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DETERMINING THE ELECTROMAGNETIC FIELD PARAMETERS TO KILL FLIES AT LIVESTOCK FACILITIES

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Розглянуто електромагнітний метод для знищення личинок мух – шкідників сільського господарства. З цією метою вирішено задачу про розподіл електромагнітних полів у їхньому організмі. Рішення проводиться на основі рівнянь Максвелла в інтегральній формі, які автоматично враховують граничні умови на поверхні розсіювачів. Оскільки пропонується електромагнітне випромінювання, довжина хвилі якого значно більша лінійних розмірів комах, отримані інтегральні рівняння визначені в наближенні квазістатики. Це дозволило перетворити інтегральні рівняння в систему лінійних неоднорідних рівнянь алгебри, рішенням яких стали компоненти електричного поля всередині личинок мух. Дослідження проведені для одношарових і двошарових комах еліпсоїдної форми. Отримані поля дають можливість визначити величини потенціалів, що виникають на покритті личинки, а також з'ясувати при яких значеннях відбувається пробій цього покриття, тобто загибель личинки мухи.

Для отримання залежності, що зв'язує кількість імаго з личинок мух з параметрами електромагнітного випромінювання при наявності адитивної перешкоди випадкового характеру, може бути застосовано повнофакторне планування другого порядку. Впливом електромагнітних полів піддавалися личинки мухи кінця другого віку. Опромінення личинок мухи електромагнітним випромінюванням здійснювалося в діапазоні частот 10,2–9,8 ГГц, щільністю потоку потужності 0,62–0,38 мВт/см^2 і експозицією 2–12 с. Розвиток личинок спостерігався до формування та виходу дорослої комахи.

На основі багатофакторного експерименту знайдено оптимальні значення частот опромінення, щільності потоку потужності і експозиції. Для пригнічення комах в тваринницьких приміщеннях, починаючи зі стадії личинки і до виходу імаго, необхідне електромагнітне випромінювання з параметрами: частота 10,2 ГГц; щільність потоку потужності 0,37 мВт/см^2; відносна нестабільність частоти генератора 10^{-8}; експозиція 6 с. Вихід імаго з лялечок личинок мух в тваринницькому приміщенні, опромінених електромагнітним випромінюванням, склав менше 5 %.

Проведений експеримент з поросятами показав, що при хімічному методі обробки приміщення приріст в живій вазі склав 7,2 %, а при електромагнітному способі – 9,2 %.

Менший приріст в живій вазі при хімічній обробці пов'язаний з тим, що хімічний розчин негативно впливає не тільки на мух і їх личинки, а й на тварин. Проведені дослідження можуть бути використані для створення промислових установок по знищенню мух в тваринницьких приміщеннях

Ключові слова: знищення личинок мух, інтегральні рівняння Максвелла, параметри електромагнітного поля

1. Introduction

One of the most urgent problems that the agrarian complex faces in the world at present is to improve the productivity of livestock. Among many factors that affect resolving a given task, a prominent place is taken by the process of improving the biological relationships between the parasitic insects and animals [1].

Insects-exoparasites reduce the productivity of cattle in meat, milk, and wool. Paper [2] established that following the destruction of flies in a pigsty, at the same amount of fodder and under the same conditions of keeping, an increase in the live weight of pigs grew from 360 to 390 g per day. If the number of flies on cattle reaches 200–300 pcs/head, the productivity of cattle reduces by 16 %, at 400–600 pcs/head – by 20–40 %. The presence of insect parasites in a pigsty leads to adult pigs losing 40 to 50 grams per day, on average. Dairy cattle productivity also falls in the range from 0.7 to 0.9 liters of milk per day [1, 3] in the presence of parasites.

Flies may also affect the sanitary quality of milk and meat, disseminating them with microbes, they spoil the silage and protein fodder, populating them with larvae. Most members of this group cause diseases by attacking the cattle. Houseflies that are in contact with sewage, sputum and other infectious material carry the bacteria on their paws or mouth parts, contaminate food and other items that they land on. Under certain conditions, flies are the most effective disseminators of infectious diseases [2]. Therefore, protecting the farm animals from insect parasites contributes to the recovery of livestock, preservation of livestock products, as well as improves the profitability of this important sector in the economy of the country [4].

It was established that in order to improve the livestock and raise the productivity, it is necessary to reduce the number of parasites-insects so that it does not exceed 10 pieces per animal [1, 2].

One of the promising directions to kill flies and their larvae at livestock facilities is the use of electromagnetic radiation. The scientific foundation of current research is the fact that electromagnetic processes are not concomitant, but the essential factors of vital activity of any living organism, including the larvae of flies. This means that at a particular exposure, surface density of power, and at relevant frequency values, the electromagnetic field will be associated with the inhibitory effect on the larvae of flies.

However, to create the electromagnetic technology, it is required to undertake a research aimed at giving an analytical description of the electromagnetic processes at the cellular, molecular and organism levels of insects [5]. The lack of theoretical studies into the influence of electromagnetic fields (EMF) in the extremely high frequency (EHF) range on the larvae of flies at livestock facilities makes it a problematic task to manage populations of insects-parasites at livestock facilities. This confirms the relevance of our research.

2. Literature review and problem statement

Papers [6, 7] consider methods to control pests at livestock facilities. The most effective form of protection of cattle from insects are chemical preparations. Chemicals are used for spraying both the herds of animals and livestock facilities.

