivity, such as copper, silver, etc. The sensitive elements have the shape of a square with dimensions $l \times l$ and thickness $\delta$ and it parallel to the sides of a square plate with dimensions $2L \times 2L$, where $L = (L + h)$ (see fig. 1).

The structural model thus formed is a double field Intensity sensor, the base of which serves as a conductive plate playing the role of the middle point, which receives the potential of the reference point [9] of the field in which the sensor is placed. The described technical solution of the sensor is presented in the operation [13].

The authors adopt the following assumptions:. Sensor elements 2-9 (fig. 1) is a thin conducting layer with a thickness of $\delta << \tau$ (\(\delta\) nanometers) is obtained by sputtering and having the shape of a square-plate with the Dimensions $2L \times 2L$, $L >> \tau$. The sensing elements are isolated from the conductive base by a dielectric layer, a thickness of $\varepsilon << \tau$ (\(\varepsilon\) nanometers).

The accepted assumptions allow the sensing elements to be considered to be no other than the part of the conductive plate of the sensor base. They serve merely to remove the electric charges induced by the electric field from certain surfaces of the plate, which are induced by the electric field. The potentials of the sensor elements 2 to 9 can be considered to be equal to the potential of the conducting plate 1, and the sensitive elements are the surface of the plate.

Thus, the sensor is generally a single conductive planar surface.

The combination of sensitive elements 2-9 (fig. 1) in opposite pairs of groups, four elements in group and their location along axis X-2, 3, 6, 7 and 4, 5, 8, 9; along axis Y-2, 5, 6, 9 and 3, 4, 7, 8; along axis Z-2, 3, 4, 5 and 6, 7, 8, 9, form double sensor used in differential connection. Such an inclusion of the sensor compensates the in-phase components and increases its sensitivity.

The output signals of the sensor may be an electric current, an electric voltage, and an electric charge. In operation [4] it is shown that the electric charge is independent of the frequency of the electric field and the capacitances formed by the sensor elements. Therefore, it can function from a metrological point of view as the output signal of the sensor.

Consider the operation of a multi-element sensor in electric fields of different non-uniformity and to optimise its sensitive elements from the point of view of the minimum of the error and the maximum of the spatial measurement range.

**Multi-element sensor in homogeneous field.** The behavior of the multi-electrode sensor in a homogeneous field is described in detail in [4], so that here will not be described here. In operation, the distinctive features of the expressions for the output signals of the sensor caused by the structural change of its sensitive elements and introduction of the new parameters of the sensor responsible for its error and the spatial measurement range are described in detail.

Placing the multi-element sensor in an electric field. Electric charges are induced on conductive sensor elements 2-9 of sensor. The values of these charges will be proportional to the measured Electric field Strength $E$.

Electric charges are observed on formed groups of sensitive elements along axes X, Y and Z, note here that pairs of groups Are Separated by coordinate planes XOZ, YOZ and XOY, relative to which double sensors are formed on each coordinate axis.

Total charges of groups of sensitive elements belonging to coordinate axes X, Y and Z will be correspondingly equal:

**The x-axis**

$$Q_{0,2,3,6,7} = -8\varepsilon\varepsilon_0 l^2 (1 - 2b)^2 \cdot E_x; \quad (1)$$

$$Q_{0,4,5,8,9} = +8\varepsilon\varepsilon_0 l^2 (1 - 2b)^2 \cdot E_x; \quad (2)$$

**The y-axis**
The z-axis

\[ Q_{02,3,4,5} = -8\varepsilon_0 e L^2 (1 - 2b)^2 \cdot E_z, \]  
\[ Q_{03,4,7,8} = +8\varepsilon_0 e L^2 (1 - 2b)^2 \cdot E_y, \]  
\[ Q_{0,2,3,4,5} = -8\varepsilon_0 e L^2 (1 - 2b)^2 \cdot E_z, \]  
\[ Q_{0,6,7,8,9} = +8\varepsilon_0 e M^2 (1 - b)^2 \cdot E_z, \]

where in expressions (1)-(6)
\[ E_x(t) = E \cdot \cos \alpha, \quad E_y(t) = E \cdot \cos \beta \quad \text{and} \quad E_z(t) = E \cdot \cos \gamma; \]  
\[ \cos^2 \alpha + \cos^2 \beta + \cos^2 \gamma = 1 \]

and defining positions of electric field intensity vector in space; \( b = \frac{h}{L} \)-parameter responsible for error and spatial measurement range.

