Electromagnetic Field Interaction with a Dielectric Body of Ellipsoidal Shape

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Abstract - **The objective of this work is to create a theoretical model and to conduct the detail research of the electromagnetic radiation interaction with granular product and insects. The theoretical research on the electromagnetic wave interaction with granular agricultural product and insects is done in the present work through the solving of electromagnetic boundary problem [1]. It is well-known that boundary problems of electrodynamics are the most complicated ones in the mathematical physics and are urgent in the theory of wave processes. We use the methods based on integral equations of macroscopic electrodynamics to avoid complications at consideration of proper boundary problems.**

Key word - **boundary problem, macroscopic electrodynamics, seed**

I. INTRODUCTION

Protection of the agricultural product from harmful insects, mites and microscopic fungi is a worldwide problem of great importance of all mankind. For a long time it has been known that a high-frequency electromagnetic field penetrating a volume of grain results in the two positive effects. Heat developed in the grain causes drying. Heating of pests living in the grain to a temperature exceeding some critical level causes their mass mortality. This effect was suggested for use of microwave energy in protection of grain from pests. Knowledge of the dielectric properties of both grain crops and insects permits creating a model of electromagnetic field interaction with these biological objects. Each individual kernel is considered as a body of ellipsoid of rotation shape.

II. METHODOLOGY

A. Basic Electrodynamics Equations

The equations, which define a state of the put into external electromagnetic field body (Fig.1), are known as the constitutive equations. In a substance electromagnetic field is described by four vectors $H(\vec{r}), E(\vec{r}), B(\vec{r}), D(\vec{r})$. For majority of substances the constitutive equation may be expressed by the generalized Ohm's law

$$\vec{j}(\vec{r}) = \sigma\vec{E}(\vec{r}) + \frac{\chi}{\mu} rot\vec{B}(\vec{r}), \tag{1}$$

where $\vec{E}(\vec{r})$ is the electric field intensity vector, $\vec{B}(\vec{r})$ is the medium magnetic induction vector, σ is the medium conductance, χ is the medium magnetic susceptibility, μ is the medium magnetic permeability, $\vec{j}(\vec{r})$ is the electric current density induced with the external electric field $\vec{E}_0, \vec{H}_0$ in a medium.

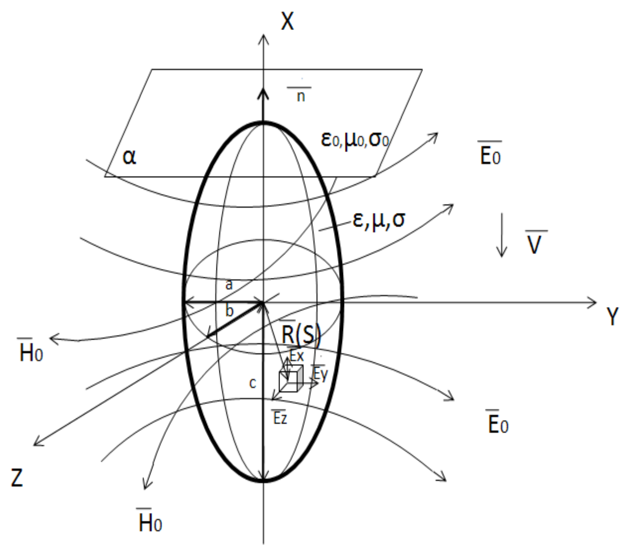

Fig. 1 Electromagnetic wave interaction with a small dielectric homogeneous ellipsoid of rotation.

The Maxwell equations for any medium are the following:

$$rot\vec{E} = -\frac{\partial\vec{B}}{\partial t},$$
$$rot\vec{H} = \frac{\partial\vec{D}}{\partial t} + \vec{j}, \tag{2}$$
$$div\vec{D} = \rho,$$
$$div\vec{B} = 0,$$

which are always completed with the constitutive equations

$$\vec{D} = \varepsilon_0\varepsilon\vec{E}$$
$$\vec{B} = \mu_0\mu\vec{H} \tag{3}$$

If to introduce the electromagnetic field potentials $\vec{A}$ and φ, therefore

$$\vec{B} = rot\vec{A}$$
$$\vec{E} = -grad\varphi - \frac{\partial\vec{A}}{\partial t}. \tag{4}$$

While executing the Lorenz calibration

$$\frac{1}{V_f^2}\frac{\partial\varphi}{\partial t} + div\vec{A} = 0 \tag{5}$$

wave equations have the form:

$$\Delta\varphi - \frac{1}{V_f^2}\frac{\partial^2\varphi}{\partial t^2} = -\frac{\rho}{\varepsilon_0\varepsilon},$$
$$\Delta\vec{A} - \frac{1}{V_f^2}\frac{\partial^2\vec{A}}{\partial t^2} = -\mu_0\mu\vec{j}, \tag{6}$$

where $V_f = c/\sqrt{\varepsilon\mu}$ is the wave phase velocity.

