

Multi-electrode sensors of the components of the electric field intensity vector in the form of the disk made of conductive material

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Abstract. The article investigates a multi-element disk sensor of the components of the low-frequency electric field intensity vector, manufactured using new technologies. The sensor is suitable for measuring the intensity of electric fields adversely affecting a person. In this regard, the problem solved in the article is relevant. The results of the study made it possible to create such a sensor, evaluate its metrological characteristics and establish their dependence on the degree of homogeneity of the electric field. The established relationship between the sensor error and the degree of heterogeneity of the electric field makes it possible to determine the spatial range of measurement from a given error or to establish the sensor error from a given spatial range of measurement. For example, a sensor error of 3% corresponds to the spatial measurement range a , determined by the distance to the field source from 0 to $5 \cdot R$ ($a \leq 0.2$), where R is the radius of the disk of the base of the sensor.

1. Introduction

To control the indicators of electric fields (EF), there are a number of measuring instruments [1-3], directly designed for these purposes. However, individual measuring instruments have significant mass-dimensional characteristics and at the right time are not at hand. In this regard, small-sized voltage sensors are required, manufactured using new technologies and able to be integrated into devices that are always at hand, such as smartphones, calculators and others.

The development of measuring instruments for studying EF is carried out both in Russia [4–8] and abroad [9, 10]. This work is devoted to the study of a multi-electrode sensor of the components of the electric field of the electric field of tension, made in the form of a disk of conductive material, structurally and technologically suitable for manufacturing by nanotechnology methods, and with guaranteed metrological characteristics.

2. Formulation of the problem

To research and consider the possibility of creating a flat multi-element sensor of the components of the electric field tension. To do this, it is necessary to solve the following tasks:

- 1) justify the choice of the shape of the base of the sensor, ensuring its integration into known gadgets;
- 2) to evaluate the error of the sensor in heterogeneous EF.



3. Theory

The construction of the sensor under study is based on the phenomenon of electrostatic induction and, formulated by the authors, the method of three secant mutually perpendicular planes. The essence of the method is reduced to conditionally dividing the body surface of a regular geometric shape by three mutually perpendicular secant planes into eight congruent surface sections. If each such surface part of the body is made of a conductive material (sprayed, glued, etched, etc.), then these areas can serve as sensitive elements of the sensor of the components of the electric field of the electric field. To ensure the symmetry of the sensor and the equality of sensitivities for each component of the electric field of the voltage vector, it is more expedient to use the body of the correct geometric shapes as the basis of the sensor (sphere [10, 11], cube [12, 13], cylinder [14], disk [15], square plate [sixteen]). For the first time, this method, without an application for its formulation, was used in [17] and further in [18].

According to the objectives, further research will be aimed at building and developing a sensor for the components of the electric field of the electric field of tension convenient for embedding into portable gadgets. In this regard, it is more expedient to put a conductive plate in the shape of a square as the basis for constructing the sensor.

According to the method of three mutually perpendicular secant planes, we divide the square plate into eight parts, as shown in Fig. 1a.