The disadvantages of chemical methods are in that they kill not only flies and their larvae, but also insects of beneficial species. In addition, chemical preparations pollute the atmosphere at tens or hundreds of kilometers from the place of its application. The disadvantages related to the chemical means for the protection of cattle from insects necessitate the development of a more efficient technology without toxic substances.

Theoretical and experimental studies reveal that at of a certain exposure, surface density of power and at the relevant frequency values, the action of an electromagnetic field will be associated with the inhibitory effect for a specific species of insects [8]. However, determining the optimal parameters for an electromagnetic field to suppress the viability of fly larvae requires the development of a model and needs theoretical studies on its basis.

Paper [9] established that in order to obtain a biological effect on insects, it is required to attain the intensity of electromagnetic influence in the range of 0.3...0.8 mW/cm^2. The magnitude of intensity of the electromagnetic influence can be determined analytically or experimentally. The magnitude of the power flux density of electromagnetic radiation to kill the larvae of flies must exceed the level of weak non-covalent bonds and noises in the larvae of flies.

Paper [10] notes that the effect of electromagnetic radiation on insects is largely due to the peculiarities of the structure and function of insects' membranes. The effect of electromagnetic radiation on biological membranes is largely attributable to the features in their structural organization. The structural organization of membranes constitutes the highly-ordered supramolecular ensembles possessing pronounced vector properties. In this case, it is very likely that the action of electromagnetic energy on larvae entails the redistribution of electrical forces involved in the stabilization of the membrane. The result is a change in the degree of binding K^+, Ca^{2+} and other ions in the membrane. The effect of electromagnetic radiation on larvae results in a change in the physical-chemical properties of the membrane surface (microviscosity, surface tension, effective charge) and leads to its destruction.

At certain parameters, EMFs are widely used to enable suppressing action on insects [11]. Paper [11] shows that the cells of insects are able to absorb the electromagnetic energy from a millimeter range of wavelengths. All changes that are significant for larvae start and finish at the cellular level. The cell is a universal complex, the initial and final stage of the implementation of all biological processes. Absorbed energy alters metabolic changes and biosynthetic processes and, under certain EMF parameters such as frequency, power, exposure, may slow down and suppress the cell growth.

The effect of electromagnetic energy, instead of chemical etching, was utilized for the treatment of such foods as grain [12]. A disinfection effect at microwave irradiation was registered at a temperature of 40...50 °C. The effect was observed for all forms of the insect development (egg, larvae, imago). At the same time, it ensured a 100 % destruction of pathogenic microflora, which negatively affects the seeds during storage. Treating the seeds with electromagnetic radiation showed that the disinfection effect could be achieved only at a certain exposure, power surface density, and frequency. The required parameters for electromagnetic radiation to suppress the vital activity of specific insects and their larvae can be obtained only theoretically.

Microwave treatment of animal feed aimed to improve their sanitary quality and nutritive properties is described in paper [13]. The disinfection effect is achieved at temperatures lower than those during traditional treatment; animal feed storage duration increases significantly. A given technology enables to reduce gastrointestinal diseases and the die-off of cattle when feeding the livestock, to improve the cattle weight gain by 13–25 %, to decrease the required amount of fodder by 50 %, to reduce the consumption of animal feed by 12–15 %.

Very effective has proven to be the use of electromagnetic energy for the decontamination and disinfection of medicinal plants, collagen bandages, structured and regenerated skin, to sterilize tools, tableware, clothing, shoes, premises [14].

Authors of papers [13, 14] applied thermal electromagnetic methods related to the large energy consumption, 10–100 W. It should be noted that the use of electromagnetic energy to suppress the vital activity of the larvae of flies with a power flow density of 0.3...0.8 mW/cm^2 is possible only at the optimal combination of biotropic EMF parameters (frequency, power flux density, exposure, etc.). However, determining the optimal parameters for EMF to kill the larvae of flies requires the construction of models that would take into consideration parameters of the EMF acting on the microorganisms, as well as the microorganisms' electrophysical parameters.

Despite the progress made in the research into effects of EMF on biological objects, many primary molecular mechanisms of these effects are almost undefined yet. This circumstance leads to the reports in the scientific literature about a large number of hypothetical mechanisms of the EMF impact, which are not substantiated physically. All this is explained, on the one hand, by the inadequacy of a purely physical approach to living matter, and, on the other hand, by the impossibility to find an adequate and simple model of the processes occurring in biological structures. Conducting a theoretical research into effects of EMF on the fly larvae would make it possible to elucidate patterns in the relationships between the molecular and systemic levels and to define the direction to combat insect pests.

3. The aim and objectives of the study

The aim of this study is to conduct theoretical and experimental research into development of the electromagnetic technology and determining the electromagnetic field parameters (frequency, power flux density, and exposure) aimed to kill the larvae of flies at livestock facilities.

To accomplish the aim, the following tasks have been set:

– to investigate theoretically the process of interaction between electromagnetic radiation (EMR) and the larvae of flies, and to substantiate the parameters of electromagnetic radiation to kill the larvae of flies;

– to carry out experimental study into the application of electromagnetic radiation to kill the larvae of flies under industrial conditions.

4. Theoretical analysis of the interaction of electromagnetic fields with insect larvae

Because it is almost impossible to conduct experimental study into the electromagnetic field distribution inside the body of fly larvae, there is an issue on solving this task using theoretical methods.

From the point of view of electrodynamics, the tasks of a given type come down to problems on diffraction (scattering and penetration) of the electromagnetic field on dielectric solids, with or without losses. Taking the larvae as a diffuser, we shall consider their body shape in the form of a triaxial ellipsoid.

