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

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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.

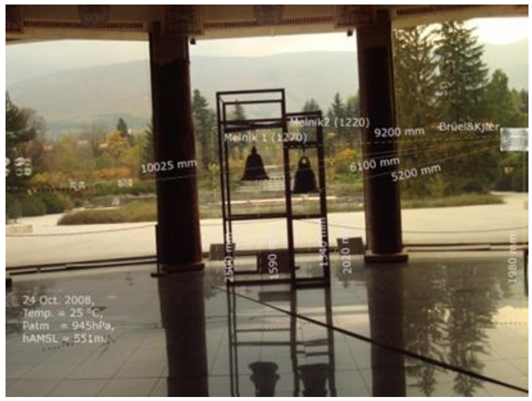

Figure 1. Measuring microphone toward XIII century bell disposition.

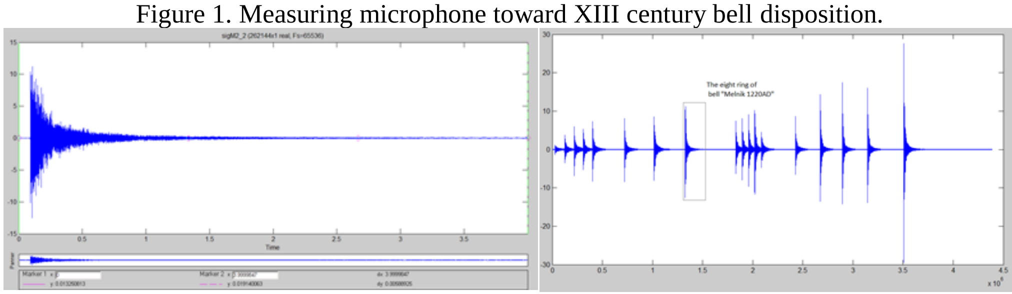

Figure 2. One waveform of Bulgarian bell stroke (XIII cent.), on the second it is separated only one bell ring (the eight), where $F_{samp} = 2^{16}$Hz, $N_{samp} = 2^{18}$

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:

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

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

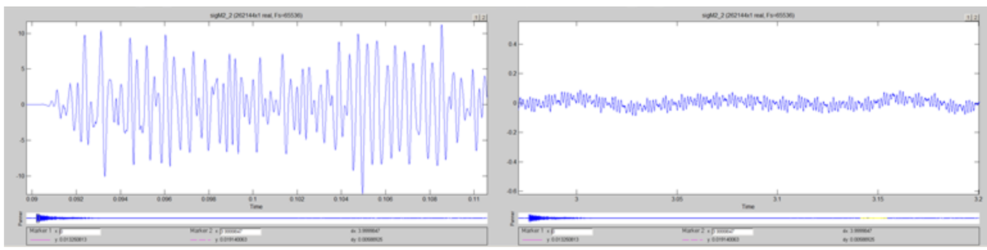

Figure 3 The front and the tail of signal from one bell ring, the eight one fig.2.

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.

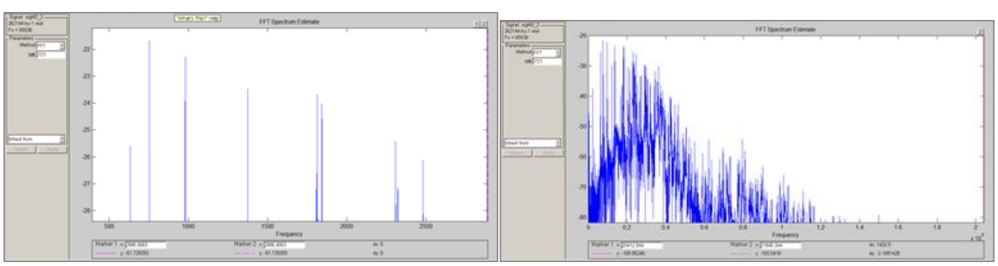

Figure 4 The log magnitude spectra of signal the Bulgarian bell ring, f=1,...,2500Hz and f=1,...,20000Hz.

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.

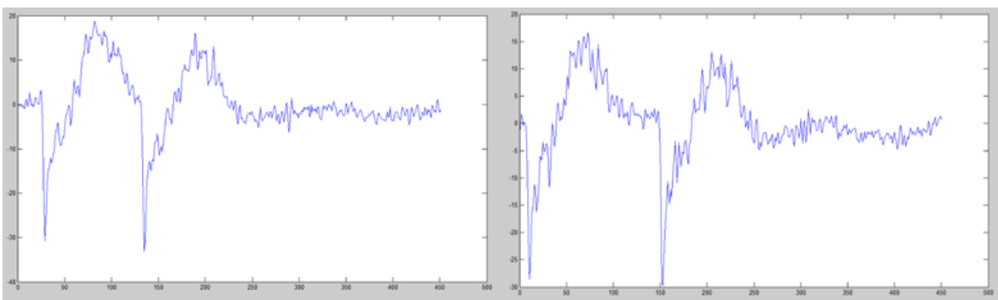

Figure 5. Waveforms from large-caliber tank machine-gun, 14,5 mm KPVT

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.

