Acoustic Riddles of Cultural Heritage

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Abstract. It is shown, that in the process of evolution, a relationship between some hidden parameters of acoustic signals and expected emotional response to them has been formed. This relationship is a necessary condition for a living creature to survive. The efficiency of the concept represented is illustrated using examples from the field of classical music, ethnic African music, as well as biolinguistic signals of animals. Reasons of a particular impact of bell rings are analyzed using acoustic signals of some Bulgarian and Russian bell rings and chimes.

Keywords: Music, acoustic impact, measurement of expected emotional response, biolinguistic signal, drum, bell.

1. Introduction

Important components of cultural heritage are legends and documentary recollections concerning extraordinary consequences of acoustic impacts on separate people or population of a whole city. There are many miracles and riddles, which relate to music influence. Bell ringing, in our opinion, is one of the greatest acoustic riddles. Bells accompany weddings and funerals, turning these individual events into some acts of an educative importance, which are significant for every participant. The bell ring can be a mean, which is applied to inspire people to fighting with enemies, extinguishing a fire or struggling with any other threat. The bell ring of such a kind generates a feeling of responsibility for a cause. Using tintinnabulation, in the Middle Ages and even in the 20th century people killed epidemics.

The present-day level of science and engineering makes it possible to attack these riddles. To proceed to this exciting work, first of all, it is necessary to understand a mechanism of music impact upon a human organism.

As they figuratively say, the greatest secret of music is that nobody knows how it influences our brain. Recently the authors of this paper have put forward the hypothesis that shows a perspective to discover "the greatest secret of music". The hypothesis links an expected emotional response of a listener and some hidden parameters of musical fragments [1]. The concept [2] – [5] developed on the basis of the hypothesis [1] allows specialists to create methods and instruments for measuring expected emotional responses to acoustic impacts and make the first steps to explain the relationship between response of a dog to a snake kiss and reaction of a man to a fragment of a Wagner's overture. Below it will be shown that basing on this concept, it is possible to propose some keys to the acoustic riddles of cultural heritage.

2. Origins of Emotional Response

In the process of evolution, living creatures acquired a need to perceive signals warning them about approaching natural disasters (tsunami, underwater volcanic eruption, etc.), enemies, as well as "food" or male (female) animals. In water living creatures could perceive such signals directly only through the sense of touch. The sense of touch enables the signals related to pressure changes in a rather low frequency range to be distinguished.

The low frequency oscillations of a medium characterized by definite amplitude and frequency, are elementary signals-stimuli causing the simplest emotions. The ability to perceive such signals contributed to survival; therefore, it was fixed genetically.

When reptiles left water and settled on land, the density of a medium surrounding a large part of their bodies became significantly less. Under the new conditions, it was necessary for them to preserve and develop an ability to perceive the signals which were important for their survival. In the process of evolution, reptiles acquired hearing apparatus [6], in particular, foretype of ears, which allowed them to perceive oscillations of air within a wider frequency range. Living creatures started perceiving the informative oscillations of the medium by body (directly) and by hearing (indirectly). An opportunity to perceive informative air oscillations within a definite frequency range depends on the sizes of ear. The ears cannot be so big to perceive oscillations with the frequencies of a few Hz or less.

Man hears air oscillations (sounds) within the range of approximately 15 – 16000 Hz. The informative oscillations mentioned above cover the field of infrasound oscillations as well as of a lower part of the sound field (hereinafter, all this range will be referred to as IFR). However, air oscillations with the frequencies higher than the boundary of the IFR, can be modulated in amplitude and/or frequency (phase) by the oscillations of the IFR, important for survival of species.

According to the author's concept, the ability to perceive information of vital importance the IFR oscillations contain, has been realized within the process of evolution by originating the non-linear conversion of sounds. The sounds are perceived by ears and converted in an "ear - brain system", the level of a converted signal non-linearly depending on the level of an input signal.