A solution to this problem can be obtained for the biological objects whose dimensions are small compared with the length of the incident wave. In this case, the problem becomes a problem of quasi-statics; the fields inside are defined by the strength of the electrical and magnetic components at the surface of the larva. Such an approach makes it possible to decompose electromagnetic fields inside and outside the scattering body by small parameter l/λ, where l are the linear body measurements, λ is the scattered length wave [15].

Let the space in which the irradiated object is, be uniform and characterized by dielectric and magnetic permeabilities ε_0 and $\mu=4\pi 10^{-7}$ Gn/m. Then the electromagnetic field $\vec{E}$ and $\vec{H}$ at all points of this space will be described by the Maxwell equations:

$$\operatorname{rot}\vec{E}+i\omega\mu_0\vec{H}=0;\quad \operatorname{rot}\vec{H}-i\omega\varepsilon_0\vec{E}=0. \tag{1}$$

In this case, the irradiated object is characterized by permeabilities ε and μ_0 (the first layer is characterized by permeabilities ε_1 and μ_0, the second – ε_2 and μ_0). In this case, at the internal points of larvae the dielectric permeability ε is considered to be a coordinate function that changes in jumps when alternating the layers. After simple transforms, applying the Green, equation (1) can be reduced to the Maxwell integral equations in conjunction with boundary conditions at the interface of two environments [15]:

$$\begin{cases}\vec{E}(\vec{r})=\vec{E}_0(\vec{r})+\dfrac{1}{4\pi}\left(\operatorname{grad}\operatorname{div}+k^2\right)\displaystyle\int_V\left(\dfrac{\varepsilon}{\varepsilon_0}-1\right)\vec{E}(\vec{r}')f\left(\left|\vec{r}-\vec{r}'\right|\right)\mathrm{d}\vec{r}';\\ \vec{H}(\vec{r})=H_0(\vec{r})+\dfrac{i\omega\varepsilon_0}{4\pi}\operatorname{rot}\displaystyle\int_V\left(\dfrac{\varepsilon}{\varepsilon_0}-1\right)\vec{E}(\vec{r}')f\left(\left|\vec{r}-\vec{r}'\right|\right)\mathrm{d}\vec{r}',\end{cases} \tag{2}$$

where

$$f\left(\left|\vec{r}-\vec{r}'\right|\right)=e^{-ik\left|\vec{r}-\vec{r}'\right|}\Big/\left|\vec{r}-\vec{r}'\right|;$$

$k=2\pi/\lambda$ is the wavenumber; $\vec{E}_0(\vec{r})$ and $\vec{H}_0(\vec{r})$ are electric and magnetic fields, respectively, that would exist at arbitrary point $\vec{r}$ if there is no a biological diffuser; r' are the coordinates of points inside the scattering object.

Integrals in equation (2) apply to the entire volume V, occupied by the larva.

If point $\vec{r}$ is inside the volume V, occupied by the larva of a fly, then fields to the left are the fields in the body of the larva. In this case, equations (2) are nothing short of heterogeneous linear integral equations that define the electromagnetic field inside the larva. If point $\vec{r}$ lies outside the region of V, equations (2) are the equalities defining the field outside of the larva through the undisturbed field (first term) and the diffused field (second term).

For the convenience of the following calculations, we shall represent the scattered wave through the Herz electric and magnetic potentials $\vec{\Pi}^E$ and $\vec{\Pi}^{\mathrm{M}}$ [16] using ratios:

$$\begin{cases}\vec{E}(\vec{r})=\vec{E}_0(\vec{r})+\left(\operatorname{grad}\operatorname{div}+k^2\right)\vec{\Pi}^E;\\ \vec{H}(\vec{r})=\vec{H}_0(\vec{r})+i\omega\varepsilon_0\operatorname{rot}\vec{\Pi}^E,\end{cases} \tag{3}$$

where

$$\vec{\Pi}^E=\frac{1}{4\pi}\int_V\left(\frac{\varepsilon}{\varepsilon_0}-1\right)\vec{E}(\vec{r}')f\left(\left|\vec{r}-\vec{r}'\right|\right)\mathrm{d}\vec{r}',$$

$$\vec{\Pi}^M=0.$$

Solutions to integral equations (2) can be greatly simplified if we take into account that we examine the insects whose linear dimensions are small compared to the length of the incident wave. In this case, expressions for the fields inside the insect, as well as in the near zone, can be decomposed by the powers of small parameter l/λ. The same can be performed with function $f\left(\left|\vec{r}-\vec{r}'\right|\right)$ [17].

By equating components with the same powers of (ik) in the left and right parts of equations (3), we obtain a system of equations for a zero approximation, which will suffice in a given case:

$$\vec{E}^{(0)}(\vec{r})=\vec{E}_0^{(0)}(\vec{r})+$$
$$+\frac{1}{4\pi}\operatorname{grad}\operatorname{div}\int_V\left(\frac{\varepsilon}{\varepsilon_0}-1\right)\vec{E}^{(0)}(\vec{r}')\frac{1}{\left|\vec{r}-\vec{r}'\right|}\mathrm{d}\vec{r}';$$

$$\vec{H}^{(0)}(\vec{r})=\vec{H}_0^{(0)}(\vec{r}). \tag{4}$$

In equations (4), the free term for zero approximation is a constant vector equal to the amplitude of the incident field.

