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The determination of rational dimensions of the inductor and the development of a PEMF therapy device

Abstract. *The problem of developing a PEMF therapy device with an inductor, the parameters of which allow obtaining an improved configuration of the magnetic field, is considered. The inductor parameters providing the required intensity of the pulsed magnetic field and its distribution pattern are determined by means of modeling. Clinical tests of the PEMF therapy device have been conducted. They confirm the undertaken decisions.*

Streszczenie. *Rozważono problem opracowania urządzenia do terapii PEMF z induktorem, którego parametry pozwalają na uzyskanie ulepszonej konfiguracji pola magnetycznego. Parametry induktora zapewniające wymaganą intensywność impulsowego pola magnetycznego i jego wzór rozkładu są określane za pomocą modelowania. Przeprowadzono testy kliniczne urządzenia do terapii PEMF. Potwierdzają one podjęte decyzje. (**Określenie racjonalnych wymiarów induktora i opracowanie urządzenia do terapii PEMF**)*

Keywords: PEMF therapy, inductor, clinical use
Słowa kluczowe: Terapia PEMF, induktor, zastosowanie kliniczne

Introduction

The special feature of the method of treatment with pulsed electromagnetic field (PEMF) therapy [1-3] consists in the fact that it involves sending short pulses of the magnetic field directly to the affected area. One of the key advantages of PEMF is that its short pulses prevent possible thermal tissue damage. The pulsed electromagnetic field is inductively coupled to the treatment area, which makes the procedure non-invasive [4]. Currently, several methods using PEMF, which are applied in the clinical treatment of a wide range of diseases, have been developed [5].

Research on PEMF therapy [6] has revealed its effectiveness and safety in the treatment of osteoarthritis, in particular, in relieving pain and improving physical function.

The method makes it quite easy to adapt the parameters of PEMF devices to a specific patient [7]. A system of non-invasive diagnostics with elements of a neural network can be used as feedback parameters, according to the parameters of the air exhaled by a person based on sensors on porous silicon [8-9].

Depending on the value of the magnetic induction pulse, devices for PEMF therapy are divided into those that generate a pulse of low-intensity magnetic induction up to 0.5 mT, a pulse of medium-intensity magnetic induction up to 100 mT, and a pulse of high-intensity magnetic induction: High-Intensity Pulsed Electromagnetic Fields (HI-PEMF) up to 1.5 T.

HI-PEMF therapy devices provide significantly deeper penetration of the magnetic field into human biological tissues, which enables their effective use in the treatment of diseases of the joints, lower back, spine, bone fractures, etc. The effectiveness of HI-PEMF treatment depends on the intensity of the magnetic induction pulse and the configuration of the magnetic field created by the inductor. The issue of determining the rational parameters of the inductor and creating a HI-PEMF therapy device that would provide the intensity of the magnetic induction pulse in the range of 0.1-1.5 T, the possibility of choosing modes of pulse formation, and the rational configuration of the magnetic field, is topical. The use of such a device will improve the effectiveness of treatment procedures.

The purpose of the paper consists in the determination of the rational parameters of the inductor and development of a HI-PEMF therapy device and its clinical verification.

Research and development of the inductive sensor

Determining the rational parameters of the inductor and developing a therapy device requires the use of modeling, circuit engineering, and metrology tools. This process is interactive, with a consistent approximation to the final result due to the results of calculations and modeling. The following methodology is used in the research.

1 Performing preliminary calculations of inductor parameters using the Tesla Flat Helical Coil Online Calculator program. At this stage, the preliminary data of the inductor, such as the thickness of the wire, the number of turns, the outer and inner diameter of the inductor, are determined.

2. Determining the distribution of the magnetic field produced by the coil using the Comsol program. The stage allows the determination of the density of the magnetic field created by the inductor by changing its parameters, such as the winding material, the number of turns.

3. Checking the electrical parameters of the inductor using the Proteus program. At this stage, the current flowing through the inductor during capacitor discharge and the voltage required to form a magnetic induction pulse of a given intensity are simulated.

4 Production of an inductor with defined rational parameters.

5. Development and production of a device that provides the formation of a magnetic induction pulse with an intensity in the range from 0.1 to 1.5 T.

6. Determination of the configuration of the magnetic field.

7. Clinical approbation of the developed device with a rational inductor.

A measurement of the vertical and horizontal components of the magnetic field induction at various points of the working space was carried out to determine the configuration of the magnetic field. This measurement is performed using the inductive magnetic sensor method (see Fig. 1).

