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MODELING THE FREY EFFECT IN ACTIVE DIELECTRICS

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Symbols and abbreviations

LF – Low frequency

HF – High frequency

AM – Amplitude modulation

AIM – Amplitude impulse modulation

KHz – Kilohertz

MHz – Megahertz

MW – Microwave

μs – Microseconds

Cochlear microacoustics – Cochlear perception of an electrical signal

SanPin (СанПин) – Russian sanitary rules and norms

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ABSTRACT: The study relates to the field of electromagnetic compatibility. The possible effects of direct exposure of high-frequency fields in physiotherapy are presented herein. The interaction mechanisms of the modulated high-frequency signal with a low-capture dielectric are considered in order to detect the acoustic effect. The microwave auditory effect is analyzed as an observable phenomenon of the modulated high-frequency electromagnetic signal transformation into an audible sound in ferromagnetic. A laboratory bench is developed to observe and study electro-acoustic effect in a liquid medium (physiological solution, circulatory system) in order to solve the problem of radio-frequency ecology. Analysis of results and proposal to continue the global researches on the topic using the suggested laboratory bench for modeling. Brief summary of modern applications of the Frey effect and discussion of the fields where it can be applied usefully. Revise and discussion of impact of mmWaves on human health and mind, as well as on development of future communication technologies and mmWave base-stations.

KEYWORDS: The Frey effect, microwave auditory effect, microwave frequency impact, electromagnetic compatibility, physiotherapy.

1. INTRODUCTION

The human auditory response to pulses of radio frequency energy was discovered in the middle of the last century and called a “radio sound” by Frey. Microwave-induced sounds can be characterized by low intensity and can be heard only in a quiet environment. The topic has been continuously researched over past years that are summarized in this paper.

The place of microwave converting to acoustic energy is located inside, on the periphery of the cochlea, and is similar to acoustic noise at high sound frequencies. It should be noted that the converting mechanism of modulated HF signal to an acoustic LF signal has not been studied yet and is presented in the form of hypotheses. Development of laboratory tools is required for a physical study of the phenomenon of the Frey Effect, which is the subject of the study. The Frey effect, or the microwave auditory effect, is analyzed as modulated high-frequency electromagnetic signal transformation into an audible sound in active dielectric. Trial or criterion measurements which confirm existence of the effect under investigation were carried out on laboratory benches.

Due to extremely low absorption power of the converter (less than 0.1 W), the effect of nonlinear polarization conversion of the modulated HF signal into the low-frequency sound on the ferroelectric converter is obtained. This opens possibilities for exploring all of the microwave and acoustically related effects in order to use them in physiotherapy. The problem of HF electromagnetic compatibility can also be solved.

With the growth of modern technologies there are more and more implications of this phenomenon appear. One of the problems with the research progress of the Frey effect is that applications of it are indirect and usually intersect in several fields of science, requiring multidisciplinary approach.

1.1 Frey’s microwave hearing effect

For research essence, let us consider an analytical article on the auditory response to pulses of radio frequency energy by Elder and Chou (2003). The human acoustic system responds to pulses of radio frequency (microwave) energy, which is usually called a radio signal, is considered a well-studied phenomenon (Tambovtsev, Baranov & Kydyrbaeva 2016). Sounds induced by radio frequencies can be characterized as low-intensity sounds, as to get auditory response to them a quiet environment is required. This sound is similar to other common sounds, such as clicking, humming, hissing, knocking or chirping. Effective radio frequencies range from 2.4 MHz to 10,000 MHz, but a person’s ability to hear microwave sounds depends on a high-frequency hearing sense aid with 5 kHz band.

The place where microwave sound is converted to acoustic energy is located within the peripheral part of the cochlea, as soon as the cochlea is stimulated, radio sound is detected and perceived in the human body, and the resulting auditory responses are similar to acoustic perception of animals. The fundamental frequency of the induced microwave sounds does not depend on the frequency of the radio waves but depends on the size and proportions of the head. Auditory system response has been proven to depend on the energy per pulse, and not on the average energy density.

A lot of evidence about microwave effects on humans and animals, as well as bogus observation, supports the thermoelastic expansion theory as an explanation of microwave hearing sense (more details are in the next chapter). Induced microwave sounds are perceived through bone conduction by thermally generated transients, that is, audible sounds are reproduced by rapid thermal expansion as a result of calculated temperature increase of only $5 \cdot 10^{-6}$ °C in tissues due to absorption of the microwave pulse energy. Appearance of induced microwave sounds at exposure levels of many orders of greater magnitude than hearing sense threshold is considered to be biological effect without harm to health. This conclusion is confirmed by comparing of the radio-frequency pulses induced in human organism and pressure associated with dangerous acoustic energy and the energy of clinical ultrasound procedures.

1.2. Audible radio frequency sound discovery

In 1947, an informational announcement appeared describing observations made on the basis of sounds appearance effect due to working radar, while the person was standing close to the antenna. People took it with skepticism and, when they told the staff about the hearing sense, then questions arose about their mental health (Airborne Instruments Laboratory 1956). Skepticism accompanying early reports of microwave sound was based on knowledge of the human hearing sense mechanism. The ear is known to be sensitive to the wave pressure but has no sensitivity to electromagnetic waves in microwave frequencies (300 MHz ... 300 GHz). Skepticism helps explain why the first systematic study of microwave sound that Frey heard in 1961 appeared many years after first observations of this phenomenon in 1947.

Frey's study described the auditory phenomena in the form of buzzing sounds, heard by people who were in the path of the microwave energy flow from the radar. The apparent location of the sound, which was described as a short distance behind the head, was the same regardless of body orientation per the radar (Cain & Rissmann 1978: 288–293). In later reports (Chou & Galambos 1979: 321–326), the auditory phenomenon of microwave sound was described as “buzz, click, hiss or bump.” Table 1 contains descriptions of these and other sounds reported by people exposed to pulsed microwave fields. When a metal shield in the form of an aluminum screen was placed between the subject and the radar, no microwave sounds were heard (Chou & Guy 1979: 193–197). A specific area that detects sounds from the radio wave was described as a region of the temporal lobe, because the placement of a small part of the metal screen (5 x 5 cm) on this area completely stopped sound (Chou & Galambos 1979). Frey's subjects (Cain & Rissmann 1978) reported that microwave increase reduced the sound level, ear plugs being used to reduce the ambient noise level (Chou, Galambos, Guy, Lovely 1975: 361–367). “The sound was like a bee buzzing on the window, but perhaps with higher frequencies. The sound seemed to come about a meter or two above the head”, according to (Frey 1961: 1140–1142). In another report (Constant 1967), the sound,

induced by microwave, was described as appearing in the ear region, on the side opposite to the antenna.
All subjects heard a buzzing sound at a pulse repetition rate (PRR) that was greater than 100 1/s, and some subjects heard sound with PRR below 100 1/s, Cain & Rissmann (1978) reported that the subjects heard individual clicks, or in the head, or behind the head, when they were influenced by pulsed fields. Individual pulses were heard as independent and separate clicks, like twitter, with a signal step corresponding to PRR (Chou, Guy, Foster, Galambos, Justesen 1979: 1143-1144).

The induced radio frequency sound seemed to originate from (or close to) the back of the head. This report also includes a note that the transmitted digital signals, encoded manually, can be accurately interpreted by the subject. Two messages described the induced microwave sounds as multi-tonal and as “tinnitus”. Radio-frequency sounds were described by volunteers who were exposed to the head by coils used in magnetic resonance imaging (MRI), like chirps or high note clicks for short pulses (<50 μs) and creaks or grit for lower frequencies of long pulses (>100 μs).

The above studies show that the human perception of pulsed radio frequency radiation, leading to sounds that change with signal modulation, is a well-established phenomenon.