When solving equations (4), a characteristic shape for the larvae of insects, satisfying requirement $l/\lambda \ll 1,$ is the ellipsoid. In this case, to solve integral equations (4), it is expedient to introduce an auxiliary function *W*, which is the Newtonian potential for a homogeneous ellipsoid [18]:

$$W(\vec{r}) = \int_V \frac{d\vec{r}'}{|\vec{r}-\vec{r}'|}. \qquad (5)$$

Variables $\vec{r}$ and $\vec{r}'$ are under the sign of the integral in the form of a linear combination $(\vec{r}-\vec{r}')$, which allows us to proceed from $d\vec{r}'$ to $d\vec{r}$ with a change in the sign of the differential:

$$W(\vec{r}) = \int_V \frac{-\mathrm{d}\vec{r}}{|\vec{r}-\vec{r}'|}. \qquad (6)$$

In this case, differential operators come down to calculating second derivatives from the Newtonian potential while the multiplier $\vec{E}^{(0)}(\vec{r}')$ is outside the integral sign. In the case when the Newtonian potential is a quadratic coordinate function, its second derivative is equal to the constant. Consequently, the character of $\vec{E}^{(0)}(\vec{r})$ depends on the free term of the integral equation.

Indeed, the first equation (4) takes the form:

$$\sum_{m=1}^{3} E_m^{(0)} \left[\delta_{nm} - \frac{1}{4\pi} \sum_{p=1}^{3} \left(\frac{\varepsilon}{\varepsilon_0} - \delta_{mp} \right) \frac{\partial^2 W}{\partial x_p \partial x_n} \right] = E_{0n}^{(0)}, \qquad (7)$$

where *m, n, p* is the number of the coordinate; δ_{mp} is the Kronecker symbol, which is equal to zero if $m \neq p$, and is equal to unity if $m=p$.

Thus, the right side of equation (7) is a constant. It follows, hence, that $\vec{E}^{(0)}(\vec{r})$ is also a constant.

In line with similar reasoning for $\vec{H}_0^{(0)}(\vec{r})$, we shall obtain that zero approximation for the inside magnetic field is a constant.

$$\vec{H}_0^{(0)}(\vec{r}) = \vec{H}_0. \qquad (8)$$

Therefore, if the external field is uniform, the internal one is also homogeneous. To calculate the internal field components, we apply expression (7). Given that number 1 corresponds to the *x*-component, 2 – to the *y*-component, and 3 – to the *z*-component, we obtain a system:

$$\begin{cases} \left[1+\frac{1}{2}\left(\frac{\varepsilon}{\varepsilon_0}-1\right)abcI_1\right]E_x^{(0)} + \frac{1}{2}\frac{\varepsilon}{\varepsilon_0}abcI_1 E_y^{(0)} + \frac{1}{2}\frac{\varepsilon}{\varepsilon_0}abcI_1 E_z^{(0)} = E_{0x}^{(0)}; \\ \frac{1}{2}\frac{\varepsilon}{\varepsilon_0}abcI_2 E_x^{(0)} + \left[1+\frac{1}{2}\left(\frac{\varepsilon}{\varepsilon_0}-1\right)abcI_2\right]E_y^{(0)} + \frac{1}{2}\frac{\varepsilon}{\varepsilon_0}abcI_2 E_z^{(0)} = E_{0y}^{(0)}; \\ \frac{1}{2}\frac{\varepsilon}{\varepsilon_0}abcI_3 E_x^{(0)} + \frac{1}{2}\frac{\varepsilon}{\varepsilon_0}abcI_3 E_y^{(0)} + \left[1+\frac{1}{2}\left(\frac{\varepsilon}{\varepsilon_0}-1\right)abcI_3\right]E_z^{(0)} = E_{0z}^{(0)}. \end{cases} \qquad (9)$$

Here *a, b, c* are the linear dimensions of semi-axes of the ellipsoid, simulating the larva;

$$I_1 = \int_0^\infty \frac{ds}{(a^2+s)R(s)}; \quad I_2 = \int_0^\infty \frac{ds}{(b^2+s)R(s)}; \quad I_3 = \int_0^\infty \frac{ds}{(c^2+s)R(s)}$$

are elliptical integrals;

$$R(s) = \sqrt{(a^2+s)(b^2+s)(c^2+s)}.$$

Linear system (9) is non-homogeneous and has a unique solution since its determinant Δ is nonzero. According to the method of Cramer [19], solution (9) takes the form:

$$E_x^{(0)} = \Delta_x/\Delta; \; E_y^{(0)} = \Delta_y/\Delta; \; E_z^{(0)} = \Delta_z/\Delta, \qquad (10)$$

where $\Delta_x\Delta_y\Delta_z$ are the identifiers composed of the corresponding coefficients of system [19].

Substituting (10) in (9), we finally obtain the following expressions for the internal fields of the insect in zero approximation:

$$\vec{E}^{(0)} = \frac{\hat{A}}{\Delta}\vec{E}_0^{(0)}; \; \vec{H}^{(0)} = \vec{H}_0^{(0)}, \qquad (11)$$

where *A* is a matrix equal to

$$\begin{Vmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{Vmatrix}. \qquad (12)$$