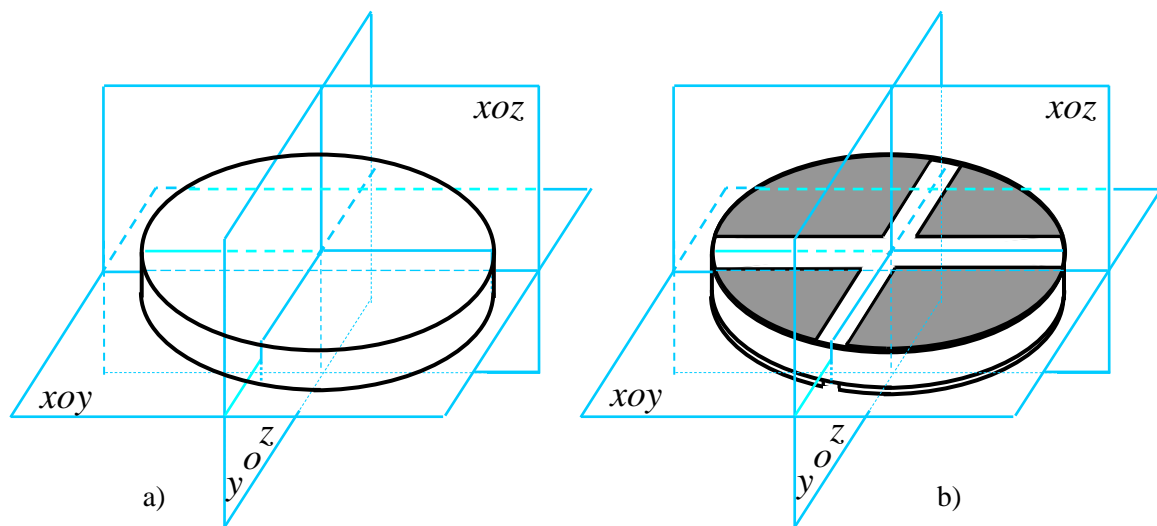


Figure 1. The division of the body of the disk by three secant planes into eight congruent parts

The plate lying at the base of the sensor can be either conductive or dielectric. The formation of the sensor's sensitive elements in the selected eight sections of the base of the plate (four sections on the upper base and four on the lower) can be performed by spraying, gluing, etching or other methods. If the plate is dielectric, then sensitive elements of a conductive material can be sprayed or glued onto it. If the dielectric plate with already applied conductive bases (foil fiberglass), then the sensitive elements can be etched. And finally, if the plate is conductive, then a thin dielectric layer with a thickness of about 10–20 μm is first deposited by spraying on its surface, and then a thin layer of conductive material. Thus formed, eight conducting sensors of the sensor are shown in Fig. 1b. As a result of the actions taken, a multi-element sensor of the components of the electric field of the electric field of tension is formed. The calculated constructive model of a multi-electrode sensor located in a homogeneous electric field with an indication of its geometric parameters is presented in Fig. 2.

The sensor consists of a conductive plate 1 having a circle shape in cross section, four pairs of conductive sensitive elements, of which four elements 2–5 are located on one base and four elements 6–9 are located on another base of the plate. Sensitive elements are distant from each other at a

distance of $2h$ and have no electrical connection between themselves and the base plate having a

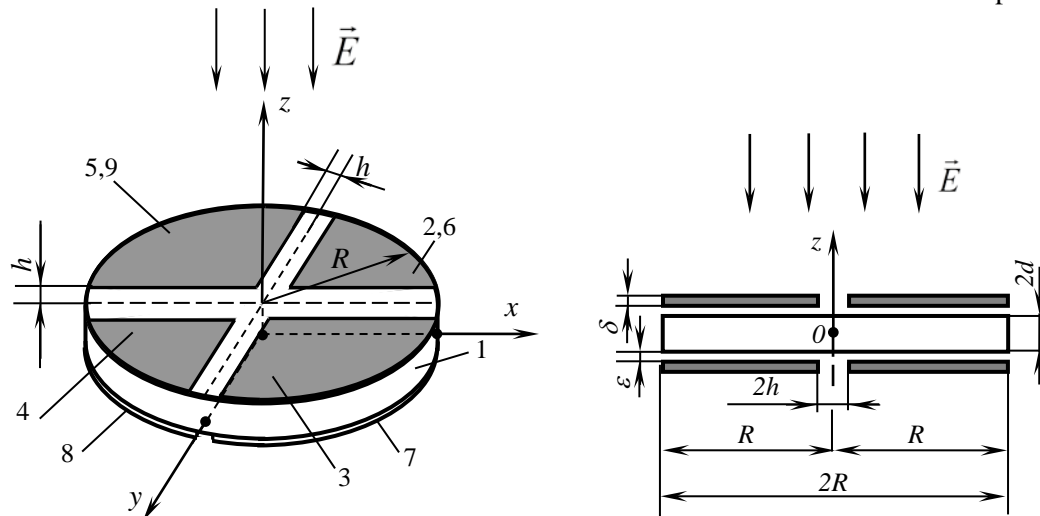


Figure 2. Calculation model of a multielectrode disk sensor in a homogeneous EF

thickness of $2d$.

