Volume 20
Number 2

December *2018*
(ISSN 1109-1606)

Journal of
APPLIED ELECTROMAGNETISM

JAE

Trans Black Sea Region Union of Applied Electromagnetism
BSUAE

Institute of Communication and Computer Systems

Athens - GREECE

Volume 20 December 2018
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CONTENTS

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The present work explores a number of modern methods for the processing of acoustic signals with a large dynamic range. As it is known, a number of difficulties arise in recording and analyzing them. Therefore, a specialized platform and a measuring microphone with the required features are used. The actual processing is performed in Matlab environment. Examples of seemingly highly different areas are considered: acoustics on the battlefield, musical acoustics - studying the bell ringing and archaeoacoustics - study of sacred Thracian sites on the territory of the Republic of Bulgaria. The methods of Fourier analysis and Wavelet analysis were used. For the visualization of the scalograms, a method of transforming them through the conformal method, described in an earlier work by two of the co-authors is proposed.

It should be emphasized, that an analogy has been made in the mathematical description of the acoustic and electromagnetic waves, and that the proposed methods could also be used for the study of electromagnetic tasks in the two-dimensional field.
The results can be used in various areas of acoustics, electrodynamics, image processing in medical diagnostics, systems of detection and localization of terrorists, tactical firing systems on the battlefield etc.

ON APPLICATION OF SIMULATION FOR INVESTIGATION OF LOW-FREQUENCY MAGNETIC FIELDS EFFECT

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Abstract

Low frequency and low intensity magnetic and electric fields are used in physiotherapy for a long time. But due to the fact that the action of these fields on living tissues is very complicated and at the moment insufficiently studied, nowadays there is no simple method to measure their curative effect. In practice the natural way of investigations is the experimental one: to observe the state of a patient during curative sessions and collect statistical data. We propose to combine practical approach with the study of processes in external environment when low intensity magnetic fields act. With this purpose we calculate and visualize the trajectories of ions in electromagnetic field generated by a magnetotherapy device. Such an approach leads to obtaining a series of images that show trajectories depending on the choice of the device parameters. That results in visual representation of typical phase portraits generated by the applied mathematical model. Visual perception helps to compare the number of procedures, parameters of the used device and the changing of patient state, and thus to form an expert knowledge in this area.

1. INTRODUCTION

To gain a better insight into the problem of effects of low intensity magnetic field on living organism one may use mathematical and computer modeling. The most natural and simple model is the distribution of intensities of magnetic field generated by a coil. In this case the calculation of the field value is based on the superposition principle: the common magnetic field is the sum of the fields generated by the contours of a coil. For several coils the magnetic field is the sum over all the coils. Induction and self-induction are supposed to be negligible quantities. Numerical methods allow calculating non-uniform magnetic field, i.e. the field changing in the space. The calculations and visualization of the resulting field for several coils in 3D were performed in [1, 3, 4], and the results of calculation were applied to a special magnetoterapy device — "magnetobed", which is actively used in medical practice.

The next step in the studying processes in an environment when electromagnetic field acts is to consider the model of the movement of charged particles (ions or cations). As a first approximation, we may use the model where an ion moves in accordance with the Newton second law, and the Lorentz force acts on it. The problem is to calculate and visualize the trajectories of different ions for given configuration of electric and magnetic fields. This model does not consider the environment where the field acts, so at first we assume that the motion is in air environment.

Medical practice shows that the action of magnetic field in mineral water improves the curative effect for patients with diabetes. To apply the described model for mineral water we should use the magnetic permeability of this environment in formulas for calculation of magnetic induction. But at the moment the dependence of the permeability on mineral water composition is insufficiently studied. So, to make the problem easier it was assumed that the magnetic permeability of mineral water is approximately the same as of ordinary water, which is a natural assumption in this mathematical model. We also assume that in a small size an ion motion in the environment can be thought of as the motion in vacuum [2].

Thus, to model an ion motion we used the method of calculation of the magnetic field of a coil, which is described above. The field is calculated in the points of a space grid. We approximated differential equations of the ion movement by discrete ones by using a second order difference scheme. If a next point of trajectory is not in the grid of points for which values of magnetic field are calculated, a linear interpolation is performed to calculate the value of the field in the point. Various cases of configuration of electrical and magnetic fields were modelled, in particular periodic effects of the fields. In this regime there are two cases — commensurable and incommensurable frequencies. The most complex phase portraits were obtained for incommensurable ones.

It should be noted that the proposed difference scheme leads to the solving linear system by Cramer's method, which is simpler than numerical integration by the Runge-Kutta method. All calculations were compared with calculation in MATLAB package. The results are similar. All the experiments were applied to a special device used in clinics.