Elements of the matrix are derived from expressions:

$$a_{11} = 1+\left(\frac{\varepsilon}{\varepsilon_0}-1\right)\frac{abc}{2}(I_2+I_3) - \left(\frac{2\varepsilon}{\varepsilon_0}-1\right)\left(\frac{abc}{2}\right)^2 I_2 I_3;$$

$$a_{12} = -\frac{\varepsilon}{\varepsilon_0}\left(\frac{abc}{2}\right)^2 I_1(I_1+I_2);$$

$$a_{13} = -\frac{\varepsilon}{\varepsilon_0}\left(\frac{abc}{2}\right)^2 I_1(I_1+I_3);$$

$$a_{21} = -\frac{\varepsilon}{\varepsilon_0}\left(\frac{abc}{2}\right)^2 I_2(I_1+I_2);$$

$$a_{22} = 1+\left(\frac{\varepsilon}{\varepsilon_0}-1\right)\frac{abc}{2}(I_1+I_3) - \left(\frac{2\varepsilon}{\varepsilon_0}-1\right)\left(\frac{abc}{2}\right)^2 I_1 I_3;$$

$$a_{23} = -\frac{\varepsilon}{\varepsilon_0}\left(\frac{abc}{2}\right)^2 I_2(I_2+I_3);$$

$$a_{31} = -\frac{\varepsilon}{\varepsilon_0}\left(\frac{abc}{2}\right)^2 I_3(I_1+I_3);$$

$$a_{32} = -\frac{\varepsilon}{\varepsilon_0}\left(\frac{abc}{2}\right)^2 I_3(I_2+I_3);$$

$$a_{33} = 1+\left(\frac{\varepsilon}{\varepsilon_0}-1\right)\frac{abc}{2}(I_1+I_2) - \left(\frac{2\varepsilon}{\varepsilon_0}-1\right)\left(\frac{abc}{2}\right)^2 I_1 I_2. \qquad (13)$$

Expressions (11) to (13) allow us to derive from (9) the electric and magnetic components of the internal field for the first approximation. In this case, one can see that the main difficulty in determining the internal fields is associated with the calculation of elliptic integrals.

The obtained expressions (11) to (13) define internal fields of the larva without taking into account their layered nature. Next, let an electromagnetic wave fall on the body of the insect of ellipsoidal shape, having two layers with the above-specified electrophysical characteristics. If the surface of the internal layer 2 is described by equation:

$$\frac{x^2}{a^2}+\frac{y^2}{b^2}+\frac{z^2}{c^2}=1, \tag{14}$$

then, considering the surfaces of the layers to be equipotential, we have for the first layer:

$$\frac{x^2}{a^2\left(1+\xi_1\right)}+\frac{y^2}{b^2\left(1+\xi_1\right)}+\frac{z^2}{c^2\left(1+\xi_1\right)}=1. \tag{15}$$

Constant ξ_1 binds dimensions of semi-axes of the second layer with the semi- axes of the first layer.

It is obvious that the incident field $\vec{E}_0$ would excite in the first layer the inner field, which in turn would excite the field in layer 2. However, the electromagnetic field in layer 2 will cause a wave scattered in the near region in layer 1. Thus, fields in layers 1 and 2 can be recorded as follows:

$$\vec{E}^1=\vec{E}^1_{fall}+\vec{E}^1_{refl}, \tag{16}$$

$$\vec{E}^2=\vec{E}^2_{fall}. \tag{17}$$

fall index here marks the fields that are excited inside the layer by electromagnetic waves that are external relative to it. Symbol refl marks the fields that are caused by scattering at the inner layer. The result is the obtained system of two equations (16) and (17).

To record the addends with index fall. in (16), (17), we shall use the result of (11):

$$\vec{E}^{(0)1}_{fall}=\frac{\hat{A}_1}{\Delta_1}\vec{E}^{(0)}_0;\quad \vec{E}^{(0)2}_{fall}=\frac{\hat{A}_2}{\Delta_2}\vec{E}^{(0)1}. \tag{18}$$

To obtain $\hat{A}_1$, it is necessary to replace *a*, *b*, *c* in (12), (13) (a), (b), (c) with $a\sqrt{1+\xi_1}$, $b\sqrt{1+\xi_1}$, $c\sqrt{1+\xi_1}$; ε_2 with ε_1. For $\hat{A}_2$, ε is necessary to substitute with ε_2, ε_0 with ε_1. Similar substitutions are performed in order to obtain Δ_1 and Δ_2.

Field $\vec{E}^{(0)1}_{refl}$ is derived from expression (7):

$$\vec{E}^{(0)1}_{refl}=\frac{\hat{A}_2}{4\pi\Delta_2}\left(\frac{\varepsilon_2}{\varepsilon_1}-1\right)\hat{P}\vec{E}^{(0)1}W_1', \tag{19}$$

where

$$\hat{P}=\begin{Vmatrix} \frac{\partial^2}{\partial x^2}+k^2 & \frac{\partial^2}{\partial x\,\partial y} & \frac{\partial^2}{\partial x\,\partial z} \\ \frac{\partial^2}{\partial x\,\partial y} & \frac{\partial^2}{\partial y^2}+k^2 & \frac{\partial^2}{\partial y\,\partial z} \\ \frac{\partial^2}{\partial x\,\partial z} & \frac{\partial^2}{\partial y\,\partial z} & \frac{\partial^2}{\partial z^2}+k^2 \end{Vmatrix};$$

$$W'(\vec{r})=\frac{2\pi}{3}\left(3l^2-x^2-y^2-z^2\right);$$

l is the greatest linear size of an insect larva.