They are made of a conductive material of small thickness δ , and have the form of a part of a quarter of a disk of radius R , the sides of which are parallel to the sides of the disk base with a radius.

Thus, a double voltage sensor is formed, the middle point of which will be a conductive base plate. In EF, this plate will take the potential of the reference point [14], i.e. that point in space in which the sensor is placed.

For further calculations, we accept the following assumptions. Sensitive elements 2–9 of the sensor (Fig. 2) are made in the form of a thin conductive layer with a thickness of $\delta \ll d$ (δ are from nanometers to microns), which has the same size and shape as a part of a quarter of a circle. Sensitive elements are isolated from the conducting surface of the plate by a dielectric layer with a thickness of $\varepsilon \ll d$ (ε is nanometers).

When a conductive plate is introduced into the electric field, electric charges are induced on its surface, which are proportional to the electric field strength [9]. To remove these charges from the necessary parts of the conductive surface of the plate, sensitive elements are used, which should be nothing more than the surface of the plate. For this, it is necessary to ensure, firstly, the isolation of the sensitive elements from the conductive plate, and, secondly, the equality of the potentials of the sensitive elements and the conductive plate. This is possible if the assumptions $\delta \ll h$ and $\varepsilon \ll d$ are accepted. Under these conditions (and additional measures taken), the potentials of the sensitive elements 2–9 can be considered equal to the potential of the conductive plate 1, and the sensitive elements - the surface of the plate. Thus, the sensor, in the General case, is something other than a flat conductive plate with square bases.

Consider the operation of the described multi-element sensor of the electric field tension in the boundary fields and evaluate its error. The boundary fields will be considered homogeneous and inhomogeneous EF. Conventionally, a homogeneous field is a field created between infinitely long conductive climbing plates, in which the sensor is located from the plates at distances much larger than its dimensions. We will consider this field as a reference and the sensor error in this field will be considered normalized. As an inhomogeneous field, we will consider a field created by a point source and having a high degree of heterogeneity. In this field, we estimate the error of the sensor caused by the heterogeneity of the EF.

Multi-electrode sensor in a uniform field. The sensor's work based on the consideration of a conducting disk of thickness d and radius R ($d \ll R$) placed in a homogeneous quasistatic EF with

intensity $E = E_m \cdot \sin \omega t$ was considered in [16]. Using the results of this work, we will conduct research on a multi-element sensor.

When the sensor is introduced into the electric field on its conductive sensitive elements 2–9, electric charges are induced whose magnitude is proportional to the measured electric field voltage E .

Electric charges on the sensing elements 2–9 of the sensor will be determined by the expression

$$Q = \iint_S \sigma \cdot dS, \quad (1)$$

Where $\sigma = -2\epsilon\epsilon_0 E_n = -2\epsilon\epsilon_0 \cdot E_O$ is the surface charge density; E_O is the intensity of a uniform electric field; S is the area of the sensing element.

By alternately directing the vector of the electric field intensity to the coordinate axes of the sensor x , y , and z , we find the electric charges induced by the electric field on parts of the plate surface, limited by the sizes of the sensitive elements 2–9.

If we direct the vector of the electric field voltage along the z axis of the sensor, then according to expression (1), the electric charges induced by the electric field on a diametrically located pair of sensitive elements 2 and 6 will be determined

$$Q_{O2,6} = \pm 2\epsilon\epsilon_0 R^2 \left[\left(1 - \frac{h}{M}\right)^2 - \left(1 - \frac{\pi}{4}\right) \right] \cdot E, \quad (2)$$

where Q_O is the charge induced by a homogeneous electron beam.

Denote the relation $\frac{h}{R} = b$ then expression (2) takes the form

$$Q_{O2,6} = \pm 2\epsilon\epsilon_0 R^2 \left[(1-b)^2 - \left(1 - \frac{\pi}{4}\right) \right] \cdot E. \quad (3)$$

Changing the boundaries of integration in expression (2), we find electric charges on other pairs of sensitive elements, such as 3 and 7, 4 and 8, 5 and 9. They will also be determined by expressions (2) and (3). Since, under the action of EP, positive charges move in the direction, and negative charges against the direction of the field, the minus sign in expression (2) will correspond to the charges on the sensitive elements 2, 3, 4 and 5, and the plus sign will correspond to the charges on the sensitive elements 6, 7, 8 and 9.