Solution of wave equations with Fourier-components of electromagnetic field potentials are written in the form:

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$$\vec{E}(\vec{r}) = \left(graddiv + k^2\varepsilon\mu\right)\cdot \vec{\Pi}(\vec{r}),$$
$$\vec{H}(\vec{r}) = \frac{jk}{w} rot\vec{\Pi}(\vec{r}), \tag{7}$$
$$\vec{\Pi}(\vec{r}) = \frac{1}{4\pi j\omega\varepsilon_0}\int \frac{\vec{j}(\vec{r})}{|\vec{r}-\vec{r}'|} e^{-jk|\vec{r}-\vec{r}'|} d\vec{r}$$

where $k = \omega\sqrt{\varepsilon_0\,\mu_0}$ is a wave vector, $w = \sqrt{\mu_0/\varepsilon_0}$ - wave resistance of free space.

More generally the electrical and magnetic induction vectors are determined by relations

$$\vec{D} = \vec{E} + 4\pi\vec{P}, \quad \vec{B} = \vec{H} + 4\pi\vec{M},$$

where vector $\vec{P}$ defines the electric polarization of a unit volume, and vector $\vec{M}$ defines its magnetic polarization. In a linear medium these dependences are: $\vec{D} = \varepsilon(\omega)\vec{E}$, $\vec{B} = \mu(\omega)\vec{H}$.

For anisotropic bodies these dependences are tensor

$$\vec{D} = \varepsilon_{ik}\vec{E}, \quad \vec{B} = \mu_{ik}\vec{H}, \tag{8}$$

where ε_{ik} and μ_{ik} are dielectric and magnetic permittivity tensors.

B. Electromagnetic wave interaction with small dielectric ellipsoid.

An electromagnetic wave of field intensities $\vec{E}_0(r)$ and $\vec{H}_0(\vec{r})$ is incident on the dielectric ellipsoid of rotation (Fig.1) of the volume V and the dielectric permittivity ε. We locate the ellipsoid into the origin of the Cartesian coordinate system, so as its surface equation have the canonical form [3]

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} = 1 \tag{9}$$

where a, b, c are the ellipsoid semi-axes. The ellipsoidal infinitesimal is prescribed with the condition $ka << 1$. To define the internal electric field it is needed to solve the integral equation

$$\vec{E}(\vec{r}) = \vec{E}_0(\vec{r}) + \frac{1}{4\pi} graddiv \int_V \frac{(\varepsilon-1)\vec{E}_0(\vec{r}')}{|\vec{r}-\vec{r}'|} d\vec{r}' \tag{10}$$

Since the ellipsoid is small, the internal field of the incident wave must be considered constant at the distances comparable with the ellipsoid size. That is for $\vec{r} \in V$ the external wave field is constant $\vec{E}_0(\vec{r}) = const$.

The Eq.(10) solution can be the Newton potential $W(\vec{r})$ [4] of the body of volume V with mass density $\mu(\vec{r})$, that is

$$W(\vec{r}) = \int_V \frac{\mu(\vec{r})d\vec{r}}{|\vec{r}-\vec{r}'|} \tag{11}$$

For the case $\mu(\vec{r}) = const$ and for the internal point of ellipsoid the Dirichlet formula takes place

$$W(\vec{r}) = C - \pi abc\mu\left(J_1x^2 + J_2y^2 + J_3z^2\right) \tag{12}$$

i.e. for internal points of homogeneous ellipsoid the volume potential is the uniform quadratic function of the Cartesian coordinates. For this case the integral Eq.(10) can be transformed into a system of simple linear algebraic equations of the following type

$$E_x = E_{ox} + \frac{1}{4\pi}\frac{\partial}{\partial x}\left\{(\varepsilon-1)E_x\frac{\partial W}{\partial x} + (\varepsilon-1)E_y\frac{\partial W}{\partial y} + (\varepsilon-1)E_z\frac{\partial W}{\partial z}\right\} \text{ etc.}$$