The non-linearity of the wave conversion in the hearing apparatus of a man is noticed by many authors [7] - [9], but it has not been studied well yet.

As it is known, when the conversion function of a converter is non-linear, an output signal spectrum becomes "richer" than an input one [10]. If the input signal spectrum includes the waves of two or more frequencies, some intermodulation products are formed in the spectrum of the output signals. An intermodulation product at the output of the non-linear converter is characterized by its frequency f and order p. The frequencies of the intermodulation products can be higher and lower than the input ones, their amplitude decreasing with the increase of p.

It is the non-linearity of the signal conversion in the "ear-brain system", which allows IFR oscillations (which are emotionally important, but absent in the input signal spectrum) to be selected from the audible sounds. This feature contributed to

preserving the experience, accumulated within the preceding evolution, and gave the reptiles possibility to survive.

Genesis of a community (a swarm, flock, or family) within the evolution process has led to improving the species viability. However, the functioning of community has resulted in:

- a more noticeable differentiation of situations of vital importance and, correspondingly, more developed palette of emotional responses,
- a need to transmit emotional information to a longer distance and receive it.

The development of emotions was realized by giving an emotional value to some ordered groups of the elementary signals-stimuli, which can be called emotional images. As a result, an emotion structure resembles a speech structure with a limited number of sounds, incommensurably wider set of words and practically unlimited possibility to transfer substantial logical information. The Cro-Magnon man (unlike the Neanderthal man) survived because he managed to enrich the emotional content of the sounds he used. At first a singing and then intonated speech evolved [11], [12].

Transmission of the emotionally important signals for longer distances required to expand the sound range, since in a medium the sound attenuation decreases when the frequency increases. As a result, even a high frequency whistle language was born.

Thus, according to the concept represented, perception of music and intonated speech was determined by the evolution necessity and fixed in genes as a response of living creatures to the IFR waves.

Measurement of expected emotional responses should be based upon experimental determination of values of physical quantities carrying emotional information. Taking into account the above, a basic problem of measuring the expected emotion responses to music and other acoustic impacts can be brought:

- at the first stage, to revealing the elementary signals-stimuli, their "emotional content" as well as measurable parameters characterizing these signals-stimuli:
- at the second stage, to revealing the content of emotional images.

3. Analytical verification of the concept

To verify the proposed concept, computer investigations of a spectrum of intermodulation products arising in a non-linear converter, was performed. The intermodulation products were obtained as a result of interaction of the simplest sets of acoustic waves carrying an emotional colour.

For classical functional music, the simplest sets of acoustic waves are basic elements of musical tonalities (thirds and triads). In accordance with [13] and conclusions of the author of [14], corresponding chords are identified by listeners as emotionally coloured ones. Evidently, the colours of major and minor keys are different. These facts determined the objects for investigations.

The sound scale of a modern equal tempered tune (12-tone equal temperament) overlaps the range from 16.35 Hz to 7902.13 Hz [8]. Only single samples of organs reproduce the sounds of organ music beginning from 8 Hz. To present day, in addition to the equal tempered tuning, the ancient Pythagorean tuning is applied. In

spite of its well-known drawbacks, it enables musicians to achieve a greater expressiveness of musical phrases. It is logical, that vocalists and musicians playing the instruments with a changing pitch, often "tweak" of the tuning in real performances away from equal temperament [15].

In a lower part of the great octave, in the contra and sub-contra octaves, the tonic third frequency differences are in the infrasound range. Since formation of such intermodulation products (the second order components) is typical both for the major and minor, these octaves are less informative for the analysis being performed. In a higher part of the second octave, as well as in the next octaves, the order of the infrasound intermodulation products increases (their amplitude decreases), i.e., the infrasound waves practically disappear from the spectrum in these octaves.