In the direction of the electric field of the electric field along the x and y axes of the sensor, electric charges on diametrically arranged pairs of sensing elements, for the x axis: 2 and 5, 3 and 4, 6 and 9, 7 and 8, and for the y axis: 5 and 4, 3 and 3, 8 and 8, 6 and 7 will also be defined by expressions (2) and (3).

If we combine the sensitive elements of 2–9 multi-element sensors (Fig. 2) into opposite pairs of groups, each of which consists of four elements: along the X axis - 2, 3, 6, 7 and 4, 5, 8, 9; along the Y axis - 2, 5, 6, 9 and 3, 4, 7, 8; along the Z axis - 2, 3, 4, 5 and 6, 7, 8, 9, separated by the coordinate planes XOZ , YOZ and XOY , a double sensor is formed of the components of the electric field of the electric field of the electric field. With that said, the total charges on the groups of sensitive elements will be respectively equal to:

x axis

first sensor

$$Q_{O2,3,6,7} = -8\epsilon\epsilon_0 R^2 \left[(1-b)^2 - \left(1 - \frac{\pi}{4}\right) \right] \cdot E_x; \quad (4)$$

second sensor

$$Q_{O4,5,8,9} = +8\epsilon\epsilon_0 R^2 \left[(1-b)^2 - \left(1 - \frac{\pi}{4}\right) \right] \cdot E_x \quad (5)$$

y axis

first sensor

$$Q_{O_{2,5,6,9}} = -8\epsilon\epsilon_0 R^2 \left[(1-b)^2 - \left(1 - \frac{\pi}{4}\right) \right] \cdot E_y; \quad (6)$$

second sensor

$$Q_{O_{3,4,7,8}} = +8\epsilon\epsilon_0 R^2 \left[(1-b)^2 - \left(1 - \frac{\pi}{4}\right) \right] \cdot E_y; \quad (7)$$

z axis

first sensor

$$Q_{O_{2,3,4,5}} = -8\epsilon\epsilon_0 M^2 \left[(1-b)^2 - \left(1 - \frac{\pi}{4}\right) \right] \cdot E_z. \quad (8)$$

second sensor

$$Q_{O_{6,7,8,9}} = +8\epsilon\epsilon_0 R^2 \left[(1-b)^2 - \left(1 - \frac{\pi}{4}\right) \right] \cdot E_z. \quad (9)$$

If you use a dual sensor in differential switching, then for the differential charges of the sensor along the x , y , and z axes, we can write

$$Q_{O_x}^{dif} = Q_{O_{4,5,8,9}} - Q_{O_{2,3,6,7}} = 16\epsilon\epsilon_0 R^2 \left[(1-b)^2 - \left(1 - \frac{\pi}{4}\right) \right] \cdot E_x; \quad (10)$$

$$Q_{O_y}^{dif} = Q_{O_{3,4,7,8}} - Q_{O_{2,5,6,9}} = 16\epsilon\epsilon_0 R^2 \left[(1-b)^2 - \left(1 - \frac{\pi}{4}\right) \right] \cdot E_y; \quad (11)$$

$$Q_{O_z}^{dif} = Q_{O_{6,7,8,9}} - Q_{O_{2,3,4,5}} = 16\epsilon\epsilon_0 R^2 \left[(1-b)^2 - \left(1 - \frac{\pi}{4}\right) \right] \cdot E_z. \quad (12)$$

From the expressions (10-12) it follows that the sensitivities of the formed EF voltage sensor along the three coordinate axes x , y , and z in a homogeneous field are the same and depend only on the radius R of the conducting disk of the sensor base and parameter b

$$G_O^{dif} = 16\epsilon\epsilon_0 R^2 \left[(1-b)^2 - \left(1 - \frac{\pi}{4}\right) \right]. \quad (13)$$

Since the size of the sensor and its parameters are unchanged, the sensitivity of the sensor, when it works in a uniform field, remains constant. Consequently, charges induced on sensitive elements proportional to the electric field strength can be a measure of the intensity of this field.

