# Role of Measuring Model in Biological and Musical Acoustics

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*Abstract. On the basis of development of a particular measurement model in the field of acoustics, the authors show prospects of investigations in various spheres. The measurement model considered in the paper is intended for measuring the parameters of emotionally important signals contained in sequences of simple and complicated sound signals. It provides an adjusted delay (short-time memory) and joint non-linear conversion of audible and retained acoustical signals, as well as selection of infrasound signals-stimuli. Recognition of emotional images is performed by identification of signals-stimuli and their ensembles. Results of analysis of bioacoustical signals applied by animals in making contacts with each other and with a man, are given.*

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## 1. Introduction

In accordance with the Professor Thomas S. Kuhn's theory, the development of science is of a discrete nature, the basis for the next scientific revolution, i.e., for forming a new step in the development of researches in some area, being a change of the scientific paradigm. According to the D.I. Mendeleyev's statement, "science begins at that time, when they begin to perform measurements." From these two statements it follows that the change of the scientific paradigm presupposes a change of a conception of relations existing among elements in a corresponding field of science. Further on, a stage of developing a new measurement model starts; the latter defines tasks of subsequent scientific researches.

Such development of events is confirmed by the history of exact sciences: astronomy, physics, chemistry, etc. However, the durations of steps in various fields of knowledge are significantly different, the cycles of economic development making a considerable impact on this difference.

In the 21-th century the approaching cycle of development is connected with an increase of the role of distinctive features of human individuals. It is exactly the reason why today the need for development of measurement models, relating to interdisciplinary fields of science, which are not referred to the exact sciences, is of current interest.

These fields are at the interface between economics and psychology, biology and art, pedagogics and neurophysiology, as well as between other sciences which usually not compatible.

The problem of developing objective methods for evaluating the person's psyche, in particularly, the ability to perceive information, subjective feeling, emotion, memory and so on, becomes to be of specific importance.

This conclusion is proved to be true by a number of scientific conceptions in which the role of psychic peculiarities of separate social groups is accentuated under the circumstances when consumers are forming decisions connected with explicit costs.

On the basis of one of such conceptions, the bank business of the "father of microfinancing," Muhammad Unus, Nobel Prize laureate in 2006 is being successfully developed, whereas his followers are making good use of the conception for developing their neuro-marketing (advertising) business.

For another confirmation it is possible to use the psycho-diagnostics and art-therapy. The latter apply various effects over an emotional sphere of patients. Increasing the interest to these spheres can be noticed on the background of an increasing number of publications, informing readers about undesirable consequences of a pharmaceutical composition intake. A list of examples can be continued…

Within the frames of the above problem, a key task of specialists in the field of metrology and measuring technique is the development of methods providing measurements of emotions. For this problem to be solved, it is necessary to join with specialists in other fields of knowledge too.

## 2. Proposed measurement model

Among the methods for transmitting and receiving information concerning an emotional state, the simplest is the acoustical one including it's the most developed musical form.

Both in psychology and musicology, the identification of emotional colouring of musical fragments is performed by experts who hear it. There is no generally accepted "scale of emotions." Taking this into account, the authors have developed a measurement model for a boundary area, connecting acoustics, biology, psychology and ethology [2 - 4]. This model concerns measurements of emotions and it could be referred to as a neuroacoustical one.

Further on, it is necessary to remind of the emotion definition, essence of the proposed measurement model taking into consideration the latest investigation results, as well as to substantiate the correctness of the model.

Thus, the emotion is the feeling that arises in an individual in the course of cognizing the reality-life. Information received produces some emotion, and the latter transmits emotion-driven information. According to [5, 6], the emotions motivate, organize and guide the perception, thought, and actions.

According to the authors' hypothesis, any acoustical impact, carrying emotional information, contains one or a number of signals-stimuli, the perception and recognition of which in a corresponding sequence cause generation of emotions.

