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MATHEMATICAL MODEL FOR DETERMINING THE INTERNAL ELECTROMAGNETIC FIELD IN A SMALL FISH (WHITEBAIT)

Н.В. Тітова, О.Є. Піротті, Є.Л. Піротті, Н.В. Манічева, С.О. Романюк. **Математична модель для визначення внутрішніх електромагнітних полів у мальках риб.** Робота присвячена розробці математичної моделі, що дозволяє визначити електромагнітні поля НВЧ діапазону всередині мальків осетрових з метою стимулювання їх розвитку. Обрана нами методика розрахунку математичної моделі внутрішніх електромагнітних полів у мальках риб планується в подальшому використовуватися для проведення експерименту. Це дозволить підвищити життєстійкість мальків, подальшого здорового зростання молоді осетрових та обрання кращих особин для подальшого штучного відтворення. Проведено літературний аналіз з проблеми впливу електромагнітного випромінювання на гідробіонти і живі організми. Розглядається вплив електромагнітного випромінювання на мальків осетрових в перші два тижні їх розвитку. У даному випадку завдання вирішені за допомогою інтегро-диференціальних рівнянь в разі квазістатіки. Відмінною рисою цього методу є те, що він автоматично задовольняє граничним умовам на поверхні елемента. Рішення задачі про визначення електромагнітних полів всередині малька риби буде проведено з урахуванням її малості в порівнянні з довжиною падаючого ЕМВ. У нашому випадку в процесі росту личинки її розміри збільшуються і нульове наближення дає досить грубий результат. Запропоновані вираження для нульового, першого, другого і т.д. наближень дозволяють враховувати зростання мальків і зміна співвідношення між їх розміром і довжиною падаючої хвилі. Слід при цьому зазначити високу точність даного методу, оскільки вже в нульовому наближенні його похибка не перевищувала 15% в порівнянні з експериментальними дослідженнями розсіювання електромагнітних полів на металевих об'єктах еліпсоїдальної форми.

Ключові слова: стимулювання розвитку, електромагнітні поля, рівняння Максвелла, інтегро-диференціальні рівняння, квазістатіка, перерассеяніе

N. Titova, A. Pirotti, E. Pirotti, N. Manicheva, S. Romanyuk. **Mathematical model for determining the internal electromagnetic field in a small fish (whitebait)**. The work is devoted to the development of a mathematical model that allows one to determine the electromagnetic fields of the microwave range inside sturgeon whitebait in order to stimulate their development. Our chosen method of calculating the mathematical model of internal electromagnetic fields in fish whitebait is planned to be used in the future for the experiment. This will increase the viability of whitebait as well as further healthy growth of sturgeon small fish and the selection of the best individuals for further artificial reproduction. A literature analysis of the influence of electromagnetic radiation on aquatic organisms and living organisms has been carried out. The effect of electromagnetic radiation on sturgeon whitebait in the first two weeks of their development is considered. In this case, the problems are solved using integro-differential equations in the case of quasi-statistics. A distinctive feature of this method is that it automatically satisfies the boundary conditions on the surface of the element. The solution of the problem of determining the electromagnetic fields inside the fish fry will be carried out taking into account its small size in comparison with the length of the falling electromagnetic radiation. In our case, as the larva grows, its size increases and the zero approximation give a rather crude

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result. Suggested expressions for zero, first, second, etc. approximations. Its allow take into account the growth of whitebait and the change in the ratio between their size and the incident wavelength. At the same time, it should be noted the high accuracy of this method, since already in the zero approximation its error did not exceed 15% in comparison with experimental studies of the scattering of electromagnetic fields on metal objects of ellipsoidal shape.

Keywords: stimulation of development, electromagnetic fields, Maxwell's equations, integro-differential equations, quasi-statics, re-scattering

Introduction

In recent years, due to a significant decrease in the fish stocks world's oceans and, accordingly, the volume of its catch, the development of various forms of aquaculture is becoming more widespread. It is quite understandable that all types of fish farms are built and operate using the developed methods. These are methods of biotechnician and biotechnologies for growing various types of fish or using the natural resources of certain water bodies.

At present, there is a growing understanding that under conditions of anthropogenic impact the biological resources of the biosphere need not only protection, but also the restoration of their numbers in the main exploited aquatic ecosystems, primarily during their artificial reproduction. Artificial reproduction of fish provides not only the preservation and increase of fish stocks, but also an improvement in the structure of biohydrocenoses and a more rational use of the productive capacities of reservoirs. This is, of course, one of the levers for the development of managed fisheries.