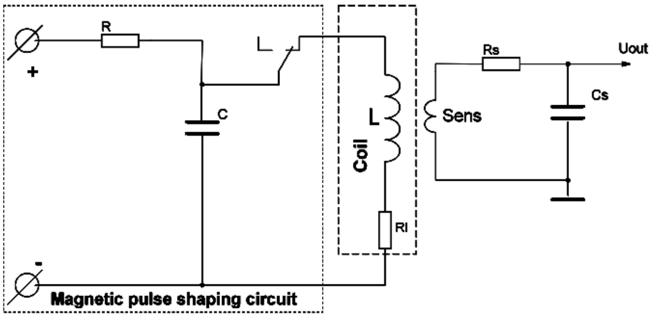

Fig.1. The circuit of measurements by the inductive magnetic sensor method

The sensor is a flat single-layer coil, which is placed relative to the inductor in such a way that the cross section of the turns is perpendicular to the direction of the magnetic field. Given that the inductor forms a magnetic field that changes rapidly in time, an induction EMF E is induced in the sensor. According to Faraday's law, this EMF is equal to

(1) $$E = -N_S \left(d\Phi / dt \right)$$

where: N_S – the number of turns of the sensor, Φ – magnetic flux in webers per turn.

The value of magnetic induction B can be calculated using the expression:

(2) $$B = \Phi / S_S$$

where S_S – sensor area.

In this way, it is finally possible to write an expression that relates the EMF value E induced in the sensor and the magnetic induction as follows:

(3) $$E = -N_S S_S \left(dB/dt \right).$$

In order to neglect the effect of external electric circuits on the sensor signal, it is necessary to meet the requirement that the internal active and inductive resistances of the sensor should be lower than the resistance of the external measuring circuit.

For the convenience of measuring magnetic induction, it is desirable to switch from EMF to voltage. This can be done by integrating expression (3) using an integrating RC circuit, the function of which is performed by $R_S C_S$ elements (Fig. 1).

An expression that can be used to get the output signal on the sensor in the form of voltage is written as follows:

(4) $$U_S = \frac{1}{R_S C_S} \int_0^t E dt.$$

Expression (4) is true if the conditions are met that the integration time t is significantly less than the value of $R_S C_S$. That is the time constant of the integrating circuit must significantly exceed the period $\tau = 1/\omega$ of the change of the magnetic field in the inductor, where ω is the angular frequency of the alternating magnetic field. Fulfillment of these restrictions makes it possible to write down the final expression for measuring magnetic induction by the method of an inductive magnetic sensor as follows:

(5) $$U_S = \frac{S_S N_S}{R_S C_S} B.$$

Based on practical considerations and taking into account the above limitations on the electrical parameters of the external elements of the sensor, the following values are chosen:

$S_S = 3.2\,\mathrm{mm}^2$, $N_S = 42$, $R_S = 4k\Omega$, $C_S = 1.8\mu F$.

The appearance of the sensor is shown in Fig. 2.

Fig.2. Magnetic induction inductive sensor

Calibration of the magnetic induction sensor is carried out using the device [10].

A digital oscilloscope [11] is used to control the shape of the magnetic induction pulse and measure the period τ.

Results and discussion

To determine the rational parameters of the magnetic field inductor, the electrical and geometric parameters of the coils are preliminarily calculated [12]. At the same time, flat single-layer coils are considered. The parameters of a coil wound with a copper wire with a diameter of 1 mm and a coil wound with a copper tape with a width of 15 mm and a thickness of 0.15 mm are calculated. For both coils, calculations are performed with variations in the number of turns in the range from 30 to 100. The obtained results of calculations are shown in Fig. 3. and Table 1.

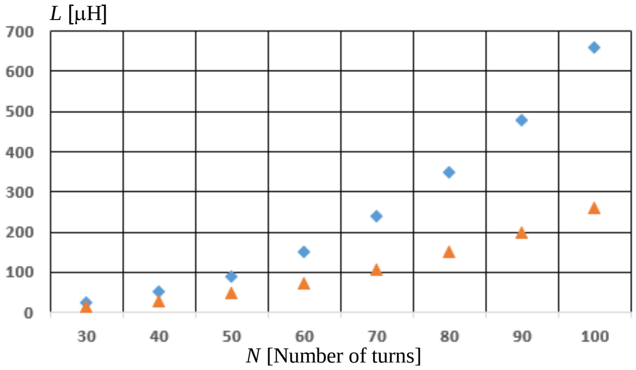

Fig.3. The dependence of the inductor coil inductance on the number of turns. ◆ – copper wire, ▲ – copper tape

Table 1. The dependence of the area of the inductor on the number of the coil turns

Number of coil turns	S_S, cm^2 (copper wire)	S_S, cm^2 (copper tape)
30	38	9
40	61	11
50	93	14
60	131	17
70	177	20
80	227	24
90	283	27
100	346	32

The analysis of the data of previous calculations revealed that it is most rational to use copper tape for the manufacture of the inductor, which, with the same number of turns, occupies a much smaller area of the inductor, which results in a more focused magnetic field of the pulse. A lower value of the inductance forms a shorter damping time of the oscillatory process.