In its turn, each of these stimuli can be characterized by one or a number of signals. Parameters of these signals can be measured and related to the known measurement units.

A set of these parameters characterize peculiarities of the emotion, i.e., its nature, similarity to the other one, intensity and so on.

Within the frames of the model proposed, the emotion value $Z(x)$ can be written as:

$Z=Z[Y_1(x_1, \quad x_i \ldots x_k), Y_2(x_1, \quad x_i \ldots x_k), \ldots, Y_m(x_1, \quad x_i \ldots x_k)]$,

where

$x_1, \quad x_i \ldots x_k$ are the parameters measured,

$Y_1, Y_2, \ldots Y_m$ are the signals-stimuli,

$m$ is the number of various signals-stimuli generating the whole set of emotions examined.

A combination of various emotions determines their variety, and their variation with time represents an emotional content.

Accordingly, the measurement of emotions contained in acoustical impacts can be brought to revealing experimentally the above signals-stimuli, quantitative evaluation of the parameters characterizing them and recognition of the emotions on the basis of the results obtained.

The model was developed using the results of the analysis of sensor systems [7 - 9], which indicated the following.

Sensor systems were acquired by living creatures in ocean for stimulating activities providing species with the ability to survive under short-term changes of the environment.

The earliest sensor system provided the sense of touch, i.e., the perception of water pressure changes. The audition is its latest "modification", adapted to the perception of oscillations of air (the medium with density which is lower than that of water).

The natural selection had to lead to generating unconditioned reflexes (prototypes of the emotions) of living creatures. These reflexes related to the responses on some types of perceptible changes of the environmental pressure.

Certainly, the frequency of perceptible changes cannot exceed a cutoff (500 Hz) of signal transmission over a sensor fiber. In fact, the frequency of perceptible pressure changes is significantly lower. A latent period of generating the emotions over the time, when the evolution of living creatures took place, did not increase many times (for a man it is about 0.15-0.3 s [10]). The frequency range of emotional response formation can be limited by approximately 30 Hz.

This frequency range covers an infrasonic and low part of the sound range. Further on, this range will be referred as IR. In the proposed model of measuring the emotions, the frequency and level of the IR signals-stimuli (or the parameters related to them) can be accepted as the main parameters $x_i$ to be measured.

It is well-known that animals and men perceive the IR waves as those which carry emotions [11 - 14]. The creatures living in air take informative IR waves too by

- body using tactile sensation of the mechanical IR waves and
- by "ear-brain" system perceiving the air waves of the sound frequency range and then recognizing the corresponding IR waves through a special mechanism.

The earliest emotions are negative. They were caused by a danger threatening to an individual organism. The genesis of a community gave rise to a need for transmitting information that was important for survival of the species to other members of the community. This information could be connected with either negative emotions or positive ones (i.e., availability of food); it could have emotionally neutral content as well.

This assumption agrees with the investigations performed by Jurgens, Blumstein and others, mentioned in the review [15], where it is proved that the majority of mammalian sounds are caused by emotions, the greater part of them being connected with a negative emotional state. In those cases when an animal experiences positive or neutral emotions, it vocalizes more rarely.

Development of the human society is connected with a greater differentiation of situations and more developed palette of emotional reactions.

The number of IR wave parameters being extremely restricted, the enrichment of emotional information was achieved by forming the emotional images on the basis of small ensembles of signals-stimuli and then taking combinations of such images in some sequence.

Such a structure resembles a speech structure with a limited number of sounds, wide set of words and unlimited possibility to transfer substantial information.

The authors explain the way of selecting the IR oscillations from the acoustical ones, by the following way. In the "ear – brain" system, a non-linear conversion of input sound signals is performed, which results in forming the IR intermodulation products with frequency $f_k$ and order $p_k$. The level of an intermolulation product rapidly, but irregularly decreases with the growth of $p_k$ since it depends on the on the fact whether $p_k$ is even or odd.

$$f_k = \left| \sum_{i=1}^{m} n_i f_i \right| \qquad p_k = \sum_{i=1}^{m} \left| n_i \right| ,$$

where

$n_i$ – is any integer (positive or negative one, or $n_i$=0 ),

*m* is their number of input signals with various frequencies.