To increase efficiency in aquaculture various technologies are used. Namely: various pharmacological additives to stimulate growth, changes in the composition of feed, low-intensity laser radiation, helium-neon lasers, stocking density, changes in temperature, oxygenation of water, and others.

However, these methods have certain drawbacks. In some cases they negatively affect the quality of the offspring, have a depressing effect, high price, bulky equipment, pharmacological stimulation of fish growth is not always beneficial to the human body.

Literature review

As a result of many years of functional and applied research, a scientifically grounded basis has been laid and approaches have been determined to implement the stimulating effect of low-intensity electromagnetic radiation on fish-biological and economically useful qualities of sturgeon planting material because of the effect of this radiation to fish embryos and sperm. It was also shown there that the efficiency of such production significantly depends on the biotropic parameters of this radiation. This indicates the possibility of its use in the technology of artificial reproduction and rearing of valuable fish species [1, 2].

Currently, the high biological activity of EMR has been reliably established and all living things are really extremely sensitive to artificial EMF (electromagnetic fields) of anthropogenic origin. Some species of living things and plants are particularly sensitive to certain frequencies. Thus, fish do not tolerate the frequency of 50 Hz at fairly high field strength.

It should be noted that the applied technique is mainly used to influence fish eggs.

Modern technological schemes for rearing larvae and early juveniles, with all their significance and development, are ambiguous. They differ in different combinations of abiotic parameters aimed at maximizing the growth rate and practically do not take into account environmental requirements at different stages of development of juvenile fish. Therefore, fish hatcheries often note its significant mortality, especially of larvae. There are no objective data on assessing the resilience of juvenile fish, including larvae, to unfavorable environmental factors.

Many studies have noted the positive effects of extremely high-frequency radiation on various living objects and studied various physiological effects caused by extremely high-frequency radiation. These are acceleration of growth and increase in biomass, intensification of photosynthesis, accompanied by increased oxygen and content in photosynthetic cells, organic compounds in the environment, changes in the reactivity of exometabolites, changes in ion transport, and others. [3]

The obtained experimental results indicate the ability of polarized electromagnetic radiation to influence metabolic processes in the body and cause a correction of the postembryonic development of sturgeons. Experimentally, this is manifested in an increase in the survival rate of juveniles under the influence of radiation, as well as in a significant reduction in the studied group of individuals with abnormal morphological characteristics [4, 5]. The most important parameter that determines the magnitude of the stimulating effect is the radiation frequency, the EMR power density and the type of its modulation [6, 7].

It should be noted that the currently available results of the application of stimulating microwave radiation to sturgeon juveniles are mainly experimental. Therefore, there is a need to create a mathematical model of the interaction of electromagnetic radiation (EMR) of the microwave range with fish fry, taking into account their physiology.

All this indicates the need for further development of technologies, methods and tools to optimize the rearing of larvae in intensive aquaculture due to electromagnetic irradiation of whitebaits.

The purpose of our study is to study the effect of electromagnetic radiation on sturgeon juveniles at the first stages of development.

Main material

Consider the effect of electromagnetic radiation on sturgeon fry in the first two weeks of their development.

This limitation will allow representing them, in the first approximation, as an elongated ellipsoid, the length of which is in the range of ≈5…15 mm.

Taking into account the linear dimensions of the fry and the centimeter range of wavelengths used for the stimulating effect, a model is proposed in the quasi-static approximation, that is, when the wavelength incident on the fry is about an order of magnitude larger than its size.

In this case, it is convenient to use the method of integro-differential equations [8]. A distinctive feature of this method is that it automatically satisfies the boundary conditions on the surface of the scattering element (fish fry). The dependence of the amplitudes of the electromagnetic field on the spatial coordinates can be considered practically absent and the considered fields can be expanded in terms of a small parameter l/λ, where l are the linear dimensions of the object, λ – is the length of the scattered wave. This will make it possible to obtain different approximations for the internal fields depending on the size of the irradiated whitebait. The proposed approach makes it possible to take into account the change in the size of the fry itself during its development.

Let us designate the dielectric and magnetic permeability of the water in which the whitebait is located ε_b, and $\mu_b = \mu_0 = 4\pi 10^{-7}$ Gn/m, respectively, and use Maxwell's equations $\vec{E}$ and $\vec{H}$ to describe the EMF components at all points of this space. In this case, we will bear in mind the harmonic dependence of the indicated vectors on time, associated with the appearance of the factor $e^{j\omega t}$ [9, 10]:

$$\begin{cases} \mathrm{rot}\vec{\mathbf{E}} + j\omega\mu_0\vec{\mathbf{H}} = 0; \\ \mathrm{rot}\vec{\mathbf{H}} - j\omega\varepsilon_b\vec{\mathbf{E}} = 0, \end{cases} \tag{1}$$

where j – is an imaginary unit;

ω – is the radiation frequency.