To analyze the magnetic flux formed by inductors made of copper wire and copper tape, a model created using the AC/DC module of the COMSOL package is used. During modeling, the number of turns varies in the range from 30 to 100, the material of the model is copper, the external environment is air. The distribution of magnetic induction B obtained as a result of modeling for the inductor made of copper tape and the inductor made of copper wire is shown in Fig. 4a and 4b.

The research of the magnetic induction distribution shows that the copper tape inductor creates a field of higher density (Fig. 5).

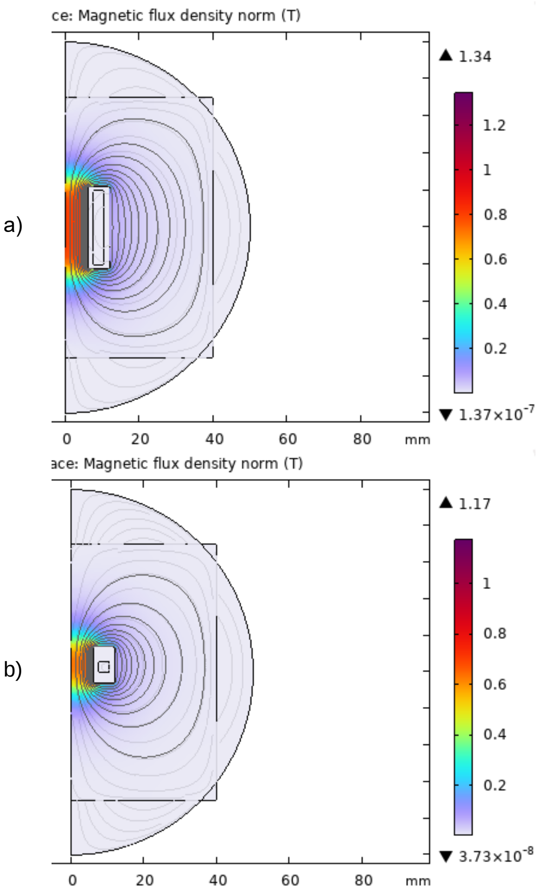

Fig.4. The distribution of magnetic induction when the number of turns of the coil is 100: a) copper tape inductor; b) copper wire inductor

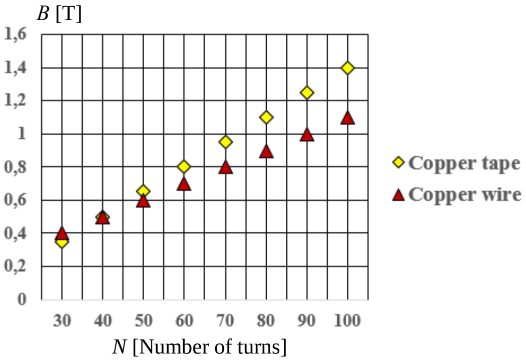

Fig.5. The dependence of the induction formed by the inductor on the number of turns

The results of modeling the magnetic induction distribution confirm the conclusion that the magnetic tape inductor is more effective for the application in the HI-PEMF therapy device.

A model in the Proteus program is used to assess the values of the inductor electrical parameters, such as the current generated when the capacitor is discharged to it, the decay time of the transient process, the shape of the induction pulse. The inductor coils made of copper tape and copper wire, each of which has 100 turns, are researched. Their calculated parameters are listed in Table 2.

Table 2. The calculated values of inductors for modeling

The type of winding material	Inductance, μH	Resistance, Ohm
Copper tape	260	0.0552
Copper wire	660	0.70886

In the model (Fig. 6), storage capacitor C1 with a capacity of 100 μF is charged through the current-limiting resistor R1 from the 1000V power source through switch SW1. The charge voltage of the capacitor is controlled by the virtual voltmeter VA1. After charging the capacitor, the power source is turned off by switch SW1, and the charged capacitor through SW2 switch is connected to the inductor, which consists of resistance R2, which is responsible for the internal resistance of the coil, and inductor L1. Parameters R2 and L1 are set according to Table. 2.