Under the conversion of the input sound signals they can be added to the same, but delayed signals.

After selecting the signals-stimuli, the identification of their ensembles and recognition of the emotional images are realized, the simplest emotional image being formed from no less than three IR signals-stimuli.

It should be explained that the non-linearity of wave conversion in a hearing apparatus of a man is noticed by many authors [16-18], but it has not been studied well.

The non-linearity of wave conversion is confirmed by:

- formation of both the microphone potential, repeating the sound wave form, and the so-called summation potential, tracing the form of sound wave envelope, in the ear cochlea;
- residual effect providing the possibility to select the IR wave pitch at the perception of a number of its harmonics by ear, as well as to "hear" the sound corresponding to the difference of wave frequencies with the maximum level at the impact of a number of non-harmonic waves;
- dependence of the amplitude-frequency characteristic of the hearing apparatus on the amplitude of an acoustic impact;
- self-adjustment of the nearest critical band (one of 24 bands which provide the sound distinguishing by frequency) to the frequency of an audible sound signal;
- finally, the fact that the "ear – brain" system is the dynamic system with variable parameters, its adjustment being realized directly in the process of audition.

Availability of adjusted delay (short-time memory) in the "ear – brain" system and joint conversion of audible and retained sounds enable a man to perceive an emotional colour of a melody.

In biolinguistic signals of mammals, including a human being, to identify the emotions of a later origination, the basic model should be complemented with a linear converter of a frequency field above the IR. Each of the frequency zones of this field has some advantages for transmitting the signals with a special emotional colour. For example, an increase in biolinguistic signal frequency increases the radius of its propagation [4]. Accordingly, the transmission of an alarm signal at a high frequency contributes to the survival of a species. The threat signal, as a rule, has a close addressee, the transmission of the latter being more effective at low frequency.

Thus, the proposed measurement model is universal and shows regularities, which are common for living creatures. Consequently, the biolinguistic signals emitted by them in order to transmit vitally important information, have to be characterized by universal parameters.

## 3. Evidence of the universality of the proposed measuring model

In [2-4] it is shown that in the classical music the emotional colour is caused by the IR oscillations. The difference in emotional perception of the major and minor tonalities corresponds to the difference in the spectrum of the intermodulation products. The simplest emotional images are formed by sequences of the attendant tonality chords and so on.

The analysis of the ethnic (African) music with a known emotional mood allowed the simplest ensembles of signals-stimuli to be identified, having connected them with the δ, θ, α and β-rhythms of a man. A version of the relationship between activated brain biorhythms and a state of a wakeful man is briefly given in Table 1. The data contained in Table 1 are of a tentative nature.

| Bio-rhythm | Frequency range, Hz | State of a wakeful man |
|---|---|---|
| δ -rhythm | 0.5 – 3.5 | Some types of a stress |
| θ -rhythm | 4.0 – 7.5 | Generation of bright images |
| α -rhythm | 8.0 – 11.5 | Increse of sensibility and muscular activity |
| β - rhythm | 12.0 – 29.5 | Emotional excitement |

Table 1. State of a wakeful man and activated brain biorhythms (a cutdown version)

It should be noticed that the most high-frequency signals-stimuli, as a rule, are associated with pleasure.

There is a reason to assume that in the process of the society evolution, when the emotional sphere has been developed very rapidly, at least, in some ranges of biorhythms, the sub-ranges have been formed. The excitation of each sub-range can slightly change the emotion. Probably, exercises of art and musical education contribute to the differentiation of biorhythms.