With differential connection of the double sensor, its differential charges along the \( x, y \) and \( z \) axes will be correspondingly equal
\[ Q_{0}^{\text{diff}}_x = Q_{04,5,8,9} - Q_{02,3,6,7} = 16\varepsilon_0 e L^2 (1 - 2b)^2 \cdot E_x; \]  
\[ Q_{0}^{\text{diff}}_y = Q_{03,4,7,8} - Q_{02,5,6,9} = 16\varepsilon_0 e L^2 (1 - 2b)^2 \cdot E_y; \]  
\[ Q_{0}^{\text{diff}}_z = Q_{06,7,8,9} - Q_{02,3,4,5} = 16\varepsilon_0 e M^2 (1 - b)^2 \cdot E_z. \]

The analysis of the expressions (9-11) shows that the sensitivity of the sensor on the coordinate axes \( x, y \) and \( z \) in the homogeneous field are identical and are functions of the structural dimension \( L \) of the conductive plate and the structural parameter of the sensor \( b \)
\[ G_{0}^{\text{diff}} = 16\varepsilon_0 e M^2 (1 - b)^2. \]

Since the design parameters of the sensor are constant, the sensitivity of the sensor in the homogeneous field remains constant. In this connection, the output electric charges of the sensor proportional to the intensity of the homogeneous electric field may act as a measure of the intensity of this field.

**Multi-element sensor in nonuniform field of point source.** The multi-element sensor in the electric field of the point positive electric charge \( q \) is represented by (fig. 2).
When analyzing the behavior of the sensor in the point charge field, the sensor will be considered as a conductive plate with a surface density of electric charge \[ \sigma \] (13),

\[
(x, y) = -\frac{2\varepsilon\varepsilon_0}{\varepsilon^2} \cdot E_{H} \cdot \left[ \frac{x^2 + y^2}{1 + \frac{x^2}{D^2} + \frac{y^2}{D^2}} \right]^{\frac{3}{2}}
\]

where \( E_{H} \) is intensity of nonuniform electric field.

Preserving all geometric relationships and design parameters of the sensor given in fig. 1 Is the electric charges induced on the sensor elements by the point charge field sensor \( q \):

Along the x-axis \( Q_{H, x} = -8\varepsilon\varepsilon_0 L^2 \times \)

\[
\frac{1}{a^2} \cdot \left[ \arctan \left( \frac{a^2 (1 - b)^2}{\sqrt{1 + 2a^2 (1 - b)^2}} \right) \right. \\
\left. - 2 \arctan \left( \frac{a^2 b (1 - b)}{\sqrt{1 + a^2 [b^2 + (1 - b)^2]}} \right) \right] + E_{H, x}.
\]

Along the y-axis \( Q_{H, y} = -8\varepsilon\varepsilon_0 L^2 \times \)

\[
\frac{1}{a^2} \cdot \left[ \arctan \left( \frac{a^2 (1 - b)^2}{\sqrt{1 + 2a^2 (1 - b)^2}} \right) \right. \\
\left. - 2 \arctan \left( \frac{a^2 b (1 - b)}{\sqrt{1 + a^2 [b^2 + (1 - b)^2]}} \right) \right] + E_{H, y}.
\]