Such a method allows us to select a set of parameters and obtain visualization of ion movement. For visualization we used ParaView package and MATLAB. In fact, an imitation model has been designed that may be used for construction some medical devices and choice the most appropriate parameters. The model includes performing the calculations, saving obtained data in files of a required format, call the ParaView to visualize magnetic field or combine visualization of the field and the ion trajectory.

This approach may help to estimate the effectiveness of the magnetotherapy by monitoring the patient state and comparing obtained data with the parameters of the device. Visualization makes this analysis more clear. Moreover, in doing so we model the processes in the external environment, where electromagnetic field acts, and this study contributes to a better comprehension of processes in internal environment – living tissue. This is practical and useful method.

To develop this technique we have to consider more complex models which take into account the interaction between particles and the structure of the environment. The questions concerning the influence of geomagnetic and artificial magnetic fields on transfer processes in aqueous media such as electrolytes and biological objects are discussed in the monography [2]. Our future investigations suggest a more detailed study of this subject.

2. MATHEMATICAL MODEL DESCRIPTION

The detailed derivation of equations for the movement of charged particle in electrical and magnetic fields is given in many textbooks, for example in [5]. We describe them briefly. Consider a charged particle with a charge q and mass m. Let $\vec{E}(x,y,z,t)$ be the intensity of electrical field in the point (x,y,z) at the moment t, and $\vec{B}(x,y,z,t)$ be the magnetic field induction. The force acting the ion in electrical field is equal to $q\vec{E}$, and the Lorentz force in magnetic field equals $q\vec{v}\times\vec{B}$. Then writing the second law of Newton we obtain $m\frac{d\vec{v}}{dt} = q(\vec{E} + \vec{v} \times \vec{B})$. Assuming that $\vec{B}$ is co-directed with Oz, and hence $B_z = B, B_x = B_y = 0$, we obtain the following system of equations:

$$\begin{cases} m\ddot{x} = q\big(E(x,y,z,t)\sin\gamma\cos\beta + \dot{y}\,B(x,y,z,t)\big) \\ m\ddot{y} = q(E(x,y,z,t)\sin\gamma\sin\beta - \dot{x}B(x,y,z,t)) \\ m\ddot{z} = qE(x,y,z,t)\cos\gamma \end{cases} \quad (1)$$

The positions of vectors electric and magnetic fields are illustrated in Fig.1

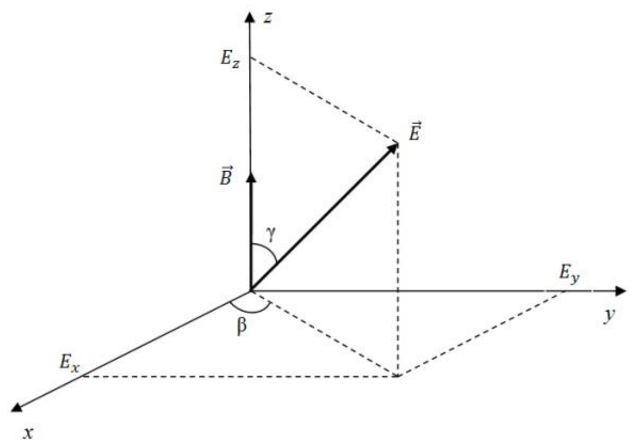

Figure 1. The disposition of vectors $\vec{\boldsymbol{B}}$ and $\vec{\boldsymbol{E}}$

It is well known that system (1) is integrable if there is no electrical field and the magnetic field is uniform and constant. Then the trajectory of an ion is screw line. But for non-integrable cases we have to apply approximate calculations. We use the second order difference system. Let $[t_0, T]$ be the time interval on which a trajectory is calculated, $t_i = t_0 + ih, i = 0, \dots n, x(t_i) = x_i, y(t_i) = y_i$, $z(t_i) = z_i$. Assume that:

$$\ddot{x} \approx \frac{x_{i+1} - 2x_i + x_{i-1}}{h^2}, \quad \ddot{y} \approx \frac{y_{i+1} - 2y_i + y_{i-1}}{h^2}, \quad \ddot{z} \approx \frac{z_{i+1} - 2z_i + z_{i-1}}{h^2}, \quad (2)$$

and

$$\dot{x} \approx \frac{x_{i+1} - x_{i-1}}{2h}, \dot{y} \approx \frac{y_{i+1} - y_{i-1}}{2h}, \dot{z} \approx \frac{z_{i+1} - z_{i-1}}{2h}. \quad (3)$$