Considering that whitebait is characterized by dielectric and magnetic permeability ε and μ_0, internal electromagnetic fields (EMF) can be described by the equations:

$$\begin{cases} \mathrm{rot}\vec{\mathbf{E}} + j\omega\mu_0\vec{\mathbf{H}} = 0; \\ \mathrm{rot}\vec{\mathbf{H}} - j\omega\varepsilon_c\,\vec{\mathbf{E}} = \vec{\mathbf{g}}, \end{cases} \tag{2}$$

where $\vec{\mathbf{g}} = j\omega(\varepsilon - \varepsilon_c)\vec{\mathbf{E}}$.

The dielectric constant ε is considered as a function of coordinates and is a variable value. On the surface of the whitebait in the direction of the environment, the dielectric constant changes abruptly from ε to ε_c. Consequently, equations (2) can be considered as describing not only the whitebait itself, but also the surrounding water.

Using the simplest transformations, the equations of system (2) are reduced to second-order differential equations that depend on only one variable $\vec{\mathbf{E}}$ or $\vec{\mathbf{H}}$ [11]:

$$\begin{cases} \mathrm{graddiv}\vec{\mathbf{E}} - \Delta\vec{\mathbf{E}} - k^2\vec{\mathbf{E}} = -j\omega\mu_0\vec{\mathbf{g}}; \\ \mathrm{graddiv}\vec{\mathbf{H}} - \Delta\vec{\mathbf{H}} - k^2\vec{\mathbf{H}} = \mathrm{rot}\vec{\mathbf{g}}, \end{cases} \qquad (3)$$

where $k=2\pi/\lambda$ is the wavenumber in the water surrounding the whitebait.

Using the relation describing the electric potential of Hertz [9]:

$$\vec{\mathbf{\Pi}}^e = \frac{1}{4\pi}\int_V \left(\frac{\varepsilon}{\varepsilon_c} - 1\right)\vec{\mathbf{E}}(\vec{\mathbf{r}})\, f\left(\left|\vec{\mathbf{r}} - \vec{\mathbf{r}}'\right|\right) d\overrightarrow{\mathbf{r}}, \qquad (4)$$

where $f\left(\left|\vec{\mathbf{r}} - \vec{\mathbf{r}}'\right|\right) = \dfrac{e^{-jk\left|\vec{\mathbf{r}} - \vec{\mathbf{r}}'\right|}}{\left|\vec{\mathbf{r}} - \vec{\mathbf{r}}'\right|}$, $\vec{\mathbf{r}}$ and $\vec{\mathbf{r}}'$ – are the radius vectors of the outer and inner points of the whitebait body, respectively, we represent the expressions for the fields scattered on the biological object as follows [9]:

$$\begin{cases} \vec{\mathbf{E}}(\vec{\mathbf{r}}) = \vec{\mathbf{E}}_0(\vec{\mathbf{r}}) + (\mathrm{graddiv} + k^2)\vec{\mathbf{\Pi}}^e; \\ \vec{\mathbf{H}}(\vec{\mathbf{r}}) = \vec{\mathbf{H}}_0(\vec{\mathbf{r}}) + j\omega\varepsilon_c \mathrm{rot}\vec{\mathbf{\Pi}}^e, \end{cases} \qquad (5)$$

The integrals that determine $\vec{\mathbf{\Pi}}^e$ in (4) and (5) apply to the entire volume *V* occupied by the whitebait.

As mentioned above, the solution of the problem of determining the electromagnetic fields inside the fish fry will be carried out taking into account its smallness in comparison with the length of the falling EMR. This condition allows us to expand the expressions for the components of the electric and magnetic fields in a power series in terms of the smallness parameter:

$$\begin{gathered} \vec{\mathbf{E}}^{(0)}(\vec{\mathbf{r}}) + (jk)\vec{\mathbf{E}}^{(1)}(\vec{\mathbf{r}}) + (jk)^2\vec{\mathbf{E}}^{(2)}(\vec{\mathbf{r}}) + \ldots = \vec{\mathbf{E}}_0^{(0)}(\vec{\mathbf{r}}) + (jk)\vec{\mathbf{E}}_0^{(1)}(\vec{\mathbf{r}}) + \\ +(jk)^2\vec{\mathbf{E}}_0^{(2)}(\vec{\mathbf{r}}) + \ldots + \frac{1}{4\pi}(\mathrm{graddiv} + k^2)\int_V \left(\frac{\varepsilon}{\varepsilon_c} - 1\right)\llbracket \vec{\mathbf{E}}^{(0)}(\vec{\mathbf{r}}') + \\ +(jk)\vec{\mathbf{E}}^{(1)}(\vec{\mathbf{r}}') + (jk)^2\vec{\mathbf{E}}^{(2)}(\vec{\mathbf{r}}') + \ldots\rrbracket \left[\frac{1}{\left|\vec{\mathbf{r}} - \vec{\mathbf{r}}'\right|} - jk - \frac{k^2}{2}\left|\vec{\mathbf{r}} - \vec{\mathbf{r}}'\right| + \ldots\right] d\vec{\mathbf{r}}'; \end{gathered} \qquad (6)$$

$$\begin{gathered} \vec{\mathbf{H}}^{(0)}(\vec{\mathbf{r}}) + (jk)\vec{\mathbf{H}}^{(1)}(\vec{\mathbf{r}}) + (jk)^2\vec{\mathbf{H}}^{(2)}(\vec{\mathbf{r}}) + \ldots = \vec{\mathbf{H}}_0^{(0)}(\vec{\mathbf{r}}) + \\ +(jk)\vec{\mathbf{H}}_0^{(1)}(\vec{\mathbf{r}}) + (jk)^2\vec{\mathbf{H}}_0^{(2)}(\vec{\mathbf{r}}) + \ldots + \frac{j\omega\varepsilon_c}{4\pi}\mathrm{rot}\int_V \left(\frac{\varepsilon}{\varepsilon_c} - 1\right)\llbracket \vec{\mathbf{E}}^{(0)}(\vec{\mathbf{r}}') + \\ +(jk)\vec{\mathbf{E}}^{(1)}(\vec{\mathbf{r}}') + (jk)^2\vec{\mathbf{E}}^{(2)}(\vec{\mathbf{r}}') + \ldots\rrbracket \left[\frac{1}{\left|\vec{\mathbf{r}} - \vec{\mathbf{r}}'\right|} - jk - \frac{k^2}{2}\left|\vec{\mathbf{r}} - \vec{\mathbf{r}}'\right| + \ldots\right] d\vec{\mathbf{r}}'. \end{gathered} \qquad (7)$$

In expressions (6), (7), the indices at the components of the electric and magnetic fields indicate the degree of approximation with which these components are located.

In our case, during the growth of the larva, its size increases and the zero approximation gives a rather rough result. Considering that for large whitebait in the centimeter wavelength range the inequality $a/\lambda \ll 1$ may no longer be strictly fulfilled, we will consider not only the zero approximation when solving equations (6) and (7), but also the first and second [10].

This problem is solved by equating the terms containing the factor (*jk*) in equal degrees to the left and right of the equal sign, which leads to a system of equations that allow finding different approximations.

Zero approximation is determined from the expressions:

$$\vec{\mathbf{E}}^{(0)}(\vec{\mathbf{r}}) = \vec{\mathbf{E}}_0^{(0)}(\vec{\mathbf{r}}) + \frac{1}{4\pi}\operatorname{graddiv}\int_V \left(\frac{\varepsilon}{\varepsilon_c} - 1\right)\vec{\mathbf{E}}^{(0)}(\vec{\mathbf{r}}^{'})\frac{1}{\left|\vec{\mathbf{r}} - \vec{\mathbf{r}}^{'}\right|}d\vec{\mathbf{r}}^{'};$$
$$\vec{\mathbf{H}}^{(0)}(\vec{\mathbf{r}}) = \vec{\mathbf{H}}_0^{(0)}(\vec{\mathbf{r}}). \tag{8}$$

First approach –

$$\vec{\mathbf{E}}^{(1)}(\vec{\mathbf{r}}) = \vec{\mathbf{E}}_0^{(1)}(\vec{\mathbf{r}}) +$$
$$+\frac{1}{4\pi}\operatorname{graddiv}\int_V \left(\frac{\varepsilon}{\varepsilon_c} - 1\right)\left[\vec{\mathbf{E}}^{(1)}(\vec{\mathbf{r}}^{'})\frac{1}{\left|\vec{\mathbf{r}} - \vec{\mathbf{r}}^{'}\right|} - \vec{\mathbf{E}}^{(0)}(\vec{\mathbf{r}}^{'})\right]d\vec{\mathbf{r}}^{'}; \tag{9}$$
$$\vec{\mathbf{H}}^{(1)}(\vec{\mathbf{r}}) = \vec{\mathbf{H}}_0^{(1)}(\vec{\mathbf{r}}) + \frac{1}{4\pi Z_c}\operatorname{rot}\int_V \left(\frac{\varepsilon}{\varepsilon_c} - 1\right)\vec{\mathbf{E}}^{(0)}(\vec{\mathbf{r}}^{'})\frac{1}{\left|\vec{\mathbf{r}} - \vec{\mathbf{r}}^{'}\right|}d\vec{\mathbf{r}}^{'},$$