The modeling results are analyzed using the built-in Proteus analyzer of analog signals, which are shown in Fig. 7.

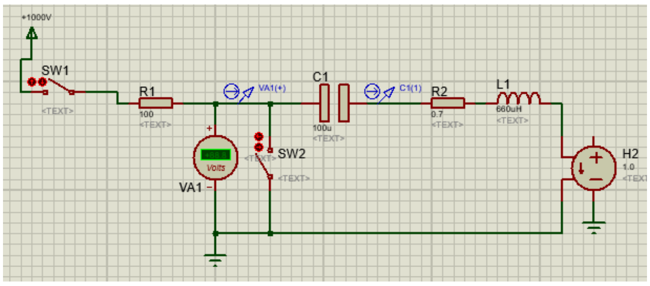

Fig.6. A model of a magnetic induction pulse generator

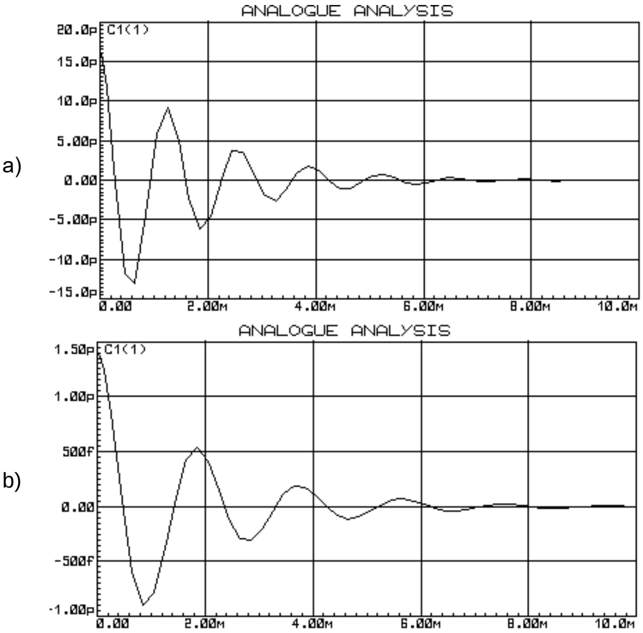

Fig.7. The transient process of changing the current in the inductor: a) the inductor is made of copper tape; b) the inductor is made of copper wire

Circuit design modeling made it possible to pre-set the inductor electrical parameters, such as the maximum current, which for the copper tape inductor is 20 kA and the transition time is 4.5 ms, and for the copper wire inductor, the maximum current is 1.5 kA, and accordingly the time of the transient process is 5.5 ms. These data are taken into account when designing the HI-PEMF therapy device.

The results of preliminary calculations and modeling made it possible to design and manufacture an inductor with rational parameters, which is shown in Fig. 8.

The inductor is based on an inductance coil made of copper tape 15 mm wide and 0.15 mm thick, and an inter-turn layer made of heat-resistant Teflon tape 0.1 mm thick. The diameter of the coil is 100 mm. The inductor is equipped with a fan for cooling the inductor during treatment procedures, as well as temperature (thermoresistance) and magnetic induction (Hall sensor) sensors to monitor the inductor operation.

Fig.8. An inductor with rational parameters

The basic circuit of the HI-PEMF therapy device is shown in Fig. 9.

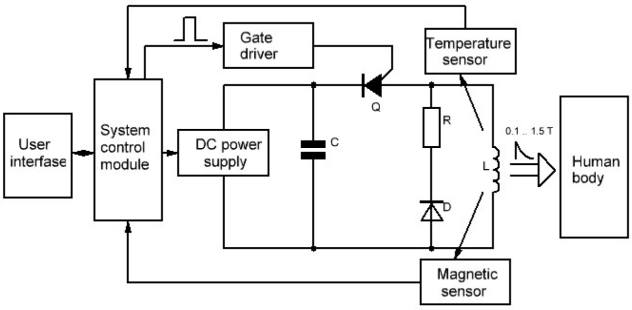

Fig.9. Basic circuit of HI-PEMF therapy device

The pulsed magnetic field is formed using three components, namely: inductor L, capacitor C, which stores energy, and switching device Q, which uses a solid-state thyristor, which controls the connection of the capacitor to the coil under the command of the microcontroller (System control module) [13]. To form field strength of about 1.5 T, the power source charges the capacity to a voltage of 1000V. The capacitor with the coil and the internal resistance of the coil form a decaying sinusoidal electric current that creates a magnetic field when the current passes through the coil. It is possible to change the energy stored on the capacitor, and thus, accordingly, change the value of the magnetic induction by changing the charging time of the capacitor. In HI-PEMF therapy device the scope of magnetic induction can be set in the range from 0.1 to 1.5 T.