The comparison of signal-stimulus ensembles for the classical and ethnic music with the similar emotional colour has confirmed that the mechanism of forming emotions has remained in the process of human civilization development. Simultaneously, this fact demonstrates the possibility to decode the emotional content of acoustical signals.

However, the proposed measurement model relates not only to receiving emotions contained in the acoustical signals by a man. When the model was developed, it was proposed that the mechanism of emotion formation has originated before the origination of mankind and fundamentals of the mechanism functioning are general for all living creatures with the developed nervous system. This presumption is confirmed by numerous facts of mutual emotional understanding between the animals and men.

The results of the biolinguistic signal analysis can become an additional confirmation that the model is universal. They were obtained on the basis descriptive information and records of such signals [19-22].

One of the oldest species of invertebrate living creatures is crustacea. They inhabit ocean in the form of big groups. To provide the survival of the species, they require to communicate. At any excitation they emit sounds of the same type, which have different intensity depending on a situation. For shrimps Alpheidae, these sounds are separate snaps of duration less than 0.1 s, produced by claws. They are packs of damping waves with the frequency no less than 10 kHz. For spiny lobsters (Palinuridae), these packs are sharp "flashes" of the chirring with the frequency up to some kHz, which are evoked by rubbing feelers (antennas) [20- 22].

On the basis of the data given it is possible to come to a conclusion that the signals with a "proto-emotion" have not been differentiated for the invertebrates considered. This is the excitation which corresponds to either danger, fear, or appeal of a female. In essence, such signals are signals of stress. To increase the radius of transmission, as a rule, these signals have the form of wave packs. Therefore, the reception of such signals assumes the non-linear conversion, i.e., the detection of them with selecting energy in the lower part of the IR, which can be conventionally related to the field of the δ- rhythm.

However, the analysis of the biolinguistic signals provides the possibility to single out from the crustacea those who have made the next step upwards in the evolution of the nervous system.

One of the crustaceous species, crab Uca annulipes, emits sounds by knocking at the frequency up to 10 Hz during 1 – 3 s with a claw. If the crab is lighted up at night, it emits a knock with the frequency of 5 – 7 Hz, but the duration of this knock is of several minutes [20, 22].

Thus, the “proto-emotions” of the Uca annulipes are differentiated: in various situations the crab generates signals with the frequency of δ orθ- rhythm, qualitatively distinguishing by emotional colour.

The vertebrates, fishes, who inhabit the ocean too, use, at least, signals of two types: separate packs containing waves with different frequencies for various types of fish (similar to a creak, cronk, or drum roll, etc.) and long-term series of waves. It is possible to meet with mention of signals of the third type, i.e., the whistle. Each of these signal types corresponds to a definite situation, for example, the series are typical for spawning, while irregular packs are characteristic of the danger appeared.

A variety of the signal types and, accordingly, a set of corresponding main emotions grow with the nervous system evolution and achieve the maximum for the mammals.

The number of the signals associated with stress, including danger or threat, should be complemented with irregular hisses emitted by reptiles, birds, e.g., geese, swans, owls, as well as a number of mammals such as beavers, rats and leopards. The predators can emit other threat signals, e.g., growling and howling which are typical for leopards and wolves, at the same time the leopards use the hisses too. All these sound versions can also be represented as packs of waves forming the signals-stimuli after the non-linear conversion in the “ear – brain” system

If single or rare sounds generate the signals-stimuli in the lower part of the IR, then the bioacoustical signals, connected with the positive emotions, should have energy splashes in the upper frequency part.

For an experimental analysis of biolinguistic signals, the authors applied software “Music 1.0” developed at the D.I.Mendeleyev Institute for Metrology earlier and used in investigations of musical fragments. This software provides the possibility to analyze the spectrum of the IR waves formed after the non-linear conversion of the acoustic fragment or its sum with the same but delayed fragment.