where $Z_c = \sqrt{\frac{\mu_0}{\varepsilon_c}}$ is the characteristic resistance of the environment surrounding the biological object. For the second approximation, we obtain the relations:

$$\vec{\mathbf{E}}^{(2)}(\vec{\mathbf{r}}) = \vec{\mathbf{E}}_0^{(2)}(\vec{\mathbf{r}}) + \frac{1}{4\pi}\operatorname{graddiv}\int_V \left(\frac{\varepsilon}{\varepsilon_c} - 1\right)\left[\!\left[\vec{\mathbf{E}}^{(2)}(\vec{\mathbf{r}}^{'})\frac{1}{\left|\vec{\mathbf{r}} - \vec{\mathbf{r}}^{'}\right|} +\right.\right.$$
$$\left.\left.+\vec{\mathbf{E}}^{(0)}(\vec{\mathbf{r}}^{'})\frac{\left|\vec{\mathbf{r}} - \vec{\mathbf{r}}^{'}\right|}{2} - +\vec{\mathbf{E}}^{(1)}(\vec{\mathbf{r}}^{'})\right]\!\right]d\vec{\mathbf{r}}^{'} - \frac{1}{4\pi}\int_V \left(\frac{\varepsilon}{\varepsilon_c} - 1\right)\vec{\mathbf{E}}^{(0)}(\vec{\mathbf{r}}^{'})\frac{d\vec{\mathbf{r}}^{'}}{\left|\vec{\mathbf{r}} - \vec{\mathbf{r}}^{'}\right|}; \tag{10}$$
$$\vec{\mathbf{H}}^{(2)}(\vec{\mathbf{r}}) = \vec{\mathbf{H}}_0^{(2)}(\vec{\mathbf{r}}) + \frac{1}{4\pi Z_c}\operatorname{rot}\int_V \left(\frac{\varepsilon}{\varepsilon_c} - 1\right)\left[\frac{\vec{\mathbf{E}}^{(1)}(\vec{\mathbf{r}}^{'})}{\left|\vec{\mathbf{r}} - \vec{\mathbf{r}}^{'}\right|} - \vec{\mathbf{E}}^{(0)}(\vec{\mathbf{r}}^{'})\right]d\vec{\mathbf{r}}^{'}.$$

In expressions (8) – (10), the terms $\vec{\mathbf{E}}_0^{(0)}(\vec{\mathbf{r}})$, $\vec{\mathbf{H}}_0^{(0)}(\vec{\mathbf{r}})$, $\vec{\mathbf{E}}_0^{(1)}(\vec{\mathbf{r}})$, $\vec{\mathbf{H}}_0^{(1)}(\vec{\mathbf{r}})$, $\vec{\mathbf{E}}_0^{(2)}(\vec{\mathbf{r}})$, $\vec{\mathbf{H}}_0^{(2)}(\vec{\mathbf{r}})$ are equal to the zero, first and second terms of the power series expansion of the electric and the magnetic component of the incident field.

Discussion of results

From expressions (8) – (10) we see that if the free term in the equations for the zero approximation is a constant vector determined by the incident field, then the free terms in the higher-order approximations are already variable vectors determined from the previous approximations. As for the expressions for the magnetic component, they are equalities that determine $\vec{\mathbf{H}}(\vec{\mathbf{r}})$ through the values found in the previous approximations, as well as through the expansion of the incident field. Higher order approximations can be found in a similar way.

Thus, relations (8) – (10) make it possible to find the components E_x, E_y, E_z of the electric and magnetic components of the internal electromagnetic field in fish fry with varying degrees of accuracy. It should be noted the high accuracy of this method, since even in the zero approximation its error did not exceed 15 % in comparison with experimental studies of the scattering of electromagnetic fields on metal objects of ellipsoidal shape [12].

Conclusions

A method is proposed for calculating internal electromagnetic fields in cylindrical biological objects using Maxwell's equations in an integral form. The results obtained can be used to describe the processes in the body of aquatic living bioorganisms under the influence of low-energy electromagnetic fields of the microwave range.

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