Therefore, the calculations have been made for chords consisting of sine waves with the frequencies related to the small, first and second octaves. These chords were simulated in twelve major and twelve minor tonalities using the equal tempered tuning and the Pythagorean one. For dominating regularities to be revealed, appropriate sharp and flat tonalities were considered as being enharmonically equivalent. The frequency of note A in the first octave was equal to 440 Hz.

In the investigation, the original method of calculation [16] – [18], which is a part of the methodology of frequency converter analysis and synthesis, developed by one of the authors of this paper, was applied. The intermodulation products were determined separately for the major and minor tonic triads as well as for the thirds built using the above kinds of the tune. The calculated values of frequency of the IFR waves having the maximum level (minimal value of *p*) are shown in Fig.1 for the frequencies no higher than 14 Hz (in the inaudible field). The results of this analytical verification can be briefly formulated in the following way.

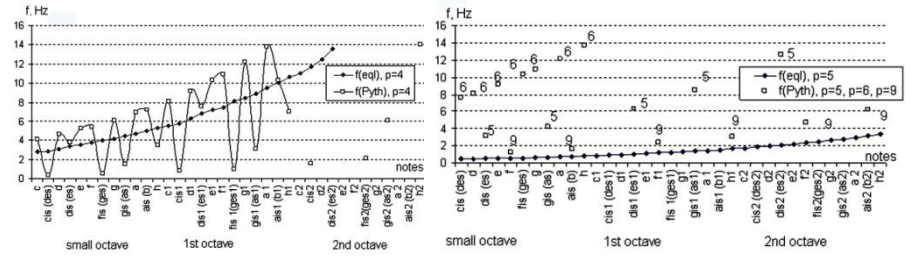

Fig. 1. Relationship between the frequency values of infrasound intermodulation products and tonics with the increase of tonic frequency (tonic triads; equal tempered *(eql)* and Pythagorean *(Pyth)* tuning; a) for major tonalities (*p*=4), the "background" components (*p*=5) being not shown; b) for minor tonalities (*p*=5, *p*=6, *p*=9)

1. The major tonalities are characterized by the higher level of the IFR waves than the minor ones. For example, major triads are characterized by the intermodulation products with *p*=4. This difference decreases in the lower and higher parts of the sound scale, music having a "major" hint in the lower part and a "minor" hint in the higher part. For the major and minor tonalities of the equal tempered

tuning, which have the same tonic, the intermodulation products of the same frequency with a higher order (p=5) are generated.

Since the non-linearity influence falls down with the reduction of the input signal level, it is clear that the difference between the major and minor tonalities has to decrease when the level of a sound volume decreases. This effect is confirmed by the fact that when one listens to an unknown music performed quietly, its emotional impact is weak.

2. For various tonalities of the Pythagorean tuning (unlike the equal tempered one), the infrasound range frequencies are significantly different, that results in various emotional colours of tonalities. For the equal tempered tuning, the correction of the perceived frequency values appears to be performed in the brain, intensifying an emotion colour. This effect corresponds to the zone theory of hearing [12].

The presence of the "background" components in the equal tempered tuning is one of the reasons why the expressiveness of this tuning is lower in comparison with the Pythagorean one.

3. The recognition of major and minor triads by listeners, if the sounds included in a triad are played consecutively, can be explained by a delay effect (memory), i.e., the effect of the joint conversion of the sounds.

The calculation results were complemented with the results of the theoretical analysis of some noted facts related to man's psychic. It is well-known that the activity of brain biorhythms is connected with a man's psychical condition. This relationship is illustrated in Table 1, where the data [19], [20] and others are summarized. Information given in the Table 1 requires for additional investigations, e.g., with regard to variation of man's state, when the frequency of a biorhythm is changing between its lower and higher boundaries, to refinement of frequency boundaries, etc. Nevertheless, information presented in Table 1, gives the basis to propose that the simplest signals-stimuli activate definite biorhythms and this is the process that generates corresponding emotions.