Substituting (2) and (3) in (1) we obtain the second order system of difference equations:

$$\begin{cases} x_{i+1} - K_i y_{i+1} = 2x_i - x_{i-1} - K_i y_{i-1} + L_i \sin\gamma \cos\beta \\ K_i x_{i+1} + y_{i+1} = 2y_i - y_{i-1} + K_i x_{i-1} + L_i \sin\gamma \sin\beta \\ z_{i+1} = 2z_i - z_{i-1} + L_i \cos\gamma, \end{cases} \quad (4)$$

where $K_i = \frac{qh}{2m} B(x_i, y_i, z_i)$ if current is constant, and $K_i = \frac{qh}{2m} B \cos\omega t_i$ in the case of variable current with frequency ω. By analogy $L_i = \frac{qh^2}{m} E(x_i, y_i, z_i)$, if electrical field depends on the point, and $L_i = \frac{qh^2}{m} E \cos\omega t_i$ for periodic field. The system (4) is linear, coordinates of z are found independently from x and y, and on every step x_{i+1}, y_{i+1} may be calculated by the Cramer method, because $\Delta = 1 + K_i^2 \neq 0$.

3. EXPERIMENTS AND RESULTS

We applied the implemented program to model ion trajectories both for arbitrary value of parameters and in a special magnetotherapy device. The device has two coils which are active simultaneously and electrodes. Magnetic and electrical fields may be periodic and have both commensurable and incommensurable frequencies.

3.1. The device description

Device parameters are the following: coils have external radius 58 mm, height — 34 mm; current intensity is 3A, the number of turns is 20, the number of windings is 25. The size of the region (in mm) is 600x300x500, the size of a cell of the lattice (in mm), where magnetic field is calculated, is 4x4x4, the step on time h (in sec) is 10^{-6}.

The beginning of the first coil has coordinates (0, 150, 250), the axis direction is (1, 0, 0). The beginning of the second coil has coordinates (600, 150, 250), the axis direction is (-1, 0, 0).

Figure 2. Magnetotherapy device

The experiments were performed for various types of ions and combinations of magnetic and electrical fields.

3.1.1 Natrium ion in magnetic field

Natrium ion has mass $m = 3.817 * 10^{-23} g$, charge $q = 1$. We take $B = 10^{-3} T$. Consider the case when only magnetic field generated by 2 coils acts. Calculate the ion trajectory with initial data $(x_0, y_0, z_0) = (100,150,250)$, $(x_1, y_1, z_1) = (100,150,250.01)$. The trajectory was calculated in 200000 points.

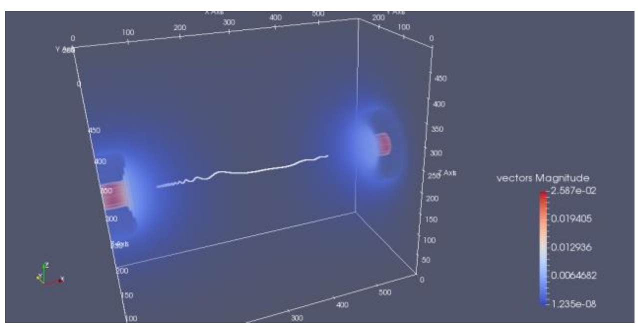

Figure 3. The trajectory of natrium ion in magnetic field

3.1.2 Natrium ion trajectory in magnetic and electrical fields

Modify the previous example and add electrical field. Assume that vector $\vec{E}$ has coordinates (0.1, 0, 0) and $(x_0, y_0, z_0) = (x_1, y_1, z_1) = (100,150,240)$. The number of points in the trajectory is 3709.

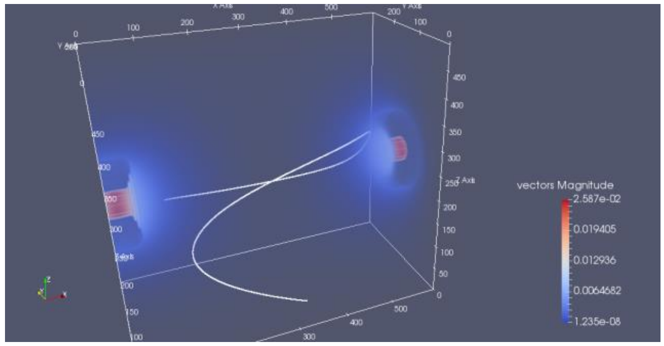

Figure 4. The trajectory of natrium ion in magnetic and electrical fields

3.1.3 Natrium ion in periodic magnetic field

Now we consider the periodic magnetic field with frequency 10 Hz, $(x_0, y_0, z_0) =$ (100,150,250), $(x_1, y_1, z_1) = (100{,}150{,}250.01)$.

The number of points is 73688.