From this we can define the components of internal electric field (Fig.1)

$$E_x = \frac{E_{0x}}{1+\frac{abc}{2}(\varepsilon-1)J_1}, \quad E_y = \frac{E_{0y}}{1+\frac{abc}{2}(\varepsilon-1)J_2},$$
$$E_z = \frac{E_{0z}}{1+\frac{abc}{2}(\varepsilon-1)J_3} \tag{13}$$

The values J_1, J_2, J_3 are called the factors of field depolarization and depend only on the ellipsoid semi-axes, i.e.

$$J_1 = \int_0^\infty \frac{ds}{(a^2+s)\sqrt{R(s)}}, \quad J_2 = \int_0^\infty \frac{ds}{(b^2+s)\sqrt{R(s)}},$$
$$J_3 = \int_0^\infty \frac{ds}{(c^2+s)\sqrt{R(s)}} \tag{14}$$

where $R(s) = (a^2+s)(b^2+s)(c^2+s)$. For different cases the given integrals are written through elliptic integrals $(a \neq b \neq c)$ or elementary functions.

C. Dependence between real and imaginary parts of the medium dielectric permittivity

A plane electromagnetic wave can be written in the form of Fourier-components of the field

$$e^{i(\omega t - k\vec{r})} \text{ or } e^{-i(\omega t - k\vec{r})} \tag{15}$$

according to the dispersion equation $\vec{k} = \omega\sqrt{\varepsilon} = \omega\sqrt{|\varepsilon|}\left(\cos\delta \pm i\sin\delta\right)$, where $tg\delta = \varepsilon''/\varepsilon'$ (loss angle tangent), the plane wave can be written in the form

$$e^{i\left(\omega t - \omega\sqrt{|\varepsilon|}\vec{n}\vec{r}\cos\delta\right)} e^{\omega\sqrt{|\varepsilon|}\vec{n}\vec{r}\sin\delta},$$
$$e^{i\left(\omega\sqrt{|\varepsilon|}\vec{n}\vec{r}\cos\delta - \omega t\right)} e^{\omega\sqrt{|\varepsilon|}\vec{n}\vec{r}\sin\delta}. \tag{16}$$

Thus, the wave behavior at $r \to \infty$ depends considerably on the value δ. Wave attenuation condition will be fulfilled if δ in the first case will be negative and in the second one it will be positive. Therefore the value $\varepsilon''(\omega) = -\varepsilon''(-\omega)$ is the frequency non-pair function. For the same reason $\varepsilon'(\omega) = \varepsilon'(-\omega)$ is the frequency pair function.

One can determine important dependences between real and imaginary parts of medium dielectric permittivity. Imagine, that $\varepsilon(\omega)$ is the analytical function of the complex variable ω in the upper half-plane $\mathrm{Im}\,\omega > 0$. If one can know $\varepsilon(\omega)$ on the contour Γ $\left(\omega = \mathrm{Re}^{i\varphi}\right), R \to \infty$, value of this function in any point ω can be written as Cauchy integral

$$\varepsilon(\omega) = \frac{1}{2\pi i}\int_\Gamma \frac{\varepsilon(t)dt}{t-\omega} \tag{17}$$

The axis Γ is expanded onto two components: the axis of real values ω $(-\infty < \omega < +\infty)$ and the semicircle $0 \le \omega \le \pi$:

$$\varepsilon(\omega) = \frac{1}{\pi i}\int_{-\infty}^{+\infty}\frac{\varepsilon(t)dt}{t-\omega} + \frac{1}{\pi i}\lim_{R\to\infty}\int_0^\pi \frac{\varepsilon\left(\mathrm{Re}^{i\varphi}\right)\mathrm{Re}^{i\varphi}\,id\varphi}{\mathrm{Re}^{i\varphi}-\omega} \tag{18}$$

At $R \to \infty$ one can consider $\varepsilon(\omega)$ as some constant. Really, the dielectric permittivity is a substance macroscopic characteristic. It takes place, when intermolecular distances are small comparatively to the wavelength. If $\omega \to \infty$ and the wavelength is small in comparison with these distances, then $\varepsilon(\infty)$ can be considered a constant value.