Multi-element sensor in an inhomogeneous field of a point source. The operation of the sensor in the electric field of a point source is based on the consideration of a conductive plate located in the field of a point positive electric charge q (Fig. 3)

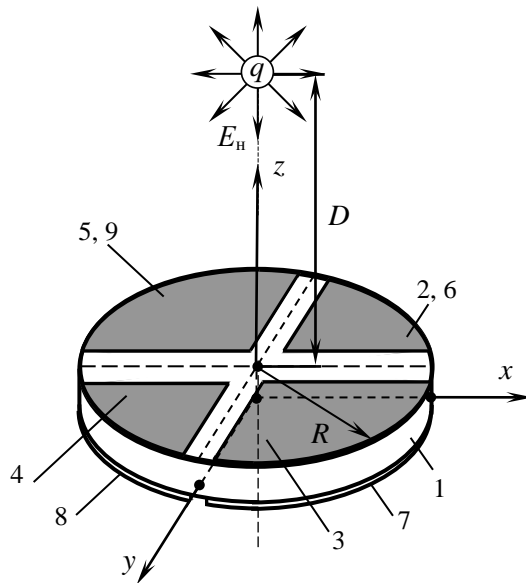


Figure 3. Multi-electrode sensor in a homogeneous electric field

We save all the geometric relationships of the sensor shown in Fig. 2 and used in considering its interaction with a uniform field. Using the above method, we find the electric charges induced on the sensitive elements of the sensor by the field of point charge q . The electric charges on the sensing elements 2–9 of the sensor will be determined by the expression (1), in which the surface charge density σ , is determined by the expression [16]

$$\sigma(x, y) = -\frac{2\epsilon\epsilon_0}{\left[1 + \frac{x^2}{D^2} + \frac{y^2}{D^2}\right]^{\frac{3}{2}}} \cdot E_H, \quad (14)$$

where E_H is the inhomogeneous field strength.

By alternately directing the vector of the electric field intensity to the coordinate axes of the sensor x , y , and z , we find the electric charges induced by the electric field on parts of the plate surface, limited by the sizes of the sensitive elements 2–9.

When the point source is directed along the z axis, the electric charges induced by the electron beam on a diametrically located pair of sensitive elements 2 and 6 are determined by the expression

$$Q_{H2,6} = \pm 2\epsilon\epsilon_0 R^2 \cdot \frac{1}{a^2} \cdot \left[\frac{\pi}{2} \left(1 - \frac{1}{\sqrt{1+a^2}} \right) - 2 \arctan \left(\frac{a^2 \cdot b}{\sqrt{1+a^2}(1+b^2)} \right) + \arctan \left(\frac{a^2 b^2}{\sqrt{1+2a^2 b^2}} \right) \right] E_H. \quad (15)$$

where Q_H is the charge induced by an inhomogeneous field; $a = \frac{R}{D}$, $b = \frac{h}{R}$, $a \cdot b = \frac{h}{D}$ – accepted normalization.

Similarly, we find electric charges on other pairs of sensitive elements, such as 3 and 7, 4 and 8, 5 and 9. They will also be determined by expression (15). In expression (15), the minus sign

corresponds to charges on the sensitive elements 2, 3, 4, and 5, and the plus sign corresponds to charges on the sensitive elements 6, 7, 8, and 9.

When the point charge is directed along the x and y axes of the sensor, electric charges on diametrically arranged pairs of sensing elements, for the x axis: 2 and 5, 3 and 4, 6 and 9, 7 and 8, and for the y axis: 5 and 4, 3 and 3, 8 and 8, 6 and 7 will also be determined by the expression (15).