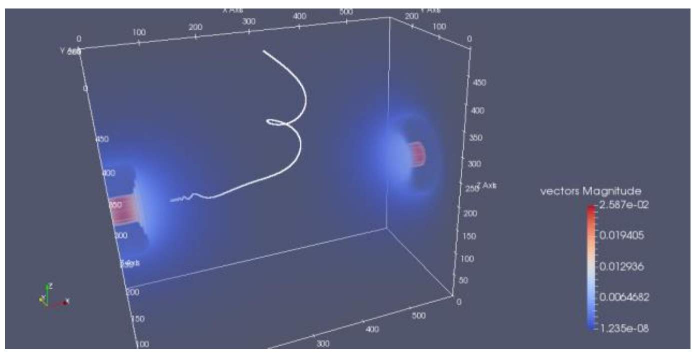

Figure 5. The trajectory of natrium ion in periodic magnetic field

3.1.4 Sulfate ion in magnetic field

Consider the motion of sulfate ion with mass $m = 16 * 10^{-23}$ g, $q = -2$ in magnetic field. The number of points is 200000.

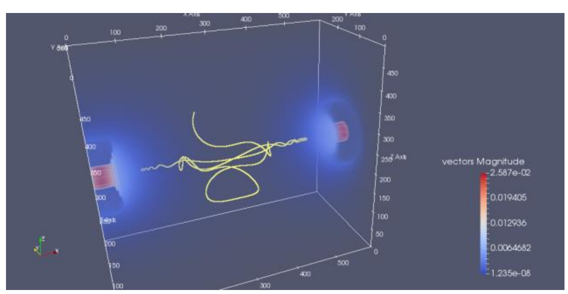

Figure 6. The trajectory of sulfate ion in magnetic field

3.2. Natrium ion in periodic magnetic and electrical fields

Now we consider periodic magnetic field with frequency 200π, and electric field with frequency 80π. The number of points is 150000.

On Fig.7 we present the results of calculations performed in accordance with system (4).

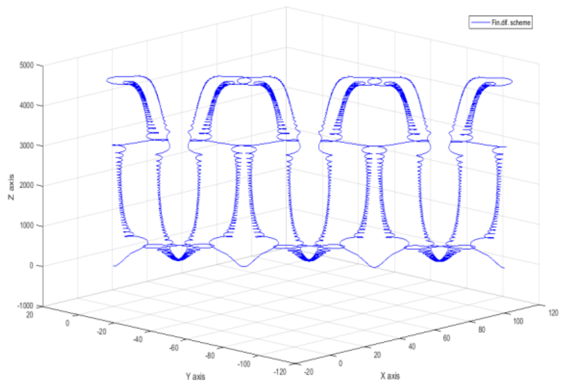

Figure 7. Natrium ion in periodic fields: commensurable frequencies

The next picture shows the results when the frequency of magnetic field is 200π, and the frequency of electrical field is $2\pi \cdot 20e$. Note that we may observe such a motion on rather long distance on z-coordinate (near 6 m). Hence in real device we would see only small part of the trajectory and the difference between these cases will not be considerable for visual perception.

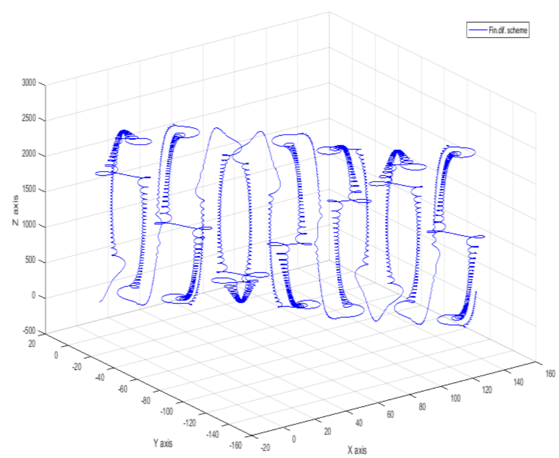

Figure 8. Natrium ion in periodic fields: incommensurable frequencies

4. CONCLUSION

The designed and implemented program is the imitation model for calculation of distribution of electric and magnetic fields and the motion of ions in these fields in magnetotherapy devices. It allows us to model and visualize the typical trajectories of different ions for given parameters of the used device. The obtained set of images may help in matching of given parameters to the results of monitoring the patient state. Thus, simulation and visualization of results are proved to be appropriate methods for interpretation of statistical data.

The future investigations of the state of environment under action of magnetic field require taking into consideration not only an ion motion, but also the interaction between particles, boundary conditions, the environment composition and many other parameters. This problem is the subject of our future investigations.

ACKNOWLEDGEMENTS

This work was partially supported by the grant Erasmus + International Mobility (KA107) / National Technical University of Athens — St. Petersburg State University.

The authors would like to thank Prof. D. Dimitrov from Technical University of Sofia for the problem statement and many fruitful discussions, and F. Uvarichev from St. Petersburg State University for help in computer experiments.