Table 1. State of an wakeful man vs. main activated brain biorhythms

Bio-rhythm	Frequency, Hz		State of an wakeful man
	From	To	
Delta - rhythm	0.3-0.5	3.5–4.0	Active interest of a man in something; stress; increase of hormone production, which contributes to physical reconditioning
Theta - rhythm	4.0	7.0–8.0	Concentration of attention; generation of bright images and recollections; decrease of the influence of original psychical sets; increased perceptivity to some new sets; origination of unexpected associations
Alpha - rhythm	7.0-8.0	11.5-14.0	Wakefulness; sharpened sensibility; readiness to increase the muscular activity sharply
Beta - rhythm	12.0–14.0	29.5-35.0	Increase in the level of attention; mental strain; emotional excitement
	12.0-14.0	20.0	Emotional strain in combination with increased concentration; mental strain
	20.0	29.5-35.0	Emotional excitement in combination with inability to concentrate attention

It is known from the oscillation theory that an excitation process is the most efficient if frequencies of an activating and activated processes are characterized by close values.

Therefore, it is possible to add the following statement to the previous ones.

4. The values of the brain biorhythm frequencies are close to those of the signal-stimulus frequencies. Thereby, the relationship between the emotional response and frequency of the signal-stimuli, originating this response, was fixed in the genetic memory of living creatures.

4. Formation of the Simplest Emotional Image in Classical Functional Music

The theoretical analysis enabled authors to characterize the emotional colour of the elementary signal-stimuli. Formation of the emotional image (mood) by the sequence of a few signals of such a kind was described in [4].

As it is known, the sequence of chords of attendant tonalities (according to steps I-IV-V), to a great extent, determines the emotional colour of compositions written in the corresponding tonality. Statistically reliable expert judgments of a listeners' response to fragments of classical musical compositions, written in various tonalities, are given in [14] (see Table 2).

Table 2. Examples of emotional content of the simplest images

Tonality	Mood according to [14]	Mood according to the results of the biorhythm analysis
Fis-dur (E. Grieg. In spring, op.43)	Contemplativeness	Recollections and associations with background of a deep grief
As-dur (F. Chopin. Polonaise No 6, op.53)	Great energy and joyful mood	Hope for the better after a tragedy
B-dur ((F. Shubert. Ave Maria, op.32)	Energy, triumph transferring to calm and harmony	Pleasant recollections and associations
A-dur (E. Grieg. Norwegian dance, op.35)	Happiness	Bright associations accompanied by a wish to intensify muscular activity
as-mol (F. Schubert. Barcarolle, op.60)	Aloofness	Vague recollections (the level of the IFR components is low, but it is the highest one for the minor tonalities)
b-mol (F. Chopin. Death march, Sonata No 2, part 3, op.35)	Aloofness, transfer from mournful insensibility to tragic mood	Feeling of tragedy after vague recollections (the level of IFR components is the lowest)
e-mol (J. Massenet. Elegy, op.10)	Melancholy, dreaminess	The mood corresponds to the interpretation of [14]
cis-mol (L. Beethoven. Sonata No 14 (Moonlight sonata), part 1, op.27	Fantasy, dream, transfer from a day-dream to aloofness and grief	The mood corresponds with the interpretation of [14]

In Table 2 these estimations are compared with the results of decoding the corresponding emotional images on the basis of the data on activation of biorhythms, caused by the signals-stimuli under the sequential performing of the chords according to steps I-IV-V.

A timbre, rhythm, tempo and articulation play a significant role in forming the spectrum of acoustic waves. These circumstances influence, to a great extent, the music perception. For example, the Russian dance "Yablochko", composed in minor key, is perceived as the major music due to a staccato applied.

It should be noted that those main emotions transmitting by music which were formed at the early stages of biological evolution (fear, anger, pleasure, and some others) are perceived by listeners at the unconscious level. More complicated emotions are perceived with the participation of consciousness. Therefore, reception of them, to a greater extent, depends on national and cultural features.