Combining the sensitive elements of 2–9 multi-element sensors in pairs in groups along the x , y , and z coordinate axes, and forming a double sensor, as was done when considering the sensor in a uniform field, the total charges on each pair of groups of sensitive elements will be respectively equal to:

x axis
first sensor

$$Q_{H2,3,6,7} = -8\varepsilon\varepsilon_0 R^2 \times \frac{1}{a^2} \cdot \left[\frac{\pi}{2} \left(1 - \frac{1}{\sqrt{1+a^2}} \right) - 2 \arctan \left(\frac{a^2 \cdot b}{\sqrt{1+a^2}(1+b^2)} \right) + \arctan \left(\frac{a^2 b^2}{\sqrt{1+2a^2 b^2}} \right) \right] E_{Hx}. \quad (16)$$

second sensor

$$Q_{H4,5,8,9} = +8\varepsilon\varepsilon_0 R^2 \times \frac{1}{a^2} \cdot \left[\frac{\pi}{2} \left(1 - \frac{1}{\sqrt{1+a^2}} \right) - 2 \arctan \left(\frac{a^2 \cdot b}{\sqrt{1+a^2}(1+b^2)} \right) + \arctan \left(\frac{a^2 b^2}{\sqrt{1+2a^2 b^2}} \right) \right] E_{Hx}. \quad (17)$$

y axis
first sensor

$$Q_{H2,5,6,} = -8\varepsilon\varepsilon_0 R^2 \times \frac{1}{a^2} \cdot \left[\frac{\pi}{2} \left(1 - \frac{1}{\sqrt{1+a^2}} \right) - 2 \arctan \left(\frac{a^2 \cdot b}{\sqrt{1+a^2}(1+b^2)} \right) + \arctan \left(\frac{a^2 b^2}{\sqrt{1+2a^2 b^2}} \right) \right] E_{Hy}. \quad (18)$$

second sensor

$$Q_{H3,4,7,8} = +8\varepsilon\varepsilon_0 R^2 \times \frac{1}{a^2} \cdot \left[\frac{\pi}{2} \left(1 - \frac{1}{\sqrt{1+a^2}} \right) - 2 \arctan \left(\frac{a^2 \cdot b}{\sqrt{1+a^2}(1+b^2)} \right) + \arctan \left(\frac{a^2 b^2}{\sqrt{1+2a^2 b^2}} \right) \right] E_{Hy}. \quad (19)$$

z axis
first sensor

$$Q_{H2,3,4,5} = -8\epsilon\epsilon_0 R^2 \times \frac{1}{a^2} \cdot \left[\frac{\pi}{2} \left(1 - \frac{1}{\sqrt{1+a^2}} \right) - 2 \arctan \left(\frac{a^2 \cdot b}{\sqrt{1+a^2}(1+b^2)} \right) + \arctan \left(\frac{a^2 b^2}{\sqrt{1+2a^2 b^2}} \right) \right] E_{Hz}. \quad (20)$$

second sensor

$$Q_{H6,7,8,9} = +8\epsilon\epsilon_0 R^2 \times \frac{1}{a^2} \cdot \left[\frac{\pi}{2} \left(1 - \frac{1}{\sqrt{1+a^2}} \right) - 2 \arctan \left(\frac{a^2 \cdot b}{\sqrt{1+a^2}(1+b^2)} \right) + \arctan \left(\frac{a^2 b^2}{\sqrt{1+2a^2 b^2}} \right) \right] E_{Hz}. \quad (21)$$

If you use a dual sensor in differential switching, then for the differential charges of the sensor along the x, y, and z axes, we can write

$$Q_{Hx}^{dif} = Q_{4,5,8,9} - Q_{2,3,6,7} = 16\epsilon\epsilon_0 R^2 \times \frac{1}{a^2} \cdot \left[\frac{\pi}{2} \left(1 - \frac{1}{\sqrt{1+a^2}} \right) - 2 \arctan \left(\frac{a^2 \cdot b}{\sqrt{1+a^2}(1+b^2)} \right) + \arctan \left(\frac{a^2 b^2}{\sqrt{1+2a^2 b^2}} \right) \right] E_{Hx}; \quad (22)$$

$$Q_{Hy}^{dif} = Q_{3,4,7,8} - Q_{2,5,6,9} = 16\epsilon\epsilon_0 R^2 \times \frac{1}{a^2} \cdot \left[\frac{\pi}{2} \left(1 - \frac{1}{\sqrt{1+a^2}} \right) - 2 \arctan \left(\frac{a^2 \cdot b}{\sqrt{1+a^2}(1+b^2)} \right) + \arctan \left(\frac{a^2 b^2}{\sqrt{1+2a^2 b^2}} \right) \right] E_{Hy}; \quad (23)$$