1.3 Effective radio frequency parameters

The brief radio frequency parameters used in clinical studies are shown in Table 1. Parameters include frequency, PRR, pulse duration, peak power density, average power density, and energy/pulse density. The threshold values for microwave sound have been reported in several studies, and they are also listed in the table. Microwave sound was present in the range from 2.4 to 10,000 MHz (see Table 1).

Table 1. Auditory effects in human beings exposed to pulsed RF energy.

			Exposure conditions							
Effect	Comment	Number of subjects	Frequency (MHz)	Pulse repetition rate (s^{-1})	Pulse width (μs)	Peak power density (mW/cm^2)	Average power density (mW/cm^2)	Energy density per pulse ($\mu J/cm^2$)	Noise level (dB)	Reference
RF hearing: heard repetition rate of radar as "high frequency components"		Not given	1300	600	2	(Peak power ~0.5 MW)				Airborne Instruments Laboratory [1956]
RF hearing: "distinct" clicks	Threshold values	8	3000	0.5	5	2500	0.006	12.5	45 (+plastic foam earmuffs)	Rissmann and Cain [1975]; Cain and Rissmann [1978]
					10	225–2000	0.001–0.01	2.3–20.0		
					15	300–1000	0.002–0.007	4.5–15.0		
RF hearing: buzz heard at PRR>100; individual pulses heard at PRR<100		3	3000	<100–1000	1–2	2500–50000	5	40		Constant [1967]
			6500	<100–1000	1–2	2500–50000	5			
No auditory response			3000	<100–1000	0.5	10000–100000	5			
			6500	<100–1000	0.5	10000–100000	5			
No auditory response			9500	<100–1000	0.5–2	2500–100000	5			
RF hearing: "buzzing sound"	Threshold values	8	1310	244	6	267	0.4		70–80 (+earplugs)	Frey [1961]
		7	2982	400	1	5000	2			
RF hearing: "buzz, clicking, hiss, or knocking"	Threshold values	Not given	216			670	4.0		70–90 (+ear stopples)	Frey [1962, 1963]
			425	27	125	263	1.0			
			425	27	250	271	1.9			
			425	27	500	229	3.2			
			425	27	1000	254	7.1			
No auditory response			8900	400	2.5	25000	25		70–90 (+ear stopples)	Frey [1962]
RF hearing: matched RF sound to 4.8 kHz acoustic sounds	Subjects were trained musicians	3	1200		12.5–50		<0.5			Frey and Eichert [1985]
RF hearing: "buzzing sound"		4	1245	50	10	370	0.19			Frey and Messenger [1973]
			1245	50	70	90	0.32			
RF hearing: "clicks, chirps"	Threshold values	2	2450	3	1–32	1250–40000	0.1	40[a]	45 (±earplugs)	Guy et al. [1975]
RF hearing: buzz	Threshold values (not at 10 GHz)	Not given	1310	244	6	(12 V/cm)	0.3			Ingalls [1967]
			2982	400	1	(18 V/cm)	0.18			
			10000							
RF hearing: "tinnitus"		Not given		100–20000	10–160					Khizhnyak et al. [1979, 1980]
RF hearing: chirps or clicks of high pitch at short pulses (<50 μs); for >100 μs pulses, creaky or gnashing clacks of lower pitch	Threshold values (head exposure to MRI coils)	6	2.4–170	1.2	3–5000	<9000		<9	(+plastic foam ear muffs)	Röschmann [1991]
RF hearing: polytonal sound		18	800	1000–1200	10–30	>500			40 (+ear stopples)	Tyazhelov et al. [1979]

[a]Calculated peak absorbed energy density per pulse is 16 mJ/kg.

Although Frey mentioned 10,000 MHz as the effective frequency, other researchers mentioned in Table 1 find that lower frequencies (8,900 and 9,500 MHz) at very high levels of exposure did not cause microwave sounds. For example, the 8,900 MHz frequency was not effective at an average energy density of 25 mW/cm^2 and a peak energy density of 25,000 mW/cm^2 (Frey 1962: 689–692). At 216 MHz, the average energy density threshold was determined as 4 mW/cm^2, and the peak energy density was determined as 670 mW/cm^2.

At the lowest effective frequencies (2.4–170 MHz) described in the literature, the peak energy density thresholds were up to 9,000 mW/cm^2. The lowest threshold value is expressed in units of the average power density of the incident radiation and is 0.001 mW/cm^2 (Cain & Rissmann 1978); this value was associated with low PRR, just 0.5/s (Table 1), since at given peak power, the average power density depends on the PRR. However, auditory system response has been said to depend on the energy per pulse, and not on the average energy density. Scientists found (Guy et al. 1975) that the microwave sound threshold of pulsed fields at 2,450 MHz was associated with an energy density of 40 J/cm^2 per pulse, or with pulse energy absorption of 16 J/g, regardless of the peak pulse power or pulse duration (less than 32 μs). Calculations showed that each pulse at this energy density would lead to increase in tissue temperature of about 5 × 10ˆ-6°C.

Comparison of the microwave auditory thresholds in the theoretical literature with the thresholds observed in humans exposed to fields from MRI coils showed compliance in wide frequency range (2.4–3,000 MHz). Another comparison in this report showed that the cat's electro physiological measurements determined the thresholds which are quite similar to the results of the microwave sound tests in humans. Review of Table 1 shows that many of the threshold values were determined in a very quiet place, or by people who used ear plugs (headphones) to reduce external noise level. As mentioned in the introduction, earplugs were used by subjects in Frey's first report in 1961. Thus, researchers tend to recognize that a quiet place was necessary, since in many cases normal noise levels outside the MRI lab and the environment mask microwave sound. In the study of Guy et al. (1975), for example, the threshold value given above was obtained in a very quiet environment with a background noise level of only 45 dB. When earplugs were used, the threshold level for each subject dropped from 35 to 28 J/cm^2. The threshold for a hearing sense of impaired subject was much higher, is about 135 J/cm^2 (without an ear tip).

1.4 Dependence of microwave acoustic sense on acoustic hearing sense capabilities

Airborne Instruments Laboratory (1956) stated that two people with hearing sense loss above 5 kHz do not perceive microwave sound so well as observers with normal hearing sense up to 15 kHz. More recent studies have provided more information on relationship between the acoustic hearing sense and the microwave one. Frey (1961) reported that prerequisite for listening of microwave sound is the ability to hear radio frequencies above 5 kHz, and not only in terms of air conduction. This conclusion was based on the results of subjects with normal hearing sense, and hearing sense with defects. One person with normal air conduction, who hears below 5 kHz, could not hear the microwave impulses; this man, as was subsequently established, had a significant loss of bone conduction of hearing sense. Another subject with hearing sense impairment, with good bone conduction, but with weak air conduction, perceived microwave sound of about the same density as people with normal hearing sense. In later study, subjects identified sounds due to repeated exposure of microwave pulses pair in the range from MHz to sound frequencies near 4.8 kHz (see Table 1).

In addition to defining standard hearing sense audiograms that measure air conduction thresholds at acoustic frequencies of 250–8,000 Hz and bone conduction up to 4,000 Hz, Cain and Rissmann (1978) measured hearing sense of eight subjects to 20 kHz. They found that, although there was no obvious correlation between ability to hear pulsed microwave fields at frequency of 3,000 MHz and hearing, as measured by standard audiograms, there is strong correlation between the hearing threshold of the microwave sound above 8 kHz. For example, three subjects who had normal hearing below 4 kHz, but the hearing deficit at frequencies above 8 kHz could not hear the microwave sounds. Studies by Frey (1961) and Cain & Rissmann (1978) show that microwave perception depends on high-frequency hearing sense, in the range of about 5–8 kHz, and bone conduction at lower sound frequencies. The calculated values of the fundamental frequencies of induced microwave sound in the human head, based on data obtained from animals or models, are somewhat similar, for example, 7–10 kHz (Chou et al., 1977: 221–227), 8 and 13 kHz and 7–9 kHz (Lin 1975: 36–47). The results of these studies are described in more detail below.