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Therefore $$\frac{1}{i\pi}\lim_{R\to\infty}\varepsilon(\infty)\int_0^{\pi}\frac{\mathrm{Re}^{i\varphi}\,id\varphi}{\mathrm{Re}^{i\varphi}-\omega}=\varepsilon(\infty) \quad (19)$$

Thus

$$\varepsilon(\omega)-\varepsilon(\infty)=\frac{1}{\pi i}\int_{\Gamma}\frac{\varepsilon(t)dt}{t-\omega} \quad (20)$$

Substituting this expression for dielectric permittivity in a form of a complex number

$$\varepsilon(\omega)=\varepsilon'(\omega)-i\varepsilon''(\omega) \quad (21)$$

and dividing the Eq. (14) into the real and imaginary parts, we have

$$\varepsilon(\omega)-\varepsilon(\infty)=\frac{1}{\pi}\int_{\Gamma}\frac{\varepsilon''(t)dt}{t-\omega}=\frac{2}{\pi}\int_0^{\infty}\frac{\varepsilon''(t)tdt}{t^2-\omega^2}$$

$$\varepsilon''(\omega)=\frac{1}{\pi}\int_{-\infty}^{+\infty}\frac{\varepsilon'(t)dt}{t-\omega}=\frac{2}{\pi}\int_0^{\infty}\frac{\varepsilon'(t)\omega dt}{t^2-\omega^2} \quad (22)$$

So the real and imaginary parts of the dielectric permittivity are the integrals of the same type.

The dielectric permittivity is related a substance conductivity.

The substance conductivity can be represented as a complex value

$$\sigma=\sigma'-i\sigma'' \quad (23)$$

The value σ' is a real conductivity as far as the electric field intensity and the current density are the co-phase values. The value σ'' is the imaginary conductivity as far as the field vector and the current density vector are displaced in phase by $\pi/2$. Thus the dielectric permittivity can be represented as

$$\varepsilon(\omega)=1+\frac{\sigma}{i\omega}=\varepsilon'-i\varepsilon'' \quad (24)$$

where

$$\varepsilon'(\omega)=1+\frac{\sigma''}{\omega},\quad \varepsilon''(\omega)=\frac{\sigma'}{\omega} \quad (25)$$

The value $\varepsilon'(\omega)$ defines the wave phase velocity in a medium, and $\varepsilon''(\omega)$ defines the wave specific energy loss.

D. *Model of wave interaction with a grain seed*

From the standpoint of electrodynamics, each seed of grain is a material body of almost ellipsoidal shape [2] with definite macroscopic characteristics, which may be expressed as a complex dielectric permittivity

$$\varepsilon=\varepsilon'-i\varepsilon'' \quad (26)$$

(field dependence on time is assigned as $\exp(i\omega t)$). The grain mass is the sum of that of the individual seeds arranged one relative to another, so that an effective permittivity of the grain mass ε is defined by the equation of Clausius – Mosotti [1]:

$$\frac{\varepsilon-1}{\varepsilon+2}=C\frac{\varepsilon_0-\varepsilon_1}{\varepsilon_0+2\varepsilon_1} \quad (27)$$

where C is the volumetric concentration, or volume fraction, of granular particles. As well known, the Clausius-Mosotti formula for quasistatic conditions is valid in the limiting case of particles very much smaller than the wavelength of the high frequency or microwaves. In practical cases it is valid for diameters of particles less than about 2% of the free-space wavelength .In the present work the dielectric permittivity of the grain is measured experimentally in the range 20-150 MHz. Energy losses in grain will be determined through dielectric properties of the individual seeds. They are related by Eq. (27).

The physical model of any individual seed of grain is a stretched ellipsoid of rotation with permittivity (26), the imaginary part of which defines the release of electromagnetic energy in the form of heat. If σ is the seed conductivity, then $\varepsilon''=4\pi\sigma/\omega$ and

$$\mathrm{tg}\,\delta=\frac{\varepsilon''}{\varepsilon'}=\frac{4\pi\sigma}{\omega\varepsilon'} \quad (28)$$

The power released as heat in any individual seed is defined by the equation

$$W=\int_V\left[\vec{j}\vec{E}\right]dV \quad (29)$$

where $\vec{j}=\sigma\vec{E}$ is an electric current density in the seed, V is volume of the seed, σ is conductivity, which may be defined through $\mathrm{tg}\,\delta$ by Eq. (28).