The use of a microcontroller for control makes it possible to improve efficiency, which enables the application of more complex protocols of pulse excitation, with the possibility of adjusting the repetition rate and the number of pulses in the package.

The sensors of the magnetic field and temperature of the inductor allow receiving feedback and control of the formation of magnetic induction pulses.

The appearance of the developed HI-PEMF therapy device with an inductor is shown in Fig. 10.

Fig.10. HI-PEMF therapy developed device

With the help of controls located on the device, it is possible to set the intensity of magnetic induction from 0.1 to 1.5 T, the duration of the treatment procedure – 5, 10 and 15 minutes. Pulse generation frequency can be set in the range from 0.5 to 5 Hz, pulse generation modes – single, double and a series of 7 pulses. The current operating modes of the device are displayed on the LCD display**.**

The research of the distribution of the magnetic induction field is carried out in the mode of forming single pulses with a frequency of 0.5 Hz and an intensity of 1.5 T. The study is carried out using an inductive magnetic induction sensor, which is described above.

The sensor is installed at specified points in space along the vertical and horizontal axes of the inductor, a pulse is formed and the value of the magnetic induction is determined. The graph of the distribution of magnetic induction in space obtained as a result of a practical experiment is shown in Fig. 11. The value of magnetic induction of 1.5 T is taken as 100%.

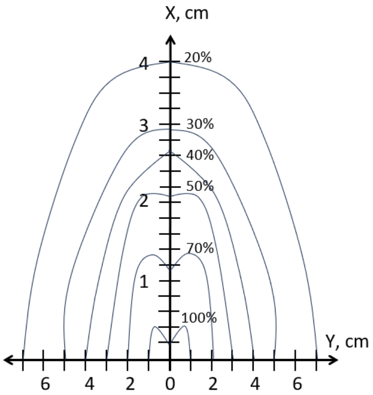

Fig.11. The determined distribution of magnetic induction

The developed device has undergone clinical trials in medical institutions of Ukraine. In order to compare the effectiveness of HI-PEMF therapy, an analysis of two groups of patients according to the seven nosological groups that occur most often, with the use of HI-PEMF therapy and without the use of HI-PEMF therapy has been carried out.

One group in the complex treatment of patients with disorders of the musculoskeletal system obtained HI-PEMF therapy with the developed device – 460 people.

The other group in the complex treatment of the musculoskeletal system obtained shock wave therapy and laser therapy – 237 people.

The analysis concerned the diseases of the musculoskeletal system that are most often encountered in medical practice: calcaneal fasciitis – 80 people; myofascial-pain syndrome of the lower back – 60 people; myofascial-pain syndrome of the thoracic spine – 40 people; myofascial-pain syndrome of the cervical spine – 55 people; diseases of the shoulder joint – 32 people; diseases of the knee joint – 40 people; diseases of the hip joint – 80 people.

The following criteria were used to assess the effectiveness of the therapeutic effect: the presence of clinical symptoms, the presence of trigger points, a change in the amplitude of movement, and the subjective state of the patient.

As a result of the research, it was concluded that, when using the developed HI-PEMF therapy device in complex treatment of the musculoskeletal system, the positive clinical effect occurred much faster, by 2-3 sessions, and was accompanied by a pronounced clinical effect.

Conclusions

A sensor for determining the intensity and distribution of magnetic field induction has been proposed and calculated.

The performed preliminary calculations of the inductance of the inductor have made it possible to compare the inductance value and the geometric parameters of the inductor made of copper wire and copper tape. It has been determined that the inductor made of copper tape has more rational geometric parameters than the inductor made of copper wire.

Mathematical modeling has demonstrated that an inductor made of copper tape provides a higher magnetic field density than an inductor made of copper wire.

A basic circuit and apparatus for HI-PEMF therapy have been proposed, which makes it possible to set the value of the magnetic induction pulse intensity, the procedure time and the number of pulses in the working cycle in a wide range.

Using the developed sensor, the distribution of the value of the magnetic induction created by the inductor has been practically researched and proven. It has been determined that at a distance of 4 centimeters from the surface of the inductor, the field intensity decreases by 80 percent.

Clinical tests of the proposed HI-PEMF therapy device have been conducted and showed a positive clinical effect of its use.

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