Figure 2. Sensor in nonuniform electric field
The $y$-axis
\[ Q_{H2,3,5,7,9} = -8\varepsilon_0 L^2 \times \]
\[
\times \frac{1}{a^2} \left[ \frac{rc \tan \left( \frac{a^2 (1-b)^2}{\sqrt{1+2a^2 (1-b)^2}} \right) - 2 \arctan \left( \frac{a^2 b (1-b)}{\sqrt{1+a^2 [b^2 + (1-b)^2]}} \right) } { + \arctan \left( \frac{a^2 b^2}{\sqrt{1+2a^2 b^2}} \right) } \right] E_{H,y}. \tag{16}
\]
\[ Q_{H3,4,7,8} = +8\varepsilon_0 L^2 \times \]
\[
\times \frac{1}{a^2} \left[ \frac{\arctan \left( \frac{a^2 (1-b)^2}{\sqrt{1+2a^2 (1-b)^2}} \right) - 2 \arctan \left( \frac{a^2 b (1-b)}{\sqrt{1+a^2 [b^2 + (1-b)^2]}} \right) } { + \arctan \left( \frac{a^2 b^2}{\sqrt{1+2a^2 b^2}} \right) } \right] E_{H,y}. \tag{17}
\]

The $z$-axis
\[ Q_{H2,3,4,5} = -8\varepsilon_0 L^2 \times \]
\[
\times \frac{1}{a^2} \left[ \frac{rc \tan \left( \frac{a^2 (1-b)^2}{\sqrt{1+2a^2 (1-b)^2}} \right) - 2 \arctan \left( \frac{a^2 b (1-b)}{\sqrt{1+a^2 [b^2 + (1-b)^2]}} \right) } { + \arctan \left( \frac{a^2 b^2}{\sqrt{1+2a^2 b^2}} \right) } \right] E_{H,z}. \tag{18}
\]
\[ Q_{H6,7,8,9} = +8\varepsilon_0 L^2 \times \]
\[
\times \frac{1}{a^2} \left[ \frac{rc \tan \left( \frac{a^2 (1-b)^2}{\sqrt{1+2a^2 (1-b)^2}} \right) - 2 \arctan \left( \frac{a^2 b (1-b)}{\sqrt{1+a^2 [b^2 + (1-b)^2]}} \right) } { + \arctan \left( \frac{a^2 b^2}{\sqrt{1+2a^2 b^2}} \right) } \right] E_{H,z}. \tag{19}
\]

For a double sensor in differential actuation, the difference of the charge along the $x$, $y$ and $z$ axes can be written
\[ Q_{H, \text{diff}} = Q_{4,5,8,9} - Q_{2,3,6,7} = 16\varepsilon_0 L^2 \times \]
\[
\times \frac{1}{a^2} \left[ \frac{\arctan \left( \frac{a^2 (1-b)^2}{\sqrt{1+2a^2 (1-b)^2}} \right) - 2 \arctan \left( \frac{a^2 b (1-b)}{\sqrt{1+a^2 [b^2 + (1-b)^2]}} \right) } { + \arctan \left( \frac{a^2 b^2}{\sqrt{1+2a^2 b^2}} \right) } \right] E_{H,z}. \tag{20}
\]
uniform field of the point charge is not constant but depends on the design parameters expression (24) and responsible for error from field nonuniformity. Structural parameter field sensor itself, and on the parameters of the reaction medium, namely the distance to the source of the determines their error. For this purpose, the sensitivity of the sensor in a homogeneous field is assumed sensor determined by expressions (12) and (23) corresponds to homogeneous and nonuniform field and For this purpose, the estimate of the sensor error caused by the field nonuniformity is estimated. Sensor interactions parameter with the field \( a = L/d \) responsible for optimization of dimensions of sensitive elements providing minimum error of sensor.