1.5 Similarity of auditory response to microwave energy and usual acoustical perception

The auditory pathway through which sound waves detected by the ear are interpreted into sound in the brain is well known. Several studies have been conducted to determine whether the electro physiological response of the auditory tract to microwave pulses is similar to the response to acoustic stimulation. The first stage of sound transduction is a mechanical distortion of the cochlear hair cells resulting in a cochlear micro acoustics, the electrical potentials of which simulate the sound waveforms of acoustic sounds. After cochlear sound detection, the electrical potentials associated with sound detection can be detected by electrodes located in neurons at various locations along the auditory pathway. Frey (1962: 689–692) suspected that microwave sound may be the result of direct cortical or nervous excitement. He wrote: “It is reasonable to suspect that possibly the electromagnetic field could interact with neuron fields.” – but the results of later studies described in this review showed that Frey’s hypothesis was incorrect. His suggestion was based, in part, on his inability to demonstrate that microwave pulses stimulate the cochlea, that is, the **cochlear micro acoustics** *(*cochlear microphone effect — the cochlear perception of electrical signal*) was not investigated at greater energies than required to trigger auditory nerve response. Chou et al. (1975) also mistakenly measured cochlear micro acoustics but found that the lack of sound was due to insufficient absorption of radio frequency energy. Chou et al. (1975) reported about success in overcoming technical problems that prevented researchers to record the cochlear micro acoustics of microwave sound in animals. The results showed that microwave energy pulses activate the cochlea, micro-acoustics was recorded, as well as one, that is similar, caused by acoustic stimulations (Chou et al. 1976: 89–103). An animal demonstration showed that microwave sound caused an auditory response and is perceived by the normal hearing system through the cochlea. This evidence counteracts the suggestion that microwave impulses directly stimulate the nervous system. Taylor and Ashleman (1974) and Chou et al. (1975) showed the cochlea importance, and that the cochlea damage cancels the induced potentials of the microwave sound at higher levels in the auditory pathway. These results indicate that the location of initial interaction of the pulse-modulated ultra-high frequencies energy with the auditory system is within, or at the periphery, of the cochlea.

In cats with an intact cochlea, Taylor and Ashleman (1974) measured electro physiological responses in three consecutive levels of the feline auditory nervous system (vestibular and cochlear nerve, medial geniculate nucleus and primary auditory cortex) to acoustic and microwave (2,450 MHz) frequencies. They found that the reactions are similar. Lebovitz and Seaman (1987) also found similar reactions of cat single auditory neurons to 915 MHz pulsed fields and acoustic clicks. Guy et al. (1975) showed that electro physiological responses of cat auditory pathway to radio frequency impulses are similar to responses to acoustic exciters and, studying the reactions after damage in successive parts of the auditory pathway, confirmed that the main location of microwave energy transduction to sound occurred in the cochlea peripheral part. Detection of electrical potentials in the auditory neurons in response to microwave exposure was expected, based on the study's results that demonstrated subjective auditory perception (Frey 1962: 689–692) and cochlear micro acoustics (Chou et al., 1975). Seaman described a model of hearing neuron thresholds for microwave pulses that are consistent with thresholds measured for a cat (pulses of 20–200 μs). Acoustic exciters are known to be able to cause induced potentials in the central regions of the nervous system outside the auditory pathway, and due to such induced potentials, Guy et al. recorded the auditory response to radio frequency impulses (1975). These authors explained that electrical potentials recorded anywhere in the central nervous system

(CNS) can be misinterpreted as a direct interaction of microwave energy with a separate nervous system in which this recording was made, as Frey reported.

In the experiment, the thresholds of caused electrical reactions of the medial cranked body in cat's auditory pathway were determined as a function of the background noise. Guy et al. (1975) found that the noise level (50–15,000 Hz bandwidth), to be increased from 60 to 80 dB, caused only a slight increase of threshold for microwave exciters and a significant increase in the threshold for a loudspeaker producing acoustic waves. The fact that the induced response to microwave exciters did not increase relative to background noise, which included acoustic frequencies of 15,000 Hz, showed that pulsed microwave energy can interact with the high-frequency part of the auditory system (above 15 kHz in cats). Additional support for assumption about dependence of microwave sound on high-frequency acoustic hearing is provided by theoretical analysis of acoustic vibrations caused in the heads of people and animals, based on thermal expansion from microwave energy pulses. Induced sound frequency was found to depend on head size and the acoustic properties of the brain tissue. Thus, the acoustic tones perceived by this subject are independent of microwave energy frequency. These calculations show that the fundamental frequency predicted by the model varies inversely with the head radius, i.e. the larger the radius, the lower the frequency of perceived microwave sound.

Scientists estimate that the approximate fundamental vibration frequencies for guinea pigs, cats, and adults were 45, 38, and 13 kHz, respectively; frequency for children's human head is estimated at about 18 kHz. These calculations provide new evidence that a necessary condition for induced microwave sounds is the ability to hear sound waves at frequencies above 5 kHz (Frey 1961). The calculated fundamental frequency (45 kHz) in guinea pigs (Lin 1975: 36–47) correlates with measurements of Chou et al. (1975), who determined 50 kHz cochlear micro acoustics for guinea pigs subjected to radio frequency pulses. In a later report, Chou et al. (1977: 221–227) found that the frequency of cochlear micro acoustics for guinea pigs and cats correlates well with size of the long brain cavity (brain cavity), and based on these data, the frequency of microwave induced cochlear micro acoustics for people can be between 7 and 10 kHz.

As mentioned above, Lin calculated the frequencies of 8 and 13 kHz. In contrast to these results, one laboratory reported about reactions in the normal range of cat's hearing that were incompatible with head resonance, having a pivotal role in microwave hearing (Seaman & Lebovitz 1987). Ghandi and Riazi (1986), calculated microwave hearing thresholds at 30–300 GHz, but if any, the physiological significance of these calculations for microwave sound is explained: (a) their calculated fundamental frequencies in the head are several hundred kilohertz, that is well above the maximum sound frequency of about 20 kHz for human hearing, and (b) there are no reports of human perception of radio frequency pulses at frequencies above 10 GHz (see Table 1).

The results of the above studies of evoked electrical potentials in the auditory system, including demonstration of pulsed microwave causing a cochlear micro acoustic response, strongly indicate that detection of induced microwave auditory sense is similar to acoustic detection. The conversion from microwave to acoustic energy is located at the periphery of the cochlea, the fundamental frequency of the induced microwave sound does not depend on the frequency of the incident microwave energy, but depends on the head size, and the pulsed microwave energy interacts with the high-frequency part of the auditory system. In order to hear induced radio frequency sounds, a person must be exposed to microwave energy pulses in the MHz range (see Table 1) and be able to hear acoustic waves in the 5 kHz range.