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ADVANCED SIGNAL PROCESSING METHODS FOR ANALYSIS OF HIGH DYNAMIC RANGE ACOUSTIC PHENOMENA

(Selected from CEMA'18 Conference)

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Abstract

The present work explores a number of modern methods for the processing of acoustic signals with a large dynamic range. As it is known, a number of difficulties arise in recording and analyzing them. Therefore, a specialized platform and a measuring microphone with the required features are used. The actual processing is performed in Matlab environment. Examples of seemingly highly different areas are considered: acoustics on the battlefield, musical acoustics - studying the bell ringing and archaeoacoustics - study of sacred Thracian sites on the territory of the Republic of Bulgaria. The methods of Fourier analysis and Wavelet analysis were used. For the visualization of the scalograms, a method of transforming them through the conformal method, described in an earlier work by two of the co-authors is proposed.

It should be emphasized, that an analogy has been made in the mathematical description of the acoustic and electromagnetic waves, and that the proposed methods could also be used for the study of electromagnetic tasks in the two-dimensional field.

The results can be used in various areas of acoustics, electrodynamics, image processing in medical diagnostics, systems of detection and localization of terrorists, tactical firing systems on the battlefield etc.

1. INTRODUCTION

There are a great number of sources of sound (including ultrasound and infrasound). The human hearing is not sensible for ultrasound and infrasound (too less or very high frequencies). On the other hand the dynamic range of some sound sources exceeds the human hearing harmless limit of 120 dB. For example, a bell ringing and gunfire of machine gun have the similar characteristics in acoustic sense. These characteristics require the use of special measuring and analyzing equipment as well as appropriate microphones.

Combination of the acoustic equipment with special software enables obtaining of visual representation of important characteristics of the sound sources both for military and civil applications [1,5]. For acoustic waves, soft (Dirichlet) or hard (Neumann) boundary conditions are imposed on scattering objects located in a homogeneous non-viscous medium. The absence of viscosity is justified for a fluid (such as air and water) in the linear approximation [2]. The radiation and diffraction theory of acoustic waves is scalar, and it is simpler than the vector theory of electromagnetic waves. Because of this, we investigate acoustic problems. The obtained results can be used in similar electromagnetic phenomena. This facilitates the study of electromagnetic problems. It is known that from a mathematical point of view, all two-dimensional diffraction problems have identical solutions for acoustic and electromagnetic waves, [2,3].

2. SOME WAVE REPRESENTATIONS AND ANALOGIES IN THE HELMHOLTZ EQUATION AND MAXWELL EQUATIONS

In [2] it is shown many analogies between acoustic and electromagnetic wave behavior that simplified electromagnetic vector theory calculations. In the linear approximation, the velocity potential u of harmonic acoustic waves satisfies the Helmholtz wave equation:

$$\nabla^2 u + k^2 u = I \tag{1}$$

Here $k = \frac{2\pi}{\lambda} = \frac{\omega}{c}$ is the wave number, λ the wavelength, ω the angular frequency, c the speed of sound, and I the source strength characteristic. The time dependence is assumed to be harmonic $e^{-i\omega t}$.

The following analytic expressions for velocity potential determined acoustic pressure p and the velocity v of fluid particles, caused by sound waves

$$p = -\rho \frac{\partial u}{\partial t}, \quad \vec{v} = \nabla u \tag{2}$$

where ρ is mass density of a fluid.

The power flux density equals:

$$\vec{P} = p\vec{v} = p\nabla u \tag{3}$$

It is the analog of the Poynting vector for electromagnetic waves. Its value averaged over the period of oscillations T equals:

$$\vec{P}_{av} = \frac{1}{2}\mathrm{Re}(p^{*}\vec{v}). \tag{4}$$

In scattering problems, the quantity u plays the role of electric field intensity $\vec{\mathrm{E}}$ or magnetic field $\vec{\mathrm{H}}$, depending on the polarization of electromagnetic waves intensity. Their power flux density, or the Poynting vector, is defined as

$$\vec{P} = \vec{E} \times \vec{H} = \frac{1}{2}Re\left(\vec{E} \times \vec{H}^{*}\right) \tag{5}$$

Therefore the acoustic problems can be expressed with scalar Helmholtz equation, as well as Maxwell equations - electromagnetic case. In two-dimensional case the lasts can be written in the form as two independent equations for electric field intensity $\vec{\mathrm{E}}$ and magnetic field $\vec{\mathrm{H}}$ with the following formulas [3]

$$\nabla^2\vec{\mathrm{E}} + k^2\vec{\mathrm{E}} = 0 \tag{6a}$$

$$\nabla^2\vec{\mathrm{H}} + k^2\vec{\mathrm{H}} = 0 \tag{6b}$$

3. SOME CHARACTERISTICS OF THE SOUND

Below we show three of the most important characteristics: damping of the sound, its spectrum and scalogram. For example it will regard sound record from unique bronze bell from XIII century 1211-1216 year, tower-belfry on the metropolitan church of St. Nicholas, Melnik, [1]. One of situations that illustrate the problems in acoustic propagation scenario is shown in Fig. 1.