\[
Q_{H,y}^{\text{eff}} = Q_{3,4,7,8} - Q_{2,5,6,9} = 16\varepsilon\varepsilon_0 L^2 \times \frac{1}{a^2} \left[ \arctan \left( \frac{a^2(1-b)^2}{\sqrt{1+2a^2(1-b)^2}} \right) - 2 \arctan \left( \frac{a^2b(1-b)}{\sqrt{1+a^2[b^2 + (1-b)^2]}} \right) \right] \quad E_{H,y}; \tag{21}
\]

\[
Q_{H,z}^{\text{eff}} = Q_{6,7,8,9} - Q_{2,3,4,5} = 16\varepsilon\varepsilon_0 L^2 \times \frac{1}{a^2} \left[ \arctan \left( \frac{a^2(1-b)^2}{\sqrt{1+2a^2(1-b)^2}} \right) - 2 \arctan \left( \frac{a^2b(1-b)}{\sqrt{1+a^2[b^2 + (1-b)^2]}} \right) \right] \quad E_{H,z}. \tag{22}
\]

According to expressions (20)-(22) differential sensitivity of the double sensor on three coordinate axes \( x, y \) and \( z \) is the same and is given by expression

\[
G_{H}^{\text{eff}} = 16\varepsilon\varepsilon_0 L^2 \frac{1}{a^2} \left[ \arctan \left( \frac{a^2(1-b)^2}{\sqrt{1+2a^2(1-b)^2}} \right) - 2 \arctan \left( \frac{a^2b(1-b)}{\sqrt{1+a^2[b^2 + (1-b)^2]}} \right) \right] + \arctan \frac{a^2b^2}{\sqrt{1+2a^2b^2}} \quad E_{H}. \tag{23}
\]

The analysis of the expression (23) shows that the differential sensitivity of the sensor in the non-uniform field of the point charge is not constant but depends on the design parameters \( L \) and \( b \) of the sensor itself, and on the parameters of the reaction medium, namely the distance to the source of the field \( a \).

4. Results

The final aim of the studies is to optimise the sensor elements of the sensor in terms of the minimum of error from the non-uniformity of the electric field and the maximum of the spatial measurement range. For this purpose, the estimate of the sensor error caused by the field nonuniformity is estimated. Sensor error arises due to its difference in sensitivity in homogeneous and nonuniform fields. Sensitivity of sensor determined by expressions (12) and (23) corresponds to homogeneous and nonuniform field and determines their error. For this purpose, the sensitivity of the sensor in a homogeneous field is assumed as a measure. Then, relative to it, the desired error of the sensor is determined by expression

\[
\delta(a,b) = \frac{G_{H}^{\text{eff}} - G_{0}^{\text{eff}}}{G_{0}^{\text{eff}}} \cdot 100 =
\begin{cases}
1 & \arctan \left( \frac{a^2(1-b)^2}{\sqrt{1+2a^2(1-b)^2}} \right) - 2 \arctan \left( \frac{a^2b(1-b)}{\sqrt{1+a^2[b^2 + (1-b)^2]}} \right) \\
+ \arctan \frac{a^2b^2}{\sqrt{1+2a^2b^2}} \quad (24)
\end{cases}
\]

The design parameters are analysed and the interaction parameters with the field included in the expression (24) and responsible for error from field nonuniformity. Structural parameter \( b = h/L \) is responsible for optimization of dimensions of sensitive elements providing minimum error of sensor. The interaction parameter with the field \( a = L/d \) is responsible for the expansion of the spatial
measurement range and determines the degree of field non-uniformity. At \( a = 0 \), the field close to the vicinity of the sensor approaches uniform, while the field tends to be 100% of the non-uniformity, and the field tends to be 100% of the non-uniformity.

By taking the mathematical program Mathcad, calculating and plotting plots of error (24) from field nonuniformity depending on parameters \( a \) and \( b \) (fig. 3).

Investigations performed on optimization of the error (24) caused by field nonuniformity using the mathematical program Mathcad have shown that a minimum of the sensor error \( \delta(a,b) \) and the maximum of the spatial measurement range \( a = L/d \) is performed at \( b = 0.5 \) (see fig. 3). At this value of parameter \( b \), however, sensor elements of the sensor are pulled to a point, so that further increase of parameter \( b \) loses its meaning. In connection with this, it is expedient to choose \( b = 0.4 \). This provides, first, saving of 20% of area of sensitive elements, and second, minimum of error at maximum of spatial measurement range.