5. Analysis of Fragments of African Ethnic Music

A possibility to decode the emotional images formed by several signals-stimuli, is considered also using the results of computer analysis of recorded fragments of African ethnic music. A choice of these acoustic impacts is determined by the fact that ethnic and partly ancient religious music was created using the simplest means. The purpose of the music of such a kind is to form bright and clear emotional images. It is the analysis of musical fragments of such a kind, which was of particular interest for verification of the concept represented.

For investigations, there were chosen fragments of African ethnic music (GUEM) with the specific titles "Festival", "Fear", and "Nightmare", performed on the drums and recorded as wav-files. Fig. 2 shows the infrasound spectra after the non-linear conversion.

For the "Festival", main maximums of the IFR waves correspond to the domain of the theta-rhythms and, to a lesser extent, for the domain of the alfa-rhythms. According to Table 1, the emotional content can be decoded as recollections of successes and an associative hope for future joyful events. These recollections and associations are complimented with a feeling that a person belongs to a community and with a motivation to move actively according to some rules (apparently, it can be a wish to dance).

It is important, that the lowest frequency of the signal-stimulus with the maximum amplitude determines the main feature of the emotional image, the higher frequency signals-stimuli detailing it.

For the "Fear", the minimum frequency of the IFR waves comes to the domain of the delta - rhythms (approximately 2.7 Hz), which corresponds to origination of stress and anxiety. Maximums in the domains of the alpha - rhythm and, to a lesser extent, beta – rhythm characterize the mobilization of attention and muscular activity (readiness for a battle or life-saving by escaping).

For the "Nightmare", the minimum frequency of the signal-stimulus is close to 1 Hz, the intensive components in the zones of the 2nd and 3rd harmonics being

noticeable. All the delta – rhythm domain is activated, that testifies to hard stress, related to a serious danger. The maximums in the domain of the alpha - and beta - rhythms (in comparison with "Fear") are smoothed, cover smaller areas and have a lower level. Taking into account a peak in the lower part of the delta - rhythm domain, it can be decoded as an uncertainty of a program of activity. A rise in the level of waves in the domain of theta - rhythms characterizes sharpening of recollections and associations. This fact can be interpreted as an intensive search of the program of activity.

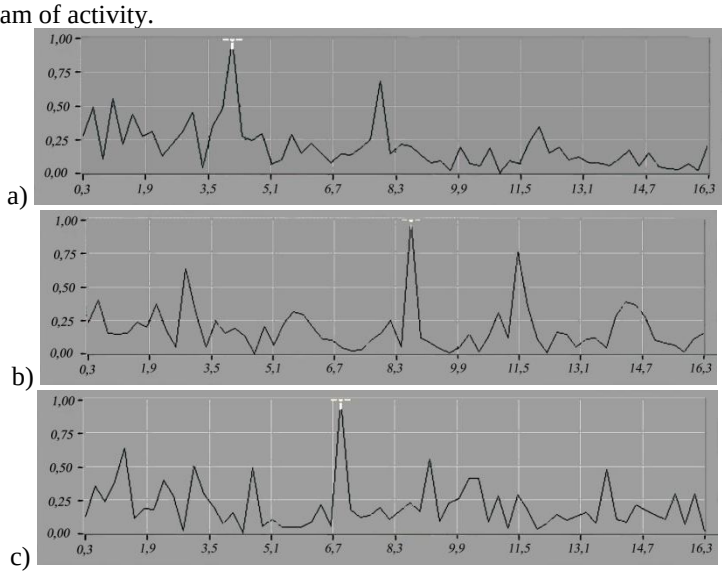

Fig. 2. Spectra of the IFR intermodulation products after non-linear conversion of the input data (*axis of abscissa* is the frequency, Hz; *ordinate axis* is the level of spectrum components, relative units; a) "Festival", b)"Fear", c) "Nightmare")

The analysis of the "Fear" and "Nightmare" gives the basis to propose that the emotion related to the feeling of danger sharpens when the frequency of the delta - rhythm decreases.