1.6 Microwave audio mechanism: thermoelastic expansion

One of the first calls for Frey theory about direct nervous excitement (Frey 1961: 1140–1142; Frey 1962: 689–692) was Sommer and von Gierke, in 1964, who suggested that cochlear stimulation through electromechanical fields of air or bone conduction turned out to be a more likely explanation of the microwave perception. Other scientists who helped to lay basis for mechanism determining were White and Gournay (in 1963 and 1966). White showed that acoustic waves could be detected in water subjected to radio frequency radiation pulses, and his analysis of waves in this system showed that, as a result of thermal expansion, the temperature gradient will generate voltage waves propagating far from the place of energy absorption. Gournay, in a detailed analysis of this phenomenon, showed that for single long pulses, the induced voltage wave is a function of the peak power (energy) density and, for shorter pulses, the voltage wave is a function of the peak power density and pulse duration (or power density in impulse). Later, Foster and Finch expanded the analysis of Gournay by conducting experiments in water and KCl solution, which were subjected to radio frequency impulses, similar to those that cause sounds in humans. They showed, both theoretically and experimentally, that changes in pressure, which can create significant acoustic oscillations in solution, will depend on absorption of radio frequency pulses. They concluded that audible sounds were produced by rapid thermal expansion due to microwave energy absorption. These results resulted to their suggestion that thermoelastic expansion is the mechanism of microwave perception. This mechanism is consistent with the following results from their experiment:

1) The microwave pulses that cause sounds in humans generated acoustic transients, which were recorded by hydrophones placed in solution (0.15 N KCl) having electrical conductivity that is similar to tissue. Acoustic transients have been detected in the blood, muscles, and brain that have been subjected to microwave pulses in test tubes.

2) The microwave wave induced pressure created in distilled water when the water was cooled below 4°C and the reaction disappeared at 4°C, in accordance with the temperature dependence of the thermal expansion properties of the water.

3) From the thermoelastic expansion theory it follows that maximum pressure in a medium is proportional to the total pulse energy for short pulses and proportional to the peak power (energy) for long pulses. The relationship between the pulse width and the microwave-generated acoustic transient in KCl solution is consistent with this theory.

Based on these findings, Foster and Finch (1974) concluded that microwave induced sounds are perceived through bone conduction of thermally generated sonic transients caused by absorption of microwave energy. The pulse can be quite short (<50 μs), therefore the maximum increase of tissues temperature after each pulse is very small (<10^-5°C). Peak pulse power intensity, however, should be moderately intense (typically, from 500 to 5,000 mW/cm^2 on the head surface). These values fall within the effective peak intensity range of 90–50,000 mW/cm^2 in the clinical studies shown in Table 1. Mathematical modeling showed that the amplitude of a thermoelastic generated acoustic signal of this magnitude completely masks other possible mechanisms, such as radiation pressure, electrostriction forces, and field induced by microwave forces. These and other results led Guy et al., Lin and the others to conclusion that the thermoelastic expansion mechanism is the most likely physical mechanism explaining the microwave induced auditory effect in humans. A year before thermoelastic theory was proposed, Foster and Finch (1974) published the results of human research, which converge with this theory. That is, loudness of microwave induced sounds in human subjects depends on the power density per peak pulse width >30 μs; for shorter pulses, loudness is a function of the total pulse energy. In the relevant study, the experiment results on animals showed a predicted threshold dependence on the pulse width. Chou and Guy found that the threshold for microwave hearing for guinea pigs caused electrical reactions in the auditory brainstem and depended on energy incident per pulse with pulse widths <30 μs associated with peak pulse power up to 500 μs. When using short pulses of width 1–10 μs, Chou, Yee and Guy (1985: 323–326) noted that the hearing threshold for rats does not depend on the pulse width. This paper is also important because these results have shown that microwave induced hearing responses occur in rats at low stresses in a circularly polarized waveguide. The threshold and volume results can be summarized as follows: energy in the first pulses determines the threshold volume levels, regardless of the pulse width. For wider pulses (>90 μs), the loudness is related to peak power, but not with energy, since energy associated with the first 30 μs pulses increases directly with peak power. Thus, if sufficient energy is deposited within 30 μs of periods, the microwave induced sounds will cease, regardless of the pulse width. And, for pulses more than 30 μs, volume increases with peak power increasing. Thus, the auditory perception undergoes a gradual transition from the energy-related effect in pulse widths <30 μs to an effect depending on the peak power per pulse duration >90 μs (Chou & Guy 1979: 193–197). A psychophysical experiment by Tyazhely (in 1979) with 18 experimental subjects showed adequacy of the thermoelastic hypothesis and quality of microwave induced sounds perception. The sound frequencies of the signals were presented alternately or simultaneously with the microwave pulses (see Table 1) under conditions in which the subject can adjust the amplitude, frequency and phase of the audio signal. Long pulses (~100 μs) led to strength decrease of microwave sound, and two test subjects who had the high-frequency hearing limit of 10 kHz could not hear short microwave pulses but heard long pulses. Tyazhely concluded that the thermoelastic expansion hypothesis adequately explains some of these findings for microwave of high peak power and short width pulses (<50 μs), but they questioned the hypothesis applicability to some observations involving near-threshold low power pulses, long duration and high pulse repetition rate See work Chou et al. (1982: 1321–1334) that criticized it. In other works, Tyazhely assumes that the thermoelastic theory constitutes low frequency, but not high frequency of microwave induced sounds. However, no other reports support their model for high-frequency pulses. A more recent report (Roschmann 1991: 197–215) on reactions of the auditory system of six people whose heads were subjected to radio frequency energy from MRI coils, reports that the dependence of the thresholds with pulse width confirms the theoretical predictions about the thermoelastic expansion theory.

In theoretical analysis Lin (1975) predicted that sound pressure, as a function of pulse duration, initially increases up to peak, then decreases and oscillates with maximum values below the peak. Human data in and animal data in Chou et al. and Lin, in general, correspond to this model of the auditory response associated with the pulse width. More detailed discussion of dependence of the pulse width and perceived sound volume, based on human data in publications of Tyazhely is given in reviews by Lin. The results of animal studies, in addition to discussed ones, support and expand our understanding of microwave perception and the thermoelastic mechanism. Some researchers have determined the threshold of the microwave induced auditory responses of the system with laboratory animals, as shown in Table 2. For cats exposed to radio frequency pulses (918 and 2,450 MHz), the threshold was associated with the energy density of the incident pulse. The energy density threshold in cat's pulse is about half of the human threshold Guy et al. (1975). The thresholds of Cain and Rissmann generally agree with the results in Guy et al., as Seaman and Lebovitz (1987) report regarding lower perception thresholds. At higher frequencies, between 8,670 and 9,160 MHz, Guy et al. 1975) found that the threshold values of the power and energy density per pulse were an order of magnitude higher than at 918 and 2,450 MHz (Table 2). By measuring acoustic pressure waves with a miniature hydrophone converter implanted in the brain of rats, cats, guinea pigs and susceptible microwave energy pulses, Lin confirmed earlier theoretical predictions of pressure waves in the head. In a later work, Lin, Su and Wang (1988: 141–147) observed that pressure waves speed of microwave induced sounds in a cat's brain was similar to usual propagation of an acoustic wave. These results confirm the thermoelastic expansion theory.

Hypothesis of Foster and Finch (1974) predicts that the effect of microwave sound is associated with thermoelastic induced mechanical vibrations in the head. Oscillations of this type can be obtained using other means, for example, using a laser pulse, or a pulsed piezoelectric crystal that comes into contact with the skull, which also causes cochlear micro acoustics in guinea pigs (Chou et al. 1976).

Frey and Coren used the holographic method to check whether the animal skull and head tissues have predicted vibrations when subjected to pulsed radio frequency field. No offsets were recorded, but subsequent analysis by Chou et al. (1980: 89–103) showed that the holographic method used by Frey and Coren did not have required sensitivity to detect small displacements associated with fluctuations from microwave induced thermoelastic expansion in biological tissues. Joines & Wilson (1981) described the Auto radiographic (auto-transferable) technique, in which [14C] 2-deoxy-D-glucose is used to display the auditory activity in the brain of rats that were exposed to acoustic exciters of pulsed and continuous wave field. Using this method, in vivo determination of metabolic activity, i.e. glucose utilization and related functional activity in the brain can be visualized.