Solving a system of equations (16), (17) with respect to (18), (19), we obtain:

$$\vec{E}^{(0)1}=\hat{B}_1^{-1}\frac{\hat{A}_1}{\Delta_1}\vec{E}^{(0)}_0,\quad \vec{E}^{(0)2}=\frac{\hat{A}_2}{\Delta_2}\hat{B}_1^{-1}\frac{\hat{A}_1}{\Delta_1}\vec{E}^{(0)}_0, \tag{20}$$

where

$$\hat{B}_1=\hat{E}-\frac{\hat{A}_2}{4\pi\Delta_2}\left(\frac{\varepsilon_2}{\varepsilon_1}-1\right)\hat{P}W_1';$$

$\hat{E}$ is the identity matrix of the same order as $\hat{A}$; $\hat{B}_1^{-1}$ is the matrix inverse to matrix $\hat{B}_1$.

Components of the magnetic field in each of the two layers in the case considered above are derived in the same way:

$$\vec{H}^{(0)1}=\vec{H}^{(0)}_0+i\omega\varepsilon_1\frac{\hat{A}_2}{4\pi\Delta_2}\left(\frac{\varepsilon_2}{\varepsilon_1}-1\right)\hat{Q}W_1'\hat{B}_1^{-1}\frac{\hat{A}_1}{\Delta_1}\vec{E}^{(0)}_0,$$

$$\vec{H}^{(0)2}=\vec{H}^{(0)1}, \tag{21}$$

where

$$\hat{Q}=\begin{Vmatrix} 0 & -\frac{\partial}{\partial z} & \frac{\partial}{\partial y} \\ \frac{\partial}{\partial z} & 0 & -\frac{\partial}{\partial x} \\ -\frac{\partial}{\partial y} & \frac{\partial}{\partial x} & 0 \end{Vmatrix}.$$

The obtained expressions (20) allow us to estimate the magnitude of strength of the electrical component of electromagnetic field both inside the larva and at its cover. Expressions (21) allow us to solve this problem for the magnetic component of the falling EMF as well. However, the main impact on the integrity of the larva cover and the destruction of membranes of its internal organs is exerted exactly the electric component of the acting field. The above analytical expressions for electromagnetic fields inside the larvae of flies make it possible to consider an issue about a paralyzing impact of these fields on the nervous system of larvae, resulting in its suppression.

As is known [19], elements of a separate neuron are very thin insulated conductors, immersed in a saline solution. Nerve fibers while forming groups create the nervous system. Taking into account the rest potential, which is approximately equal to 70 mV, the strength of electrical field at the membrane of a nerve fiber reaches 70000 V/cm. A signal that propagates along a fiber is a short pulse, which is accompanied by membrane depolarization.

An unmyelinated fiber is a pipe with a diameter of the order of 0,3...1,3 microns. The propagation speed of action potential is defined by the diameter of a fiber and is about 0,5...2,3 m/s. To describe such a fiber, it is convenient to use a model of the coaxial RC cable section [20].

Because the energy of a microwave range, defined by the above expressions (20), (21), propagates inside the larva of a fly when it is exposed to electromagnetic fields, we shall find out how it affects the membrane of a neuron.

It follows from the boundary conditions at the surface of the coaxial RC-cable that

$$\dot{\varepsilon}\vec{E}_e=\dot{\varepsilon}_i\vec{E}_i, \tag{22}$$

where

$$\dot{\varepsilon}=\varepsilon+j\frac{g}{\omega}$$

describes an environment external to the nerve fiber, containing significant amounts of water; g is the conductance of external environment; $\dot{\varepsilon}_i$ is the dielectric permittivity of the internal part of the nerve fiber.

It follows from (22) that

$$\left|\vec{E}_i\right|=\frac{\varepsilon}{\varepsilon_i}\sqrt{1+\left(\frac{g}{\varepsilon\omega}\right)^2}\left|\vec{E}_e\right|. \tag{23}$$

Here $\vec{E}_e$ is nothing short of $\vec{E}^{(0)2}$ from (20).

Based on the model of the coaxial RC-cable [20], potential at the membrane of a nerve fiber is derived from expression

$$U_v=\frac{\varepsilon}{\varepsilon_i}\sqrt{1+\left(\frac{g}{\varepsilon\omega}\right)^2}\,r_i\ln\frac{r_i}{r_e}\left|\vec{E}^{(0)2}\right|. \tag{24}$$

Thus, knowing $\vec{E}_e$, while this is nothing short of the value for the electric component of EMF inside the larva of a fly $\vec{E}^{(0)2}$, one can find U_v. We shall consider a process of transferring the electrical pulse of excitation induced by the external electromagnetic radiation in the unmyelinated nerve fiber. Voltage and current at each point are a time function t and the longitudinal coordinate z function. Since the axon is a linear system, we shall consider the spectrum of the signal propagating along a fiber in the form of a Laplace transform [21].

Solving the equation that describes the propagation of a signal along a RC-cable [21] produces the magnitude of the signal at point z equal to

$$U(z,\,p)=U_{entry}(p)e^{-\sqrt{\frac{z\rho C p}{S}}}, \tag{25}$$

where S is the cross-sectional area of the axon; ρ is the resistivity of the length of the axon.

It is known form the scientific literature [19] that information transmitted along a nerve fiber is encoded by pauses between the pulses. In this case, the information pulses themselves represent the δ-functions.