The usefulness of converting just like this sum in measuring the emotions the authors mentioned before [3, 4] when they examined musical fragments. But in analyzing the biolinguistic signals the efficiency of the model with the delay appeared to be particularly noticeable. The experience has demonstrated that when the delay is close to a latent period of emotion formation (about 0.2 s), on the spectrograms of IR waves, obtained after conversion, the zones of energy splashes are more distinct. Just this version of the model has been used for further experiments.

The analysis of the IR spectra for a howl, growling and hiss of cheetah (acinonyx jubatus) after the square-conversion of input and delayed signal sum was performed. As the comparison has shown, the main energy is concentrated in each of the signals in the bottom zone of the δ- rhythm field (Table 1). An increased level in the fields of θ and α-rhythms as well as of the β-rhythm in the bottom zone (12 – 16 Hz) can be noticed.

For the howl the signal-stimulus of the δ-rhythm is limited with the frequency of 1.5 Hz; the ratio of its level to the level of the signal-stimulus in the zones of the θ and α-rhythms, $h_{\delta\theta}$ and $h_{\delta\alpha}$ are close to 0.2 and the level in the zone of the β-rhythm is noticeably lower. The howl is functionally connected with the cheetah “claim” by which it “announces” its right to be the master of territory [23].

At a growl the width of the zone with an increased energy of the δ, α and β- rhythms slightly grows due to a drop of the $h_{\delta\theta}$ and $h_{\delta\alpha}$ values down to 0.15, the level in the zone of the β-rhythm becoming higher.

At a hiss (Fig. 1) the energy in the β-rhythm zone grows up and becomes stronger. If one accepts that the relations between the psychic state and bio-rythms, indicated for a man in Table 1, can be extended to the animals, then the cheetah emotions can be decoded. The warning growl is followed by the hiss that is the signal of readiness to make a lunge.

It is typical that in [23] both vocalizations are referred to the aggressive ones, the fact that hissing often follows growling in vocal sequences. Both the hissing and growling are accompanied by threatening poses.

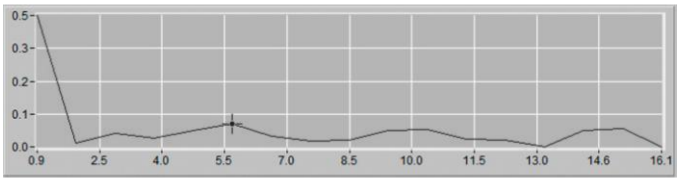
The spectrum of the IR waves of cheetah female purring in a comfort state (Fig. 1b) is of another quality .The main energy is concentrated outside the δ-rhythm. The growth of the level and covered frequency zone becomes noticeable as the transfer from θ to α and β-rhythms takes place. The energy peak is close to 25 Hz.

In the spectrum of a scream of a yellow ground squirrel (spermophilus fulvus), taken out of a hole, the stress of the latter can be clearly seen. Almost the whole energy splash covers the δ-rhythm field and lower part of the α-rhythm field.

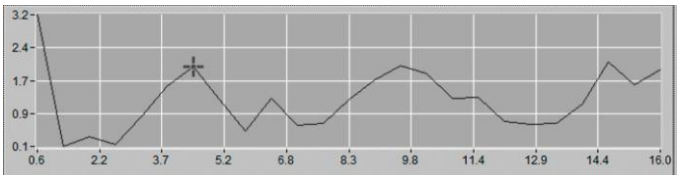
The carrier frequency of mammal sounds demonstrates whether a stress is caused by fear or it is due to an aggressive threat addressed to another animal. Therefore, the above measurement model was supplemented with the linear conversion of acoustical waves, which enables the emotion identification to be detailed. The fear signal is emitted at a high frequency that is maximal for an animal in order to transmit it to a greater number of animals of the same species. The signal of threat addressed to the animal that is nearby, is transmitted at a low frequency of sounds, because it is not necessary to pass it to other animals. An addressless threat signal, howl, is transmitted at the frequency of the medium sound range.