Table 2. Threshold for auditory system responses in animals to pulsed RF energy.

Effect	Species (n)	Exposure conditions: Frequency (MHz)	Repetition rate (s^{-1})	Pulse width (μs)	Peak power density (mW/cm^2)	Average power density (mW/cm^2)	Energy density per pulse ($\mu J/cm^2$)	Peak absorbed energy density per pulse (μJ/g)	Reference
Response obtained with scalp electrodes	Cat (2) [also dog and chinchilla]	3000	0.5	5	2200, 2800		11, 14		Rissmann and Cain [1975]; Cain and Rissmann [1978]
				10	1300		13		
				15	580		8.7		
Response obtained with carbon-loaded Teflon® electrodes	Guinea pig (n not given)	918	30	10–500	62–156	0.02–1.4	1.56–46.8	6–180	Chou and Guy [1979]
Response obtained from round window with carbon lead	Guinea pig (5)	918	100	1–10	[a]	[a]		20	Chou et al. [1975]
Brainstem evoked response	Rat (10)	2450	10	1–10	150–3000		1.5–3	0.9–1.8	Chou et al. [1985]
Electrode implanted in brain stem	Cat (11)	1200–1525	12–130	10	60	0.03			Frey [1967]
Response obtained from medial geniculate with glass electrode	Cat (2)	918	1	3–32	800–5800	0.017–0.028	17.4–28.3	12.3–20.0	Guy et al. [1975]
		2450	1	0.5–32	600–356000	0.015–0.047	15.2–47.0	8.7–26.7	
		8670–9160	1	32	14800–38800	0.472–1.24	472–1240		
Response obtained from individual auditory neurons with glass electrode	Cat (7)	915	<10	25–250		≤1.0		4–40	Lebovitz and Seaman [1977a,b]
Neuronal action potentials in cochlea	Cat (18)	915		20–700				0.6	Seaman and Lebovitz [1989]

[a] Direct comparison of power density in the circular waveguide exposure system to free field power density is improper because the efficiency of energy coupling is ten times higher than that for free field exposure [see Chou et al., 1975, p. 362].

Before exposure of acoustic exciters or microwaves, one middle ear was removed to block detection of sound waves in one side of the head. The expected bilateral asymmetry of radioactive absorption in the auditory system of rats exposed to acoustic clicks or low background noise was demonstrated. In contrast, symmetrical absorption was found in the brain of animals subjected to radio frequency pulses. These results confirm the auto radiographic findings that microwave hearing does not involve the middle ear of a person (Frey, 1961: 1140–1142) and guinea pigs (Chou & Galambos, 1979: 321–326). Unexpectedly Joines & Wilson (1981) found an increasing uptake of a radioactive tracer in the auditory system of rats exposed to continuous wave fields, but in a later report this microwave effect is attributed to intra cochlear heating (Joines & Wilson, 1981). Continuous field wave results were not independently reproduced and there are no known reports of continuous wave signals causing microwave induced sound in humans, or RF induced auditory responses in experimental animals.

In general, research data from human subjects, laboratory animals, and modeling supports the thermoelastic expansion theory, as a mechanism for the phenomenon of microwave hearing. Evidence includes measurements of acoustic transients in water, KCl solution having electrical properties which are similar to that found in cells, tissues, (Foster & Finch 1974) and also in materials simulated muscle (Olsen & Hammer 1980: 45–54); relations with a threshold value for the pulse duration (Foster & Finch 1974; Chou & Guy 1979]; microwave characteristics that caused cochlear micro acoustics in laboratory animals (Chou et al. 1975; Chou et al. 1977) and the calculated fundamental frequency in the human head (Chou et al. 1977), correlates well with perception of high frequency sounds in the kHz range above 5 kHz.

1.7 Importance of radio frequency hearing perception

The potential of pulsed fields exposure to human that could induce microwave hearing phenomena raises two questions about the effect significance. One of them — is microwave sound a psychological influence? Secondly, aside from sounds perception: is the physiological value of the impact of pulsed radio frequency radiation by intensity of level above than the hearing threshold?

Hearing effects of microwave sound at threshold exposure levels are considered a biological non-damaging effect and, therefore, are not a side effect. This conclusion is based on the following points. The sounds associated with the microwave auditory phenomenon are not unusual, but are similar to other common sounds, such as clicking, humming, hissing, knocking, or tweeting (see Table 1). In addition, microwave induced sounds can be characterized as low-intensity sounds, because, in general, it should be quiet enough for the subject to hear these sounds. It should be noted that most of the subjects in the studies listed in Table 1, use earplugs to create conditions that are quiet enough to hear radio frequency sounds. The apparent arrangement of sounds, however, may vary within the following limits: interiorly or above the head. In some cases, with long-term exposure of microwave to induce sound, sounds can become annoying, however, at present, knowledge of effective operating conditions (see Table 1) is enough to develop measures to eliminate the negative effect of microwave sound. One of the solutions is to move farther away from the radio frequency antenna. Clinical studies review in Table 1 shows that most of the studies were done under laboratory conditions, in which the subjects were close to the microwave antenna. In three of the four field studies, the distance of the subjects from the radar was in the range of six feet to several hundred feet. This distance was necessary to achieve an effective, moderately high peak power intensity, ranging from 90 to 50,000 mW/cm^2 (see Table 1). If it is not possible to increase the distance from the source, the recovery measures may include a metal screen and changes in the operation process of the microwave device.

In addition to perception of sound, it is important to consider physiological significance of susceptibility to radio frequency impulses above the threshold of hearing. One approach is to compare pressure of the microwave induced acoustic wave in the head with pressure from other sources. The power levels, peak and duration of the high-frequency impulses used for MRI of a human head can meet the requirements for microwave sounds (Roschmann 1991: 197–215). Microwave transmitter power levels of up to 15 kW, if applied to a head with exposure of MRI coil, would cause a microwave induced sound pressure of about 100 times higher than the microwave hearing threshold. According to Roschmann (1991), the discomfort level of caused by microwave transients in the head is avoided if the peak power of the microwave pulses (>100 μs) for the coil head is limited to 30 kW (6 kW for the surface coils); this limit is based on the discomfort threshold [dB Sound Pressure Level 110 (SPL)] for external sound exciters. Dangerous thresholds of external sound exciters for pain (140 dB SPL), and for damage to the auditory system (150–160 dB SPL) will be several orders of magnitude greater than 110 dB. Roschmann (1991) stated that there was no evidence of the known harmful health effects of microwave induced noise generated by MRI at peak power levels of up to 15 kW, but this is the power level that was available during his article creation.

Based on the calculated pressures, as a result of the absorbed pulse energy of 915 MHz in models of the human head, it was found (Watanabe, Tanaka, Taki & Watanabe 2000: 2126–2132) that the microwave-induced pressure at the hearing threshold was only 0.18 Pa or more than 42,000 times less than the pressure induced by ultrasonic, 7,700 Pa in a lower value (2 mW/cm^2) in the range of ultrasound diagnostic effects. The limit for fetal imaging is 720 mW/cm^2 allows medicine to visualize the human fetus, this pressure is more than 15 x 106 times greater than the microwave hearing threshold. Another comparison with completely different physical strength shows that pressure at the threshold of microwave hearing event is approximately 1,000,000 times less than the pressure on the brain surface, which produce changes in electroencephalogram and have less pressure on the brain tissue (1.5 x 105 and 3 x 105 Pa, respectively), based on studies of traumatic brain damage. Compared with pressure exerted by acoustic energy with dangerous threshold of medical exposure by ultrasound and traumatic injury, the microwave-hearing effect is unlikely to be dangerous at the threshold level (Guy et al. 1975; Gandhi & Riazi 1986).