$$Q_{Hz}^{dif} = Q_{6,7,8,9} - Q_{2,3,4,5} = 16\epsilon\epsilon_0 R^2 \times \frac{1}{a^2} \cdot \left[\frac{\pi}{2} \left(1 - \frac{1}{\sqrt{1+a^2}} \right) - 2 \arctan \left(\frac{a^2 \cdot b}{\sqrt{1+a^2}(1+b^2)} \right) + \arctan \left(\frac{a^2 b^2}{\sqrt{1+2a^2 b^2}} \right) \right] E_{Hz}. \quad (24)$$

From the expressions (22-24) it follows that the differential sensitivity of the double voltage sensor of the electric field along the three coordinate axes x, y and z is the same and is determined by the expression

$$G_H^{dif} = 16\epsilon\epsilon_0 R^2 \frac{1}{a^2} \cdot \left[\frac{\pi}{2} \left(1 - \frac{1}{\sqrt{1+a^2}} \right) - 2 \arctan \left(\frac{a^2 \cdot b}{\sqrt{1+a^2}(1+b^2)} \right) + \arctan \left(\frac{a^2 b^2}{\sqrt{1+2a^2 b^2}} \right) \right]. \quad (25)$$

According to (25), the differential sensitivity of the sensor located in an inhomogeneous field does not remain constant, but depends both on the design parameters R and b of the sensor itself, and on the parameters of the interacting medium, namely, on the distance to the field source a .

4. Results

Let us estimate the error of the sensor caused by the inhomogeneity of the field. To do this, we compare the sensitivity of the sensor located in uniform (13) and inhomogeneous (25) fields. We take the sensitivity of the sensor in a homogeneous field as a measure corresponding to a homogeneous field. Then, with respect to it, the desired error of the sensor is determined by the expression

$$\delta(a, b) = \frac{G_H^{dif} - G_O^{dif}}{G_O^{dif}} \cdot 100 =$$

$$= \left\{ \frac{1}{a^2 \left[(1-b)^2 - \left(1 - \frac{\pi}{4} \right) \right]} \cdot \left[\frac{\pi}{2} \left(1 - \frac{1}{\sqrt{1+a^2}} \right) - 2 \arctan \left(\frac{a^2 \cdot b}{\sqrt{1+a^2(1+b^2)}} \right) + \right. \right. \right. \quad (26)$$

$$\left. \left. \left. + \arctan \left(\frac{a^2 b^2}{\sqrt{1+2a^2 b^2}} \right) \right] - 1 \right\} \cdot 100.$$

We analyze and evaluate the error (26) of the sensor from the heterogeneity of the electron beam. To do this, we take into account the previously introduced normalizations $a = R/D$, $b = h/R$, where R is the radius of the disk of the base of the sensor; D is the distance from the center of the sensor to the source of the field. The normalizing parameter a determines the degree of field heterogeneity and characterizes the proximity of the sensor to the field source. Thus, with the distance of the sensor from the source of the electron beam ($a \rightarrow 0$), the field near the vicinity of the sensor approaches a uniform field. The most acceptable range of variation of the relative parameter a is from 0 to 1. In this case, the field varies from a uniform $a = 0$ to a field with 100% heterogeneity, $a = 1$. The normalizing parameter b is responsible for the design dimensions of the sensitive elements, the optimization of the sizes of which will allow to reduce the sensor error from field heterogeneity to the desired minimum.

We calculate and plot the error graphs (26) against the field inhomogeneity depending on the parameters a and b . To do this, we will use the mathematical editor MathCAD 14. The graph of the error from the inhomogeneity of the electromagnetism for a sensor with sensitive elements in the form of parts of a circle spaced $2h$ apart from each other, depending on the relative distance a and various values of the parameter $b = h/R$, is presented in Fig. 4.