Here is represented the experimental setup with the two unique bronze bell in the museum hall of the National Historical Museum in Sofia, [6]. It can be seen the position of measuring microphone 4193 [9], as well as the characteristic distances and the distribution of frequencies are shown in Figs. 2,3.

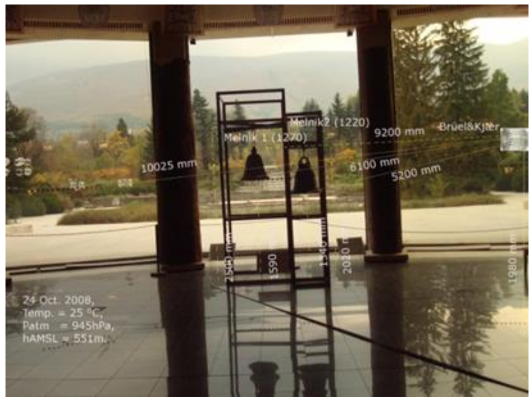

Figure 1. Measuring microphone toward XIII century bell disposition.

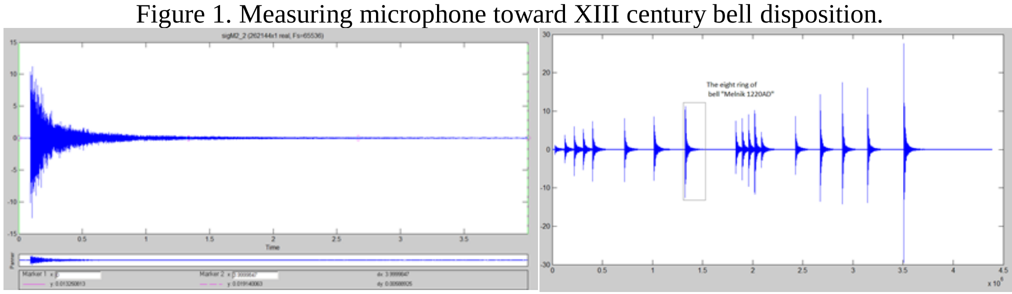

Figure 2. One waveform of Bulgarian bell stroke (XIII cent.), on the second it is separated only one bell ring (the eight), where $F_{samp} = 2^{16}$Hz, $N_{samp} = 2^{18}$

The calculations was produced in MatLab where signal’s power spectral density (PSD) was analyzed with the nonparametric method of Discrete Fourier Transform by Fast Fourier Transform algorithm (FFT).

For above example it can be note that the bell is a complicated sound source with a very wide frequency range and an unique dynamic range of the transmitted signal. Its spectrum consist many partials. The biggest spectral components are seen in Table 1 [scalogram – continuous wavelet transform (CWT)].

Starting with Haar's functions and today Daubechies and other families of wavelets [4] this time-scale analysis become very useful tool in advanced digital signal processing. More precisely, suppose that $a \in \mathbb{R}^+, b \in \mathbb{R}$, or ($a$,$b$) determine one point in right-half plane, then the continuous wavelet transform (CWT) of a continuous, square-integrable function is expressed by:

$$\mathrm{CWT_f}(a,b) = \langle \mathrm{f}(t), \psi_{a,b}\, \mathrm{f}(t)\rangle = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} \mathrm{f}(t) \psi^* \left(\frac{t-b}{a}\right) \mathrm{dt} \quad (7)$$

where $\langle , \rangle$ denotes the inner product. The wavelet transform of a one-dimensional signal is a two-dimensional time-scale joint representation [7].

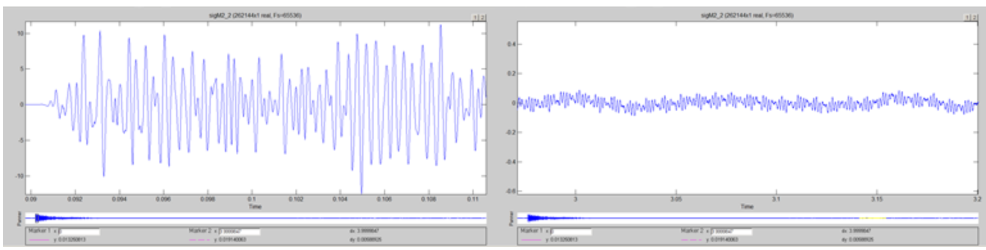

Figure 3 The front and the tail of signal from one bell ring, the eight one fig.2.