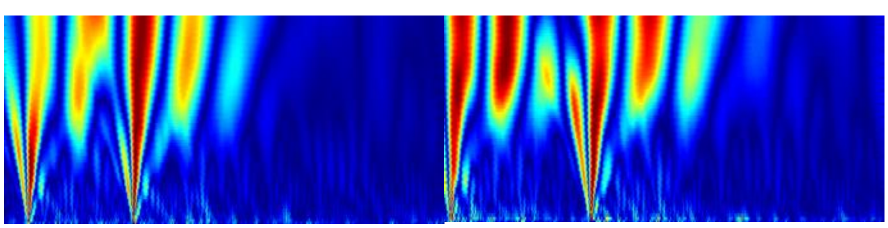

Figure 6. Calculated scalograms for 14,5 mm KPVT waveforms correspondingly to fig. 5., a=1,...,64, Daubechies db3.

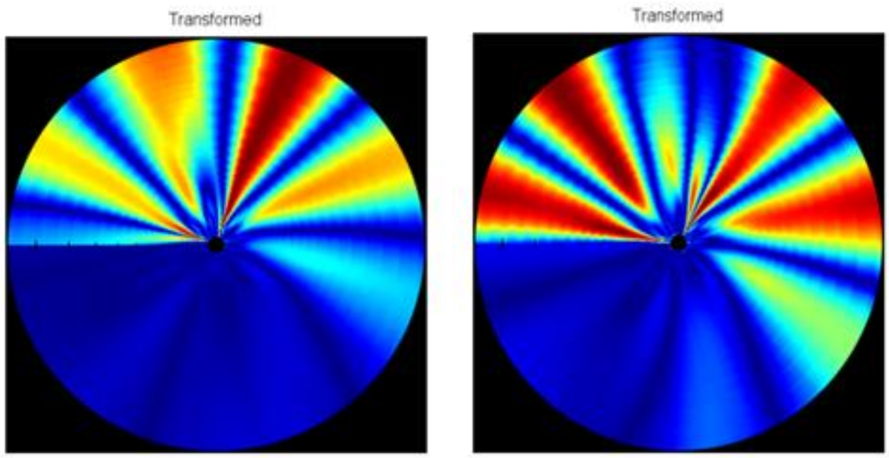

Figure 7. Calculated scalogram transformations (sound prints) for 14,5 mm KPVT correspondingly to fig. 5 and 6, a = 1,...,64, Daubechies db3.

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

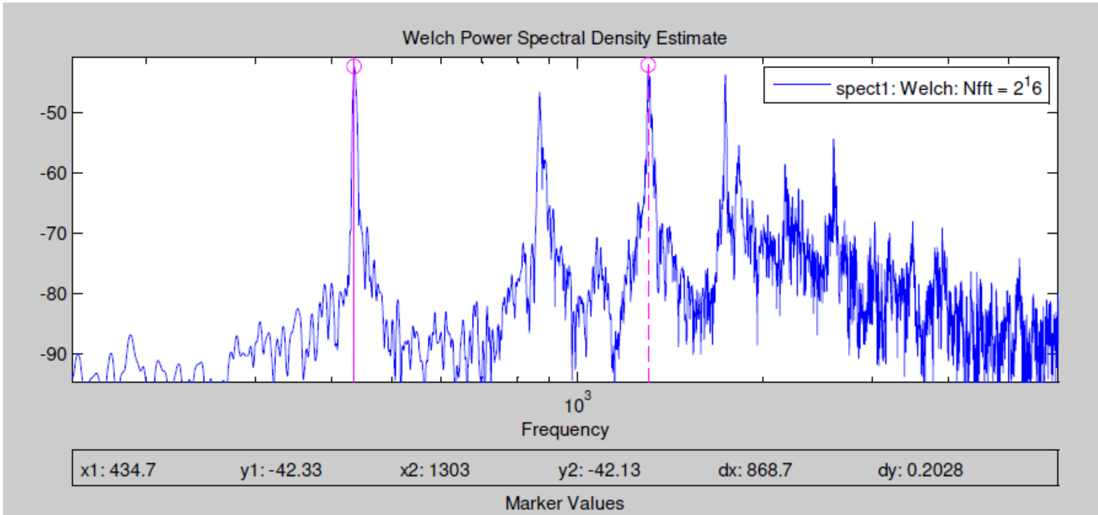

Figure 9. Spectral components of the flute in current time

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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