The task leads to the definition of the field $\vec{E}$ inside the material body of ellipsoidal geometry in the approximation, when the wavelength considerably exceeds the linear dimensions of the ellipsoid. It is well-known that in this case [1] is presented as

$$\vec{E}=\begin{bmatrix}\frac{1}{1+\frac{a^2c}{2}(\varepsilon-1)l_1} & 0 & 0\\ 0 & \frac{1}{1+\frac{a^2c}{2}(\varepsilon-1)l_2} & 0\\ 0 & 0 & \frac{1}{1+\frac{a^2c}{2}(\varepsilon-1)l_3}\end{bmatrix}\cdot\begin{bmatrix}E_{ox}\\ E_{oy}\\ E_{oz}\end{bmatrix} \quad (30)$$

where

$$l_1=l_2=\frac{1}{\left(c^2-a^2\right)^{3/1}}\left(\frac{c}{a^2}\sqrt{c^2-a^2}-\ln\frac{c+\sqrt{c^2-a^2}}{a}\right),$$

$$l_3=\frac{1}{\left(c^2-a^2\right)^{3/1}}\left(\ln\frac{c+\sqrt{c^2-a^2}}{a}-\frac{1}{c}\sqrt{c^2-a^2}\right) \quad (31)$$

are depolarization parameters of the ellipsoid with semi-axis a, a and c, E_{0x}, E_{0y} and E_{0z} are the values of external electric field intensity. For spherical particles $l_1=l_2=l_3=\frac{2}{3}a^3$, where a is the radius, and therefore

$$\vec{E}=3\vec{E}_0^2\cdot(\varepsilon+2)^{-1} \quad (32)$$

If the deviation from the sphericity is not considerable, then

$$l_1=l_2=\frac{2}{3a^2\sqrt{1-e^2}}\left\{1-\frac{2e^2}{5}+0\left(e^4\right)\right\},$$

$$l_3=\frac{2}{3a^2\sqrt{1-e^2}}\left\{1-\frac{13}{5}e^2+0\left(e^4\right)\right\}, \quad (33)$$

where $e=\sqrt{1-(a/c)^2}$ is an eccentricity of the particle.

Finally one can define that

$$W=\sigma\cdot V\sum_{s=1}^{3}\frac{E_{0s}^2}{\left[1+\frac{3V}{8\pi}\left(\frac{\varepsilon'}{\varepsilon_1}-1\right)\cdot l_s\right]^2+\left(\frac{3V\sigma}{2\omega}l_s\right)^2}$$

for a stretched ellipsoid of rotation, and

$$W=\frac{9V\varepsilon_1E_{00}^2}{(\varepsilon+2\varepsilon_1)^2+(4\pi\sigma/\omega)^2} \quad (34)$$

for a sphere. Double reflection of electromagnetic field from individual particles of the granular body is taken into consideration through ε_1. Further the equations for spherical particles will be used, because, while ellipsoidal eccentricity varies over a rather wide range $0.1\le\varepsilon\le1.0$ the value of the released energy is the same as for spherical particles as follows.

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It is convenient to transform W

$$W = W_1 \cdot W_2 - W_1 \cdot \frac{9}{4\pi}\omega V \cdot \mathrm{tg}\,\delta \cdot E_0^2 \quad , \quad (35)$$

where W_1 is only a function of geometry of a dissipating body. For the ellipsoid

$$W = \frac{1}{9}\sum_{s=1}^{3} \frac{\varepsilon_1 \left(E_{0s}/E_{0,on}\right)^2}{\left[1+\frac{3V}{8\pi}\left(\frac{\varepsilon'}{\varepsilon_1}-1\right) I_s\right]^2 + \left(\frac{3V\sigma}{2\omega} I_s\right)^2}. \quad (36)$$

For the sphere (in the condition of $4\pi\sigma/\omega << (\varepsilon + 2\varepsilon_1$))

$$W_1 = \frac{\varepsilon_1}{(\varepsilon + 2\varepsilon_1)^2} \quad (37)$$

One can evaluate the function W_2 by the formula:

$$W_2 = \frac{9}{4\pi}\omega_0 V_{0n} tg\delta \cdot E_{0,on}^2 \left(\frac{V}{V_{on}}\right)\left(\frac{E}{E_{0,on}}\right)^2 \left(\frac{\omega}{\omega_0}\right). \quad (38)$$

This is an operating formula, which may be used for calculations, where V, E and ω are in fixed units and are not connected with an available system of units.