We turn our attention to the scalograms. Especially, to change their rectangular shape to another one - this will be more convenient for further investigations, see [5]. If we make known conformal mapping, the rectangular graph will be transformed to a circular graph.

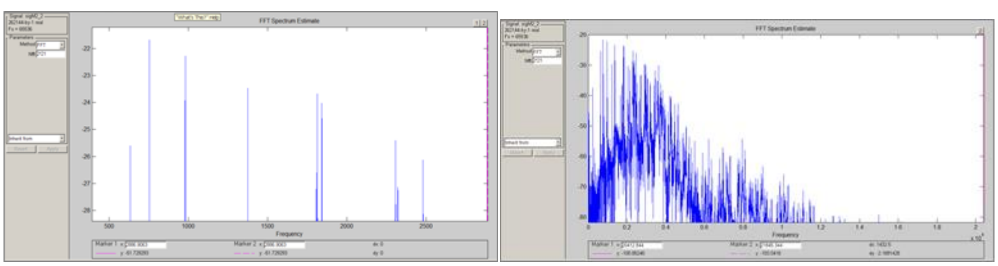

Figure 4 The log magnitude spectra of signal the Bulgarian bell ring, f=1,...,2500Hz and f=1,...,20000Hz.

Table 1. The biggest spectral components of the bell "Melnik 1220AD"

Number	**Frequency, (Hz)**	**Magnitude, (dB)**
1	635,6	-25,59
2	755,3	-21,67
3	981,4	-22,27
4	1374,8	-23,46
5	1813,6	-23,68
6	1841,5	-24,03

7	2306,5	-25,41
8	2479,2	-26,13

4. EXAMPLES OF EXPERIMENTS AND SCALOGRAM TRANSFORMATIONS

The battlefield is a disorienting place and it is very hard to identify where enemy is located. Acoustic sensors are very convenient in this situation.

The data from the training range, collected during the tactical exercises, were exported from PULSE platform as mat files (or ASCII files), to be processed in MATLAB®. The signals, captured from the microphone, are analyzed in time-frequency domain and time-scale domain [5,6]. Fig. 4 below illustrates the comparison.

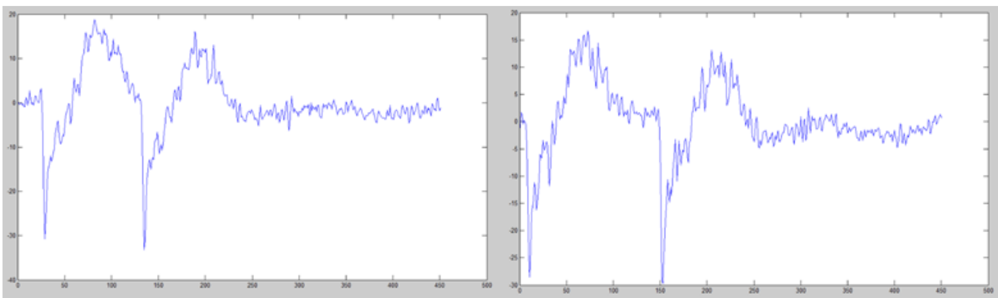

Figure 5. Waveforms from large-caliber tank machine-gun, 14,5 mm KPVT

In figure 5 we show example for two 14.5mm-caliber KPVT waveforms, where KPVT is an abbreviation for “Krupnokaliberniy Pulemyot Vladimirova Tankoviy” Russian, i.e. large-caliber tank machine gun. Figure 5 shows a typical acoustic signal waveform of KPVT machine gun shots, recorded from the exercise area and exported to MatLab. The corresponding calculated scalograms, or CWT, are illustrated on Figure 6, where scale parameter a = 1,...,64. The scalograms, transformed into circular ring (sound print) are shown on Figure 7.

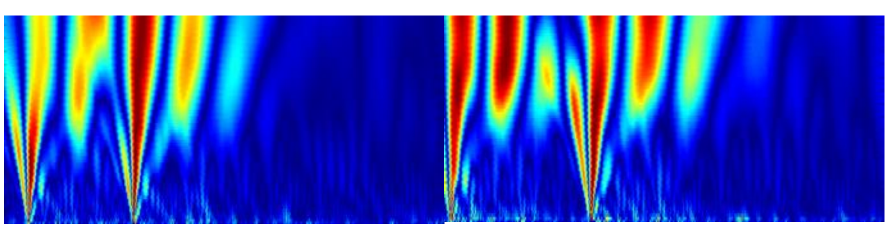

Figure 6. Calculated scalograms for 14,5 mm KPVT waveforms correspondingly to fig. 5., a=1,...,64, Daubechies db3.