We assume that $U_{entry}(t)$ is a δ-pulse, then its Laplace transform $U_{entry}(p)$ is equal to 1 [21]. Given the above, expression (25) takes the form:

$$U(z,\,p)=e^{-\sqrt{\frac{z\rho C p}{S}}}. \tag{26}$$

If the output of the nerve fiber is affected at point $z=0$, in addition to the δ-pulse, by a signal induced by the external electromagnetic radiation

$$U_v\cos\omega t, \tag{27}$$

the representation of the total signal at point z will change and will take the following form:

$$U(z,\,p)=\left(1+\frac{m\,p}{p^2+\omega^2}\right)e^{-\sqrt{\frac{z\rho C p}{S}}}. \tag{28}$$

where

$$m=\frac{U_{\mathrm{v}}}{\mathrm{U}_{entry}}.$$

By finding an original for a given representation, we shall obtain an expression for the total signal itself at point z of the nerve fiber:

$$U(z,t)=\frac{1}{2}\sqrt{\frac{\rho C z}{\pi S t}}\,e^{-\frac{\rho C z}{4St}}+m\,e^{-\frac{\rho C z}{4St}}\cos\left(\omega t-\frac{\rho C\omega z}{8\pi S}\right)-$$
$$-\frac{1}{\pi}\int_0^{\infty}e^{-ut}\sin\left(\frac{\rho C u z}{S}\right)\frac{u\,du}{u^2+\omega^2}. \tag{29}$$

In expression (29), the first term is the reaction of a nerve fiber to the input δ pulse, the second term is the reaction to the external superhigh-frequency signal. The contribution of the third term in the total sum is quite small because the integrand is a rapidly oscillating function, which is why a given term can be neglected.

The result obtained shows that in the presence of an external electromagnetic radiation, under certain conditions, it will not only distort the nerve pulses that would lead to the disruption of the vital activity of a larva, but it will also significantly increase the action potential at the membrane of nerve fibers. Such an increase, as is know from the scientific literature [19], may cause breakdown of the membrane, lead to failure in the action of a potassium-sodium pump in the propagation process of nerve pulses and, ultimately, to the death of the larva.

To this end, based on expression (29), we built dependences of voltage U, induced at the membrane of a nerve fiber of the fly larva on exposure t, frequency f, and the longitudinal coordinate z of a nerve fiber.

Fig. 1 shows the dependence of voltage, induced at the membrane of a fiber, on frequency of the electromagnetic field that irradiates the larva. The axis of ordinates contains coefficient m, which is equal to the ratio of voltage, induced at the membrane of a nerve fiber, to the voltage existing at it under normal conditions (–70–100 mV).

Calculations were based on the following data: density of the incident energy flux density D=0.5 mW/cm^2; the semi-axes of a larva model were selected equal to $a=1{,}5$ mm, $b=c=0{,}5$ mm; diameter of a nerve fiber is 0.3–1.3 μm; permittivity inside the larvae is 5.7. Data on electro-physical characteristics of the larval tissues were acquired from ref. [22, 23].

An analysis of the results obtained reveals that when the frequency of irradiation reaches a magnitude less than 10.00 GHz (Fig. 1), the magnitude of the voltage, induced at the membrane of a nerve fiber, has a maximum value, while exceeding by roughly three times the amplitude of voltage that exists at a given membrane under normal conditions. This result was obtained for the exposure time magnitude t=7 s.

Thus, it follows from the results obtained that in the development of the electromagnetic technology for killing the larvae of insects, it is expedient to apply the UHF sources of radiation with the following parameters: frequency of radiation is 9.8–10.2 GHz; exposure time is 2–12 s; radiation power is 0.38–0.62 mW/cm^2. The range of frequency change, exposure and power flux density, was determined from the condition for exceeding the magnitude of the induced voltage at the membrane of a nerve fiber of larvae by three times in relation to the voltage under normal conditions.

Refinement of biotropic parameters of the information electromagnetic field to kill the larvae of flies was performed under laboratory conditions. The object of research was the larvae of flies at the end of the second age. Development of larvae was observed until the formation and release of an adult insect. To clarify the biotropic parameters for the information electromagnetic field, we employed a full-factorial second-order planning. Values of factors and their variation intervals are given in Table 1.

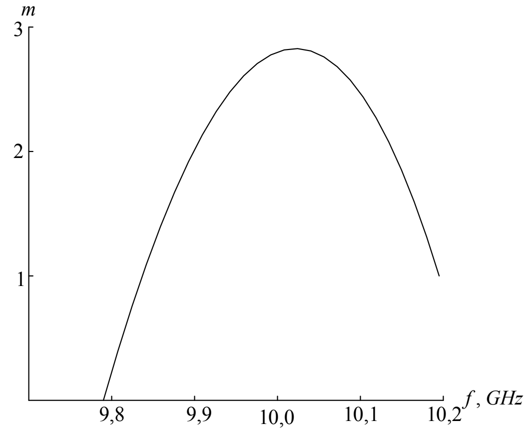

Fig. 1. Dependence of the voltage coefficient, induced at the membrane of a nerve fiber of the larva, on the frequency of its irradiation

Table 1

Value of factors in the experiment

Variation interval and level of factors	Frequency, GHz	Power flux density, mW/cm^2	Exposure, s
	x_1	x_2	x_3
Zero level x_i=0	10	0.50	7
Variation interval λ_i	0.2	0.12	5
Upper level x_i=+1	10.2	0.62	12
Lower level x_i=−1	9.8	0.38	2

Upon taking measurements and performing calculations, we derived a regression equation related to the release of flies from pupae of larvae:

$$Y = 30 - 13X_1 + 36X_2 + 37X_3 + 10X_1X_2 - \\ -20X_1X_3 + 10X_2X_3 + 10X_1^2 + +20X_2^2 + 15X_3^2, \quad (30)$$

where Y is the output parameter (the yield of imago from pupae of larvae of flies); X_1 is the frequency of EMR; X_2 is the power flux density; X_s is the radiation time for the larvae of fly.