From the plots of fig. 3 it follows that the error of the sensor in the whole spatial measurement range is negative and for the optimum \( b = 0.4 \) does not go beyond 3% in the whole spatial range \( 0 \leq a \leq 0.2 \). The sensor can be used for measuring at distances from the source of the field \( d \) equal to five linear dimensions \( L \) (\( d = 5L \)). Compared to the sensor used in [4, 14], the sensor discussed in the article has better metrological characteristics.

5. Conclusions
The results of the study make it possible to make the following conclusions: :
1) it is confirmed that it is possible to create a planar multi-element sensor of the components of the Field Strength vector with optimal dimensions of the sensitive elements providing minimum error at the maximum possible spatial measurement range;
2) it has been found that the multi-element sensor provides an error of measurement of the electric field strength to 3% in the spatial measurement range \( 0 \leq a \leq 0.2 \), and has the average metrological characteristics;
3) it has been found that in connection with negative error, the output signal of the sensor is proportional to the expected value of the charge.
In conclusion, it can be noted that in order to improve the metrological characteristics of the sensors considered in the article, it is necessary to search for new paths, not only with the dimensions of the sensor elements and the sensor, but also their forms.

References

[1] Meter of intensity of electrostatic field of ST-01. Manual MGFK 410000.001. URL: https://ntm.ru/UserFiles/File/product/EMF/ST01/manual_ST01.pdf (date of the application: 18.04.2019).
[2] Electrostatic field parameter meter IPEP-1. Manual УШЯИ.411153.002. URL: http://www.priborelektro.ru/price/IPEP-1.php4?deviceid=854 (date of the application: 12.04.2019).
[3] Meter of parameters of electric and magnetic fields VE-meter -AT-003 – 3D. Manual БВЕК43 1440.07. URL: http://ciklon-pribor.ru (date of the application: 12.04.2019).
[4] Biryukov S V and Tyukin A V 2019 Theoretical investigation of multi-electrode sensor of electric field intensity vector components in the form of square plate of conductive material (Omsk Scientific Herald. 2019 No 3 (165) p 46–53
[5] Misakian M Kotter F and Kahler R Miniature ELF Electric Field Probe (Instruments for scientific research. 1978 vol. 7) p 933-935
[6] Kamra A K Spherical field meter for measurement of the electric field vector (Review of Scientific Instruments. 1983. Vol. 54 (10) p 1401–1406. DOI: 10.1063/1.1137255.
[7] Pittman E P, Stanford R A 1972 Electric field sensor (US patent No. 3,641,427; filed September 24th, 1969; published February 08th, 1972).
[8] Gatman S 1968 Dual electric field meter with protection (Instruments for scientific research No. 1) pp 45-49
[9] Shchiglovskiy K B Akselrod V S 1978 Devices for measuring parameters of electrostatic field and their calibration (Measurement technology 1978. No. 5) p 63-65
[10] Biryukov S V and Korolyova M A 2017 Electroinduction disk sensor of electric field strength (IOP Conf. Series: Journal of Physics: Conf Series vol 944) p 012017-1 – 012017-8. DOI: 10.1088 / 1742-6596 / 944/1/012017
[11] Berent G. N. Electric Field sensor / G. N., Berent, I. R. Plays. // Instruments for scientific research. – 1971. – Vol. 6. – P.141-142.
[12] Biryukov S V and Shchapova L V 2017 The electric field intensity sensor in the form of a flat conductive plate in the form of a square (Omsk Scientific Bulletin No 5 (155) p 126-130.
[13] Biryukov S V and Blesman A I 2018 Electric field strength sensor (Russian Federation No. 194784 G01R29/12 / - No. 2019133600; Stated 23.10.2019; Publ. 23.12.2019, Bull. Number 36)
[14] Baicry M, Le Prado M 2016 Device for measuring an electric field in a conducting medium and method of calibrating such a device (US patent 0238646A1; filed February 17th, 2016; published August 18th, 2016)