Analysis Fig. 4 shows that the error of the multielectrode sensor in the entire spatial measurement range $a = R/D$ is negative. Moreover, the error of the sensor is minimal in a given spatial range of measurement a , if its sensitive elements are made in the form of a quarter circle, that is, at $h = 0$. For this case, the error of the sensor from the heterogeneity of the electric field $\delta = 3\%$ limits the spatial range of the measurement to $a \leq 0.2$. This corresponds to a distance from the source of the field D equal to approximately five radii R of the disk of the sensor base ($D \approx 5R$).

In comparison with the sensor used in [19], the sensor considered in the article has the best metrological characteristics.

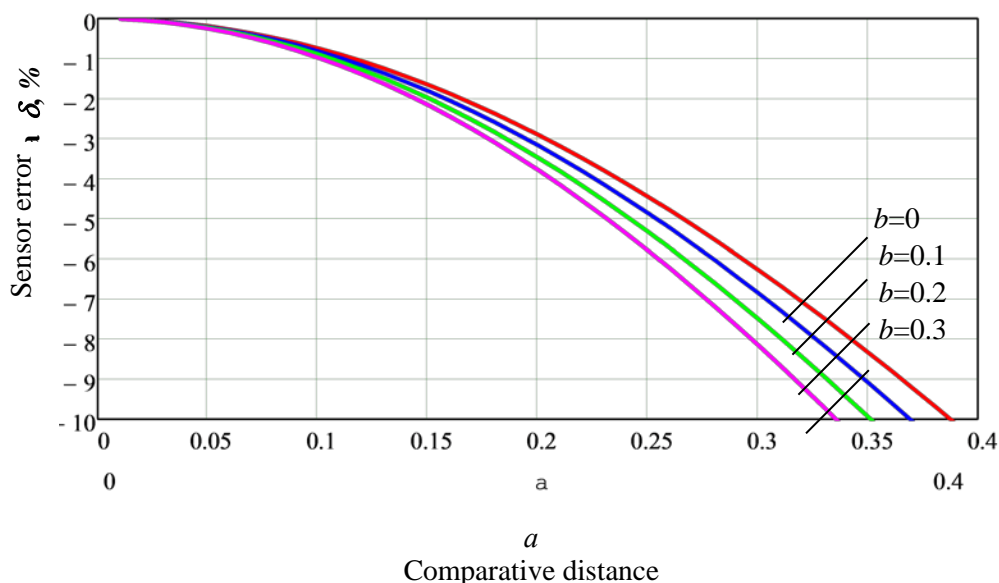


Figure 4. The error of the sensor from field inhomogeneity depending from the relative distance a and various values of the parameter $b = h/R$

5. Conclusions

The results of the study allow us to draw the following conclusions:

- 1) the method of three secant mutually perpendicular planes is formulated, which allows to obtain sensors of the components of the electric field of the electric field;
- 2) the possibility of creating a flat multi-element sensor of the components of the electric field of the electric field using the method of three secant mutually perpendicular planes is confirmed;
- 3) it was found that a multi-element sensor of electric field tension has a smaller error from the heterogeneity of electric field at the maximum possible spatial range of measurement with sensitive elements made in the form of a quarter circle;
- 4) it was found that the multi-element sensor of electric field tension has average metrological characteristics (error up to 3% with a spatial range of $a \approx 0.2$);
- 5) a restriction was established on the spatial range a of the sensor measurement by the limiting distance D to the field source with the given sensor error δ from the field inhomogeneity. For example, at $\delta = 3\%$, the spatial range is $a \approx 0.2$, then $D \approx 5R$, where R is the radius of the disk of the base of the sensor, and already at $\delta = 10\%$, $a \approx 0.38$, and $D \approx 2.6R$.
- 6) the sensor generates a signal proportional to the underestimated value of the charge induced by the inhomogeneous field, which will lead to a biased assessment of the effect of the electric field intensity on technical and biological objects.
- 7) the sensor has a layered structure representing the alternation of dielectric and conductive layers, the thickness of which can be tens of nanometers. This allows the sensor to be manufactured using nanotechnology methods.

In conclusion, it can be noted that the metrological characteristics of the sensor can be improved by solving the problem of optimizing the size of the sensitive elements of the sensor. Further research will be conducted in this direction.

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