The examples given prove the opportunity to decode the emotional content of emotional images created by drum music fragments.

6. Analysis of Biolinguistic Signals

The presumption that the system of reception-transmission of the acoustical signals-stimuli was formed in the process of living creature evolution, is confirmed by numerous facts of mutual emotional understanding between animals and men.

The results of the biolinguistic signal analysis, presented below, can become an additional confirmation that the concept is universal. They were obtained on the basis descriptive information and records of biolinguistic signals [21].

At the lowest stages of the living creature evolution, a biolinguistic signal was the signal of anxiety (e.g., for shrimps Alpheidae, these sounds are separate packs of

damping waves with the carrier frequency of no less than 10 kHz, duration of less than 0.1 s and frequency, conventionally, in the delta – rhythm domain).

Crab Uca annulipes generates signals with the frequency of the delta - or theta - rhythm, qualitatively distinguishing by emotional colour. Fishes use signals of 2 - 3 types. Each of these signal types corresponds to a definite situation. The signals associated with danger or threat, are emitted by reptiles, birds, as well as a number of mammals, including predators.

All these signals can be represented as the packs of waves forming the signals-stimuli after the non-linear conversion in the "ear – brain" system.

An example: for growling and hiss of cheetah (acinonyx jubatus), the main energy is concentrated in the bottom zone of the delta - rhythm field (that means stress). An increased level of the energy spectrum in the domains of the theta - and alfa - rhythms as well as bottom zone (12 – 16 Hz) of the beta - rhythm, can be noticed. For hiss, energy in the beta - rhythm domain increases. The cheetah emotions can be decoded: the warning growl is followed by the hiss that is the signal of readiness to make a lunge.

Single or rare biolinguistic signals, to a greater extent, related to negative emotions, generate the signals-stimuli in the lower part of the IFR. The signals originated later, mainly, connected with positive emotions, apparently have to have energy splashes of a higher frequency. (Some additional details are given in [5]).

It is representative that a spectrum of the IFR waves of a cheetah female purring in a comfort state is of another quality. The main energy is concentrated outside the delta - rhythm. The energy peak is close to 25 Hz. This fact characterizes emotional excitement not related to the necessity to solve a definite task.

7. Possible Solutions of Acoustic Riddles of Cultural Heritage

The key to the bell ring mystery relates to the fact that besides an increased acoustic power, a bell is characterized by a complicated spectrum of acoustic waves, caused by crosscut, longitudinal and shear forms of mechanical oscillations. The spectrum of acoustic waves for a bell can activate biorhythms, generating various listener's images depending on a situation.

For illustration, Table 3 demonstrates fields of energy rise in the IFR spectrum of bells. The results were calculated by the non-linear conversion of data contained in files with records of Bulgarian bell rings. (The files were recorded by researchers working at the Institute of Mathematics and Informatics, Bulgarian Academy of Sciences).

Table 3 confirms that bells in a church are different with regard to their impact on a man. Therefore, it is possible to form a purposive impact on the basis of some sequence of emotional images, combining strikes of separate bells and their chime.

Table 3. Characteristics of the spectrum of some bells, obtained after the non-linear conversion of input signals

Object	Bell No.	Delta – rhythm	Theta - rhythm	Alfa - rhythm	Beta - rhythm
The St. Alexander	2	+	+	+	+
Nevsky Cathedral,	7	+	+		+
Sofia	9		+	+	
The Church of the	1	+			
St. Navity of	2		+		
Christ, Shipka	3	+			
	4	+	+		
	5	+		+	

Fig. 3 represents diagrams of the Joyful ringing of bells [22] (The Cathedral of the St.Yury's Monastery, Veliky Novgorod, Russia) converted into the IFR. As the bell sound develops (Fig. 3a, b, c), sounds of new bells are added and a chime of the bells grows. The spectrum shifts to higher frequencies. One can notice a rise in a signal-stimulus in the domain of theta - rhythm, which reminds the diagram of the spectrum for the musical piece "Festival" performed on the drums.