An individual seed of grain is considered as a stretched ellipsoid of rotation with semi-axes $a = 0.15cm, c = 0.3cm, V = (0.025 - 0.028)cm^3$. This means that a granular density covers a range 0.5-0.85, i.e. 1 cm^3 contains about 30-35 seeds. The dielectric permittivity of grain at the frequency 150 MHz is established as $\varepsilon = 2$ and $tg\delta = 0.04$.

Evaluating the multiplier W_1 one can note that its magnitude does not depend upon the shape of the seed and its dielectric permittivity. If $\varepsilon \approx 2.5$ and the spherical form of an individual seed is selected,

$$W_1 \approx 0.05 \quad (39)$$

and therefore the energy released in an individual seed per second at continuous operation of a generator will be:

$$W_2 = 0.35\left(\frac{V}{V_{on}}\right)\left(\frac{E}{E_{0,on}}\right)^2\left(\frac{\omega}{\omega_0}\right), J/s \quad (40)$$

In the case of pulsed operation of the high-frequency generator with pulse period to pulse duration ratio γ, the energy released in an individual seed will be defined by the equation:

$$W = \frac{0.35}{\gamma}\left(\frac{V}{V_{on}}\right)\left(\frac{E}{E_{0,on}}\right)^2\left(\frac{\omega}{\omega_0}\right), J/s \quad (41)$$

One can note that for heating of a seed to a temperature $T = T_0 + \Delta T$ (where T_0 is an initial temperature) the amount of heat required is

$$\Delta Q_1 = \rho \cdot V \cdot C_\rho \cdot \Delta T, kJ, \quad (42)$$

where C_p is specific heat capacity of grain.

Since both energy release in the region of grain W and the amount of heat necessary for its heating ΔQ have been proportional to seed volume, the value ΔT finally does not depend upon the volume of an individual seed and is defined by the equation:

$$\Delta T = \frac{0.35}{m_{0\rho}\gamma C_\rho}\left(\frac{E}{E_{=,on}}\right)^2\left(\frac{\omega}{\omega_{on}}\right), \quad (43)$$

where $m_{0\rho} = \rho \cdot V_{on}$ is the mass (kg) of an individual seed with a volume equal to the fixed one. To withdraw moisture of grain more energy expense is need for moisture evaporation Q_2.

Therefore, total energy expense to withdraw moisture of grain is equal to

$$\Delta Q = \Delta Q_1 + \Delta Q_2, \quad (44)$$

where $\Delta Q_2 = \frac{m_{0\rho}}{100}(L_F - L_I)q_n$, $L_{F,I}$ are final and initial moisture content of grain in %, q_n is specific heat of evaporation (kJ/kg). Taking into consideration heat losses for evaporation, one can define a temperature increase

$$\Delta T = \left[\frac{0.35}{m_{0\rho}\cdot\gamma C_\rho}\left(\frac{E}{E_{=,on}}\right)^2\left(\frac{\omega}{\omega_{on}}\right) - \frac{L_F - L_I}{100}\left(\frac{q_n}{C_\rho}\right)\right]. \quad (45)$$

III. CONCLUSIONS

From the mentioned above statements we can make the conclusions:

1. If a small homogeneous ellipsoid is put into the uniform external field, then the internal ellipsoid field will also be uniform.
2. Ellipsoid is the only convex figure, the Newton potential of which is the uniform quadratic function of Cartesian coordinates by the body homogeneous density. It means that the dielectric ellipsoid is the only figure, which has the uniform internal field in the external uniform electric field.

The objective of this work is mainly theoretical such as creating the model of electromagnetic interaction with a dielectric body of ellipsoid of rotation shape (an individual kernel or an insect). Nevertheless, through the solving of electromagnetic boundary problem one can understand deeper the necessity of both study and measurement of dielectric parameters of biological structures. These contribute significantly to the precise mathematical description of the present theoretical model. The dielectric parameters measurement and study relates the theoretical investigation with the experimental part of great importance that is grain drying and insect control. All these areas complete the knowledge on the complex technology of grain processing and insect control by the high-frequency electromagnetic radiation with the future perspective and advances for agriculture of Mexico and abroad.

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