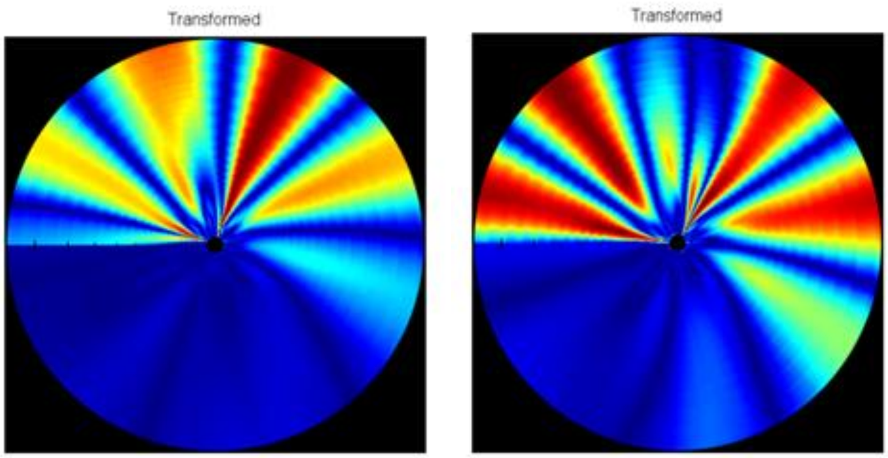

Figure 7. Calculated scalogram transformations (sound prints) for 14,5 mm KPVT correspondingly to fig. 5 and 6, a = 1,...,64, Daubechies db3.

Figure 8.Record of kaval- ancient Bulgarian flute “in situ” in King mound, Sveshtari.

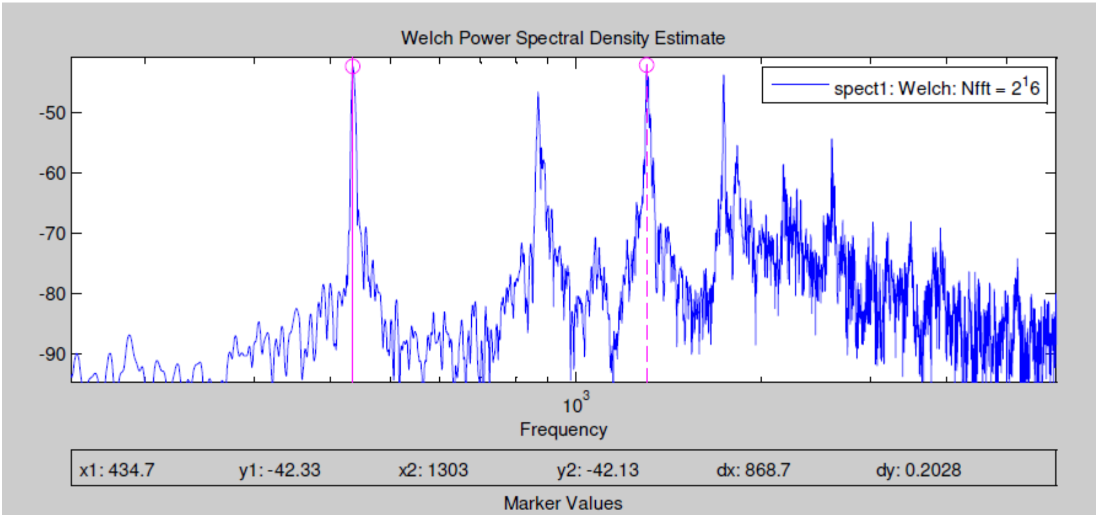

Figure 9. Spectral components of the flute in current time

Figure 8 shows an experiment in the chamber of the Thracian tomb in Sveshtari, where the world-famous Bulgarian musician Theodosii Spassov participated. Figure 9 shows the spectral components. Preliminary analyzes of the acoustic studies of this and other sacred Thracian sites show that despite the small volume of the rooms, they have very good parameters in the reproduction of low frequencies (in the range of 100 and below 100 Hz). According to some scientists who works on project "Thracians - genesis and development of ethnicity, cultural identities, interactions and civilizational heritage of antiquity", [8] this is due to the fact that rituals have been performed in these rooms exclusively by men whose voices are known to be located in the low-frequency sound range. Research and analyzes of raw results continue.

5. CONCLUSION

It should be noted that the methods, used for analyzing and presenting acoustic results can very easily be adapted to analyze electromagnetic tasks. As highlighted above, in the two-dimensional area the mathematical description of acoustic and electromagnetic wave is practically analogous (of course, taking into account the polarization of electromagnetic phenomena and boundary conditions). In the end, it is worth to remark that the scalogram conformal mapping gives better visualization of the special features of the acoustic signal. The conformal transform gives adaptation to the different scales and sound prints of different sound sources could be collected to create records in database which will facilitate the recognition of the unknown records.

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