Coefficients in equation (30) are given in the normalized form.

To find the optimal process parameters, we solved a system of equations derived by equating to zero values of components gradients calculated from expression:

$$\frac{dY}{dX_1} = b_1 + 2b_n X_1 + \sum_{j=1}^{n} b_{Ij} X_1, \quad (31)$$

where X_1, X_j are the encoded values of factors from which the derivative is taken, which interacts with them, respectively: b_1, b_n, d_{Ij} are the coefficients for the regression equation.

We derived the following system of equations for expression (31):

$$\left.\begin{aligned} &\frac{\partial Y}{\partial X_1} = -13 + 10X_2 - 20X_3 + 20X_1 = 0; \\ &\frac{\partial Y}{\partial X_2} = 36 + 10X_1 + 10X_3 + 40X_2 = 0; \\ &\frac{\partial Y}{\partial X_3} = 37 - 20X_1 + 10X_2 + 30X_3 = 0. \end{aligned}\right\} \quad (32)$$

Solving the system of equations (32) produces the following factors at the optimal point: X_{1opt}=1.0; X_{2opt}=−1.1; X_{3opt}=−0.2, which corresponds to the following values of natural parameters: frequency of electromagnetic radiation is 10.2 GHz; power flux density is 0.37 mW/cm^2; exposure is 6 s. The generator frequency instability amounted to a magnitude of 10^{-8}. To attain such a high stability of the generator frequency, we applied a phase-locked loop of a high-power stabilized generator based on the reference one that operated at a frequency of 5.0 MHz. The generator power output was 50 mW while the irregularity of an amplitude-frequency characteristic did not exceed 2 dB.

5. Experimental study into application of the information electromagnetic radiation under industrial conditions

The experiment to kill harmful insects was conducted at two pig farms with an area of 720 m^2 each. One of them was used for chemical treatment, the other one – for electromagnetic radiation. A third farm was used as control. No protective activities were undertaken at it. All farms operated under the same conditions. The concentration of insects at farms was up to 200 pcs. per animal. We determined the concentration of insects during minimal activity of pests (01:00 a.m. to 3:00 a.m.) based on the average number of insects.

The number of insects was determined at a single area of the walls, based on the number of insects killed by the electrical-physical installation. The chemical treatment was performed with the solution DDVF at a rate of 3 ml of a 1 % solution per 1 m^3 of the premises. Surfaces in the premises were treated with the aggregate AG-UD-22 (Plant Pavlogradchimmash, Ukraine). Due to the high concentration of insects, the treatment of premises with the solution DDVF was repeated in 10 days. The treatment of the second premises was conducted using electromagnetic radiation at a frequency of 10.2 GHz, exposure 6 s, and power flux density 0.37–0.38 mW/cm^2. The treatment of premises with electromagnetic radiation was repeated in 10 days.

6. Discussion of results of studying the interaction between information electromagnetic radiation and the insect larvae

Results of the experiment demonstrate that during the first 10 days more efficient is the chemical method. By day 20, a difference in the chemical and electromagnetic method of destruction of insects is levelled off. On day 20, the number of insects when applying both chemical and electromagnetic methods decreased to 8 pcs. per head. An analysis of the larvae pupate over separate days reveals that on day five pupation in control reached 96 % while in the experiment it did not exceed 5 %. The pupation of larvae irradiated with electromagnetic radiation terminated 3 days earlier than in control. The yield of imago in the experiment was less than 1 % while it reached 90 % in control.

The experiment with piglets demonstrated that when the chemical method of treatment of premises was employed, the live weight gain amounted to 7.2 %; when the electromagnetic method was applied, it was 9.2 %. A smaller increase in the live weight at chemical treatment is due to that the chemical solution has a negative effect not only on flies and their larvae, but also on cattle.

The application of electromagnetic method at livestock facilities is not inferior to the chemical one in terms of efficiency. The experiment with piglets showed that the electromagnetic method had no negative impact on animals and contributes to a growth in the live weight, which is 2–4 % greater than when the chemical method is used. The electromagnetic method to destroy the larvae of flies is cheaper, more effective, and safer, compared to the electrophysical fly traps. If we accept the cost of chemical treatment of livestock premises to constitute 100 %, the cost of the electromagnetic method would be cheaper by 50 %. The obtained power flux density of 0.37–0.38 mW/cm^2 to kill larvae is safe for humans and animals at a frequency of 10.2 GHz (SNiP RCh).

The disadvantage of the electromagnetic method is the complexity of measurements to determine the biotropic parameters when conducting a multifactor experiment.

7. Conclusions

1. To calculate internal electromagnetic fields in the biological objects of an ellipsoidal shape, one should use Maxwell's equations in the integral form. To suppress insects at livestock facilities, starting from the larval stage and up to the release of imago, the electromagnetic radiation is needed with the following parameters: frequency is 10.2 GHz; power flux density is 0.37–0.38 mW/cm^2; exposure is 6 s; relative instability of the generator frequency is 10^{-8}.

The calculation procedure could be used in analyzing the processes in the organisms of insects under the influence of information electromagnetic fields**.**

2. The field experiment on the effect of electromagnetic radiation on the larvae of flies at livestock facilities demonstrated that the yield of imago in the experiment was less than 1 %, while it was 90 % in control.

The experiment with piglets showed that when the chemical method for treating the premises was applied, a gain in the live weight amounted to 7.2 %; when the electromagnetic method was employed, it was 9.2 %.

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