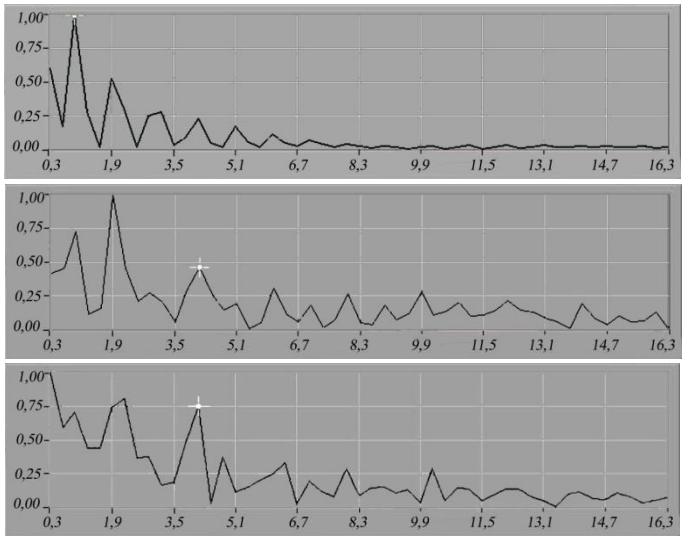

Fig. 3. Joyful ringing of bells (The Cathedral of the St.Yury's Monastery, Veliky Novgorod, Russia). Spectra of the IFR intermodulation products after non-linear conversion of the input data (*axis of abscissa* is the frequency, Hz; *ordinate axis* is the level of spectrum components, relative units). a), b and c) correspond to sequential fragments of the musical piece.

A funeral knell has the other character. For example, in the funeral knell No5 [22], recorded in one of the churches of the Russian Gold Ring, at the beginning, one can see an energy maximum in the delta – rhythm domain, in the rest of domain the level being small. Some rise can be noticed near 27 Hz. Such a spectrum corresponds to the

feeling of tragedy and inability to concentrate attention on a future. Further the low frequency maximum widens and includes the theta – rhythm domain activating imaginative thought. The high frequency maximum shifts to 20 Hz and then degenerates, which taking into account a preliminary mood of people presented at funerals, can be explained by a gradual perception of a reality and reminder about a heavenly life. Non-believers can perceive this part of ringing as an impact that generates images related to their future life. It is natural, that the preliminary mood of people, a great number of them and visual sensations accompanied the bell ringing, multiply the acoustic impact. The anti-epidemic effect of the bell in the past, can be explained by two factors. Powerful acoustic waves in the delta - and theta – rhythm domains frightened rats, carriers of a disease and made them run from a locality where the bells are audible. Besides, this ringing inspired believers to a hope for a help from heavens, which increased the resistance of their organism. Thus, key to the mystery of the bell ring impact on psychics of men and their health can be elucidated by unique combination of: the variety of signals-stimuli formed directly in the bells, the high acoustic power of bells.

The same approach can be applied to an interpretation of a legend about Siren's singing in the Homer's poem and explanation of the facts concerning derelict ship tragedies.

8. Conclusions

Solutions of the riddles of cultural heritage, considered above, illustrate possibilities of the proposed concept, which gives an opportunity to evaluate quantitatively (to measure) the expected emotional response of living creatures, in the first place, men, on acoustic signals of various nature. This concept opens ways for applied investigations in many fields. However, to develop the concept further, it is necessary to study more deeply the relationship between the biorhythms of the brain, its functioning and emotions. One of the main trends of future scientific investigations is a further study of music impact on a man. From this position, a work on recording and preservation of the bell rings, folk instruments and religious music, being performed at the Institute of Mathematics and Informatics of Bulgarian Academy of Sciences [23] is extremely important.

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