The spectrum in which the maximum part of energy is concentrated in the field of the θ-rhythms and the noticeable uprises are in the fields of the α and β-rhythms (in the zones of 12 - 16 Hz and 25 Hz), corresponds to the peaceful interaction of dholes (cuon alpinus) in a group. Possible decoding: vivid images, muscle activity and increased emotional excitation peculiar to playing.

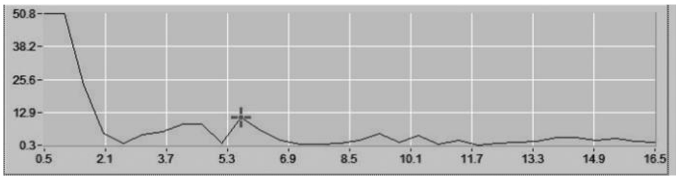
It should be noted that the model used also allows the emotional colour of the biolinguistic sound signals of living creatures to be measured independently of their mass and dimensions, range of the frequency of the sounds they emit and even of the level of living creature development and complexity of its apparatus emitting sounds.



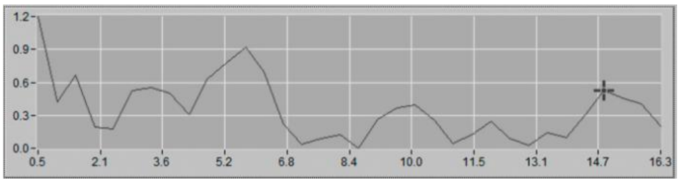

a)




b)




c)




d)

Fig.1. Spectra of the IFR intermodulation components after non-linear conversion of the input data ((axis of abscissa is the frequency, Hz; ordinate axis is the level of spectrum components determined in conventional units)
a) cheetah hiss; b) cheetah female purring; c) scream of a yellow ground squirrel, taken out of a hole; d) peaceful interaction of dholes

The possibility to read the emotions contained in sound signals of living creatures with the help of the model that has been used in the analysis of musical fragments, proves its universal nature.

This proof enables to make some remarks relating to the concepts accepted in biology which explain the peculiarities of biolinguistic sound signals. In particular, in [24] it is stated that the resemblance of hissing and growling as well as of other signals emitted by different animals, can be explained by imitation of sounds (onomatopoeia).

In [15, 25] an idea is put forward that the estimates of the emotion excitation obtained on the basis of energy parameters and shift of the acoustic energy to the high frequency field of the spectrum are the most reliable ones and, consequently, just these parameters of biolinguistic signals contribute to mutual understanding of men and animals.

As we see, both ability of species to communicate and the similarity of sound signals are determined by the same mechanism of the emotional colour of biolinguistic signals.

It should be also said that the approach to formation of the measurement model, the authors have developed, can be extended to the sphere of receiving – transmitting emotionally coloured information of a visual nature.

## 4. Conclusion

The measurement model above considered, which is intended for measuring emotions contained in acoustic signals, reflects the regularities common for living creatures. The model efficiency, proved before in the investigation of musical fragments, has been confirmed by the results obtained in the analysis of biolinguistic signals.

The model proposed opens new lines for investigations in biology, ethology, psychology, musicology and in a number of technical sciences.

The list of main problems, connected with the uncertainty of results obtained in measuring the emotions which are present in acoustic fragments should include the insufficient knowledge of:

- relationship of the neuro-process frequencies, particularly, the brain bio-rhythms frequencies, and mood;
- boundaries between different emotions;
- influence of genetic predisposition, psycho-type, upbringing and cultural traditions on formation of the emotional response in hearing acoustical signals.

A progress in solution of these problems together with improvement of the dynamic characteristics of the measurement model will contribute to increasing the efficiency of its usage.

The nearest perspectives of applying the model, to our opinion, are mostly noticeable in the fields connected with the reception and transmission of emotionally coloured acoustical signals, as well as with the purposeful influence of the emotional sphere of an animal or man.

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