In addition, this comparison shows that the microwave induced pressure would have to be many orders of magnitude greater than the pressure at the hearing threshold to cause side effects. This conclusion is supported by the following facts. Very high intensity microwave pulses will cause side effects, such as convulsions and unconsciousness (stun effect), as evidenced by Chou et al. (1982: 1321–1334). These authors determined the threshold for these effects for rats to single high intensity, 915 MHz pulse, which caused increase in brain temperature of 8°C, leading to small and large epileptic seizures lasting for 1 min after exposure, and then to 4–5 minutes of unconsciousness. Brain temperature returned to normal within 5 min after exposure, and animals began to move when the brain temperature was returned to within 1°C of normal. As a result of a limited histological study of four rats, significant changes were detected, including neurons demyelination in one day after exposure, and cerebral edema after 1 month. The damaging effect threshold was 680 J, regardless of the peak pulse power and width, or about 28 kJ/kg, expressed in terms of peak specific absorption. The damaging effect threshold for humans is 100,000 times higher than for rats (5–180 mJ/kg versus 16 MJ/kg) (Guy et al., 1975).

Although the field did not pulsate and the microwave induced sounds did not occur, the recent reports from 2000-s refer to potentially functional changes in the auditory system of irradiated animals, that is, changes in otoacoustic emission from the cochlea can serve as an indicator of the external subclinical hair cell or clinical pathology. No effect of otoacoustic emission of microwave-exposed rats was found in this report, with an average SAR of 0.2 (950 MHz) and 1 W/kg (936 and 950 MHz) in the head.

2 ELECTRO-ACOUSTIC EFFECT THEORETICAL STUDY

2.1 Modulated microwave signal effect for substance

We are close to the issue of acoustic perception of radio frequency sound. But regarding physics, the mechanism of its appearance is not completely clear (Tambovtsev et al. 2016). And since the mechanism is unclear, then the possibilities that the study of this phenomenon can open are unknown. But, based on the fact that acoustic wave generation occurs due to deformation of the cochlea tissues, as well as through bone conduction, it is possible to check the microwave induced sound using a piezoelectric sensor. It can be used as a simplified model of acoustic sound perception (after all, if there is sound pressure, the sensor will produce an electrical signal). A source of microwave-induced sound can be a substance (placebo), as a simplified model of tissue in the human head. The question in this paper lies in the field of electromagnetic compatibility in the field of ecology and physiology. A person, having created sources of electromagnetic radiation, is not able to do without them. However, the "electromagnetic smog" in the entire frequency range significantly exceeds the natural background, which may provoke irreversible consequences.

2.2 Microwave effect of high frequency signal converting to low-frequency one

At present, there is still no unambiguous physical justification for the microwave hearing phenomenon. In undergraduate work, the microwave sound effect is analyzed as an observable phenomenon of converting a high-frequency modulated radio signal into low-frequency acoustic oscillations.

In 1956, it was noticed that people who happened to be in the radar range felt sound hallucinations, even if the ears were protected by noise suppressing filters (Airborne Instruments Laboratory 1956). Subjects were alternately positioned behind a screen with a quarter-wave diameter hole at a distance of 1.5–2.0 m from the antenna horn. The 500 kW transmitter operated at the frequency of 1.3 GHz, a pulse duration was 2 μs and a repetition rate was 600 Hz (power is given for a radio pulse). The survey showed that the sounds are felt at the harmonics, and the main frequency is missing. The results of systematic observations and first studies were published in 1961 by Alan Frey, and the microwave auditory phenomenon was called Frey's microwave hearing effect.

Research conducted on volunteers has led to natural difficulties in determining quantitative and objective assessments. It turned out that when a person was exposed to microwave radiation with amplitude-pulse manipulation of relatively high intensity (6 meters from the radar antenna with frequencies of 1.31 and 2.982 GHz), perceived sounds appeared directly inside the skull, which were felt as if from a sound source located behind back of the head. The threshold of sensitivity was determined as 80 mW/cm^2, which corresponds to (with a geometric cross section of the head about 250 cm^2) absorbed power up to 20 W. This is a large absorbed radiation power for the head, even for a short-time radio pulse.

2.3 Microwave impact of cell phone

Microwave impact on the head with mobile phone pressed to the ear. For comparison, one can evaluate the microwave impact of mobile phone pressed to the ear with a spherical diagram of radiation directivity and radiation power of 0.5 W (see. Fig. 1). So, the absorption direction is a hemisphere, the absorbed power is up to 50% of the radiation power, effective absorption occurs inside the head. Therefore, we obtain the estimated value of the power density: 0.5 (0.5 W / 250 cm^2) = 1 mW/cm^2.

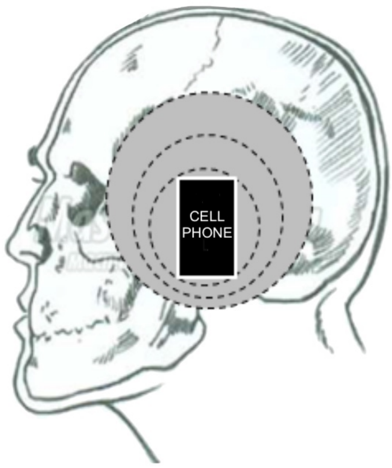


Figure 1. A cellphone attached to head with a geometric cross section of 250 cm^2.

The radio sound effect is naturally absent here, since sensitivity threshold (see above) is 80 mW/cm^2. This is by orders of magnitude greater than the sanitary and hygienic norms for the beginning of the gigahertz range, presented in Table 3 (Airborne Instruments Laboratory 1956). In general, the biological system acting as an acceptor responds more actively not to stationary values, but to their changes and rates of change. Pulse manipulation acts more efficiently than single-frequency amplitude modulation (SanPin [СанПин] 1996).

Table 3. Maximum permissible values of the radiant exposure per 8-hour work shift.

Frequency range, GHz	Exposure rate level of energy flux density, mW/cm^2	Note
0.3–300 GHz	25 μW/cm^2 x 8 hours	The rate of microwave EMR is estimated by the values of the energy flux density — EFD: W/m^2, μW/cm^2.

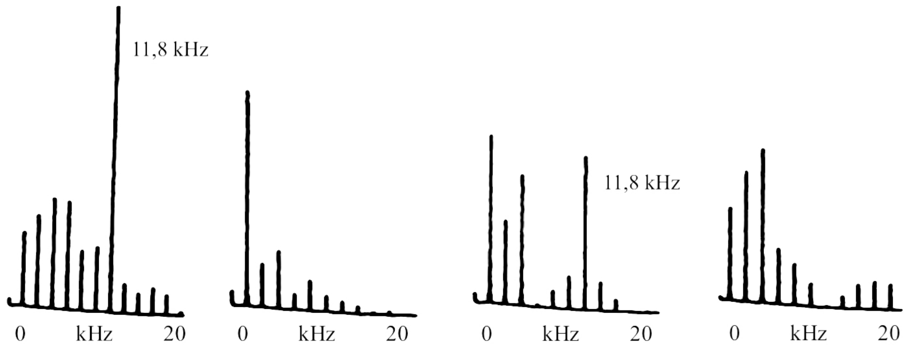
Alan Frey suggested the hypothesis that in parts of the inner ear radiation interacted with thermoelastic tissues, possibly accompanied by their periodic deformation. During this process, at the amplitude-pulse manipulation, mechanical shock waves appear, perceived by a person as an internal sound, which isn't connected with the eardrum oscillation. This sensory-acoustic effect is a physical phenomenon associated with electromagnetic energy conversion in low-frequency mechanical vibrations on the way to the receptor apparatus through bone conduction. It was also found that with appropriate choice of amplitude-modulated signal, it is possible to transmit information to a person in the form of separate words, phrases and other sounds. Volume of the perceived sound can be increased, but acoustic trauma cannot be inflicted, because the eardrum does not participate in the process (Elder & Chou 2003). Forming spectrum, perceived by a person in the form of an auditory sense, is determined by the interaction of anatomical structures representing, as it were, a system of acoustic resonators with a dynamic coupling, above the critical one (Tigranyan & Shorokhov 1990).

2.4 Physical Transduction Mechanism

In early studies and later publications devoted to radio sound effect (see, for example, (Tigranyan & Shorokhov 1990), there is, as a rule, a focus on the physiological interpretation of this phenomenon, which is associated with auditory system features or the direct impact of a modulated ultra-high frequencies electromagnetic field on brain structures. Direct physical measurements with the electronic sensor elements were impossible. Experiments on animals with implanted electrodes did not give comparable results due to lack of an adequate response of the test animals to radio (MW) sound. In addition, the probe electrodes themselves were under electromagnetic radiation influence, which was accompanied, most likely, by detection and galvanic effect.

We are interested in the direct mechanism for modulated high-frequency signal converting in a low-frequency sound, without reference to the physiological characteristics of the person. The authors are interested in the objective study of the electro acoustical conversion, as opposed to the microwave hearing effect that is subjectively observed on volunteers. Moreover, in the microwave hearing effect, it is most likely that acoustic oscillations excitation occurs in perpendicular direction to the electromagnetic wave propagation, and in an electro-acoustic effect, sound must propagate in the direction of the electric field. Therefore, we can assume that the proposed studies are original in the production part. Researches should also ensure objectivity and reliability of the obtained results. Consideration of the amplitude-modulated signal is explained by the fact that it is possible to conduct sound detection using rather simple means, for example, using a piezoelectric sensor or a dynamic microphone. A simple signal is obtained with amplitude modulation, it is convenient for frequency analysis and further full-scale spectral research. Studies with amplitude-pulse modulation and with amplitude manipulation are also not excluded.

Imagine a study of the possible effects of direct exposure of high-frequency fields in medical practice or physiotherapy (Tigranyan & Shorokhov 1990; Elder & Chou 2003). The interaction mechanisms of the modulated high-frequency signal with a low-capture substance to detect the electro-acoustic effect are considered and analyzed. Low conductivity is necessary in order to the electrodynamic interaction takes place not at the interface, but in a considerable volume, which is determined by the size of the skin layer. It is possible that the periodic deformation is accompanied either by expansion during substance heating or compression, if dielectric polarization occurs. To understand the transformation mechanism of a modulated high-frequency signal into sound, it is necessary to imagine its spectral changes, accompanied by acoustic effects. In further research work, a laboratory layout is developed that will allow to perform criterion experiments, and to discuss their results.



a) b) c) d)

Figure 2. Acoustic spectrum for a sphere filled with ethanol. RF pulse spacing frequency is 1.7 kHz, their duration is: a — 40 μs, b— 80 μs, c — 120 μs, g — 160 μs. The seventh harmonic is highlighted (figure borrowed from Cain & Rissman 1978).

2.5 Combination spectral conditioning

Many substances in states when the conducting properties of the medium correspond to dielectric ones can be classified as low absorbing media. This is analytically determined by the ratio between the values of the real and imaginary components of the complex dielectric constant. The same can be said about complex conductivity. For most substances, this state is reached only in a certain frequency domain, due to dependence of the dielectric constant and conductivity on the electromagnetic wave frequency. Note that low conducting media, including soil, water and saline solution (Chou et al. 1976), have non-linear current-voltage characteristics (Darovskih, Tambovtsev & Shishkova 2014), which allows us to assume that the spectrum part of the output signal is in the low frequency range. This provides the so-called signal cross detection (Chou et al. 1977).

Media interface also has a significant nonlinearity, which is not discussed here. In the criterion experiment proposed below, amplitude modulated signal (AM) and amplitude-pulse manipulation are used. Using of the AM signal assumes ease of analysis and the uniqueness of the result.

AM signal can be represented as:

$$E_c(t) = A\cos(\omega_c t) + \frac{1}{2}Am\cos(\omega_c - \omega_s)t + \frac{1}{2}Am\cos(\omega_c + \omega_s)t \quad , \quad (1)$$

Where m – modulation index, ω_c – frequency of HF signal, ω_s – frequency of HF signal.

From expression (1), the presence of three frequency components in the signal is obvious. In general case, suppose that the VAC of the medium is representable by a nonlinear function *I=f(U)*, which is approximated in a certain neighborhood of the point U_0 by Taylor polynomial:

$$I = f(U_0) + a_1(U - U_0) + a_2(U - U_0)^2 + \ldots + a_n(U - U_0)^n \, , \quad (2)$$

Ultimately, we can talk about the harmonic set event in the signal spectrum, determined by combinatoric formula:

$$\left[\begin{array}{l} n\omega_1 + k\omega_2 \\ |k\omega_2 - n\omega_1| \end{array}\right. , \quad \text{where} \quad (k,n) \in Z \qquad (3)$$

Based on the spectrum of the amplitude-modulated signal (1), we find that the lowest-frequency component of the signal is defined as | k ($\omega_c - \omega_s$) – nωc | at $k = n = 1$ — this is one of the sidebands directly connected to the modulating signal.

It can be noted that in the combination spectrum (3), it is specified the low-frequency signals that are associated with the frequency of the modulating signal ω_s. In the medium, currents and conductivity or displacement at this frequency and its first harmonics can also occur. It is obvious that the spectra of acoustic oscillations in Fig. 2, and those observed on other acoustic models (Airborne Instruments Laboratory 1956; Chou et al. 1975), also obey the law of combinatorics (3).

The combinatorial relations considered here do not take into account inertial effects, which are more dependent on the carrier signal frequency and show as, for example, in ferroelectrics when approaching the HF radio range.

3 THE FREY EFFECT RESEARCH INSTALLATION

To perform the experiment we used the GRG–450B laboratory oscillator with amplitude modulation and amplitude-pulse manipulation at sound frequencies. The modulating signal was created on the (GZ–112) Г3–112 generator. There was a sound on the (TGM-25E) ТГМ–25E ferroelectric converter (dimensions: d=17 mm, h=2 mm). Also, in subsequent experiments, the electrical signal from the converter was fed to the GOS-620 electronic oscilloscope. The photo of installation is presented in Fig. 3.

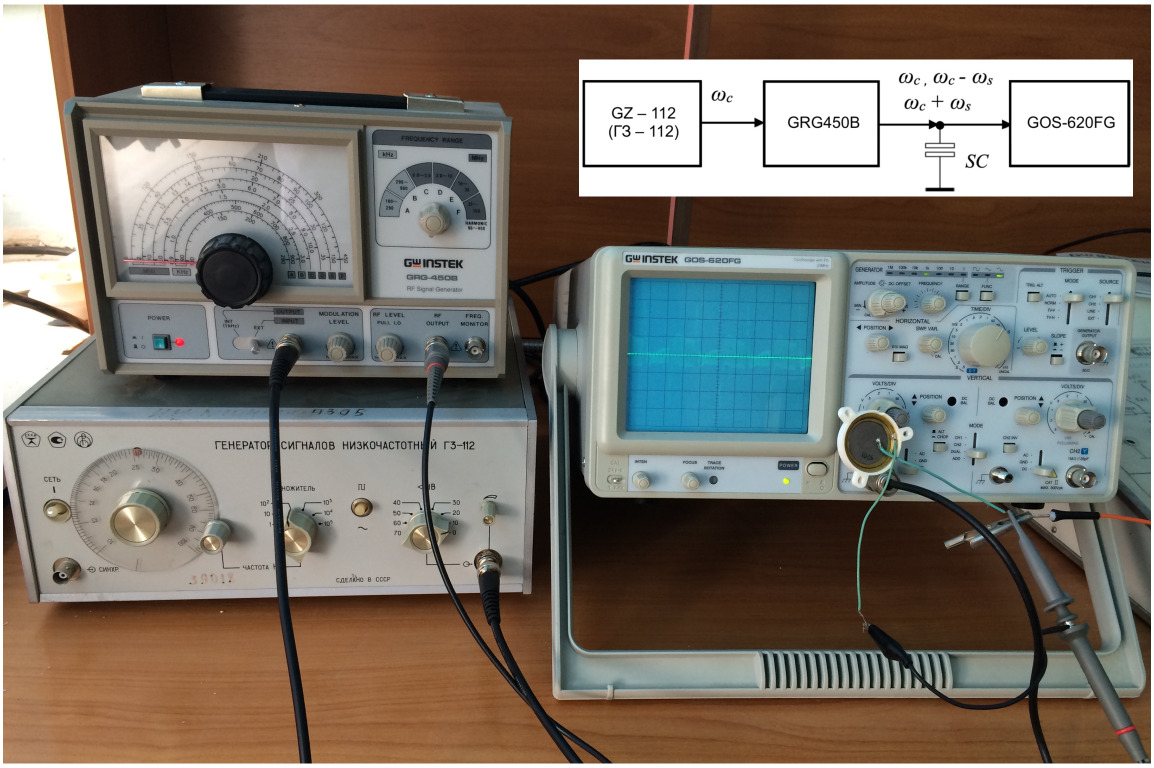


Figure 3. Laboratory bench for electro-acoustic effect studying at ТГМ–25E ferroelectric converter with block scheme.

Using this installation and a KCl placebo liquid we can prepare and perform the experiment on the Frey effect electromagnetic signal transformation. This equipment is the most accessible for most of the universities or scientific institutions so it is good choice for initial research in the field. Depending on further tasks, the laboratory bench can be easily improved.

3.1 High frequency signal amplitude modulation

Oscilloscopes are given, taken from the oscilloscope screen with amplitude modulation in the experimental conditions carried out on laboratory instruments. Sensitivity: 50 mV/cm (side of the square).

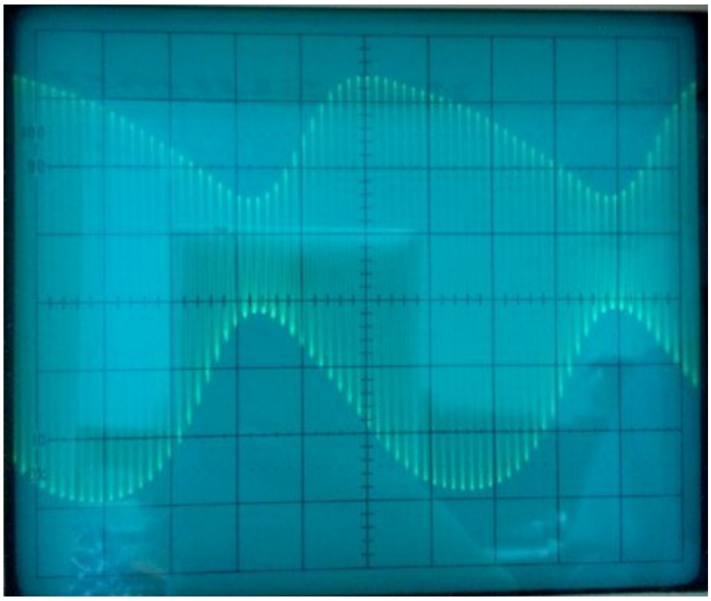


Figure 4. Modulated signal at carrier frequency of 100 kHz.

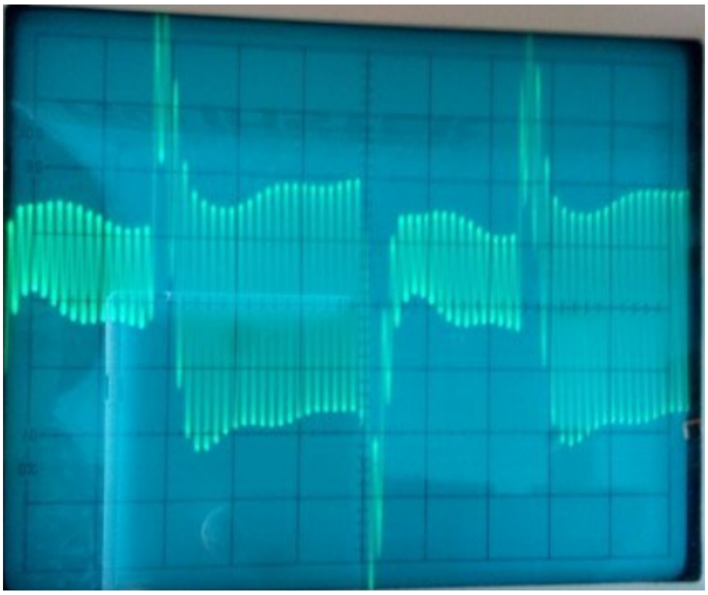


Figure 5. AM. The frequency of the carrier signal of 100 kHz.

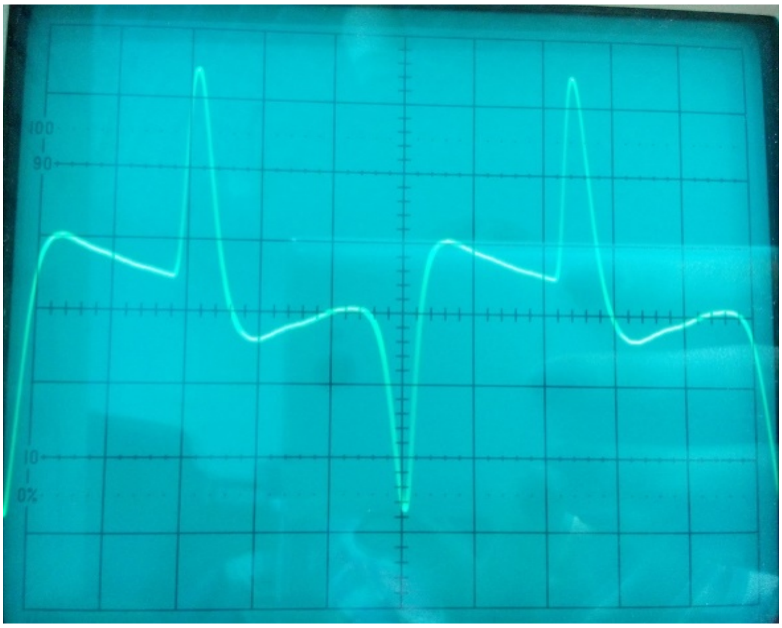


Figure 6. AM. The frequency of the carrier signal of 450 kHz.

The high-frequency component is observed in Fig. 4 because the frequency of 100 KHz is still deployed by the oscilloscope, in which the frequency limit is 6 MHz. Fig. 5 and Fig. 6 show the signal oscilloscope at the converter resonant frequency of 2.5 kHz. Carrier frequencies are different in tests. It may be noted that at Fig. 5 and Fig. 6 acoustic signal is significantly different from a sinusoid, but the pulse repetition rate is 2.5 kHz.

3.2 Amplitude-pulse modulation of the high frequency signal

Pulse modulation has a wide frequency spectrum, which cannot affect, as we believe, on the shape of the low-frequency signal. Fig. 7 shows the form of modulated oscillations at frequency of 100 KHz. Sensitivity: 50 mV/cm — the height of the square on the screen. Figures 8 and 9 show oscillograms obtained on a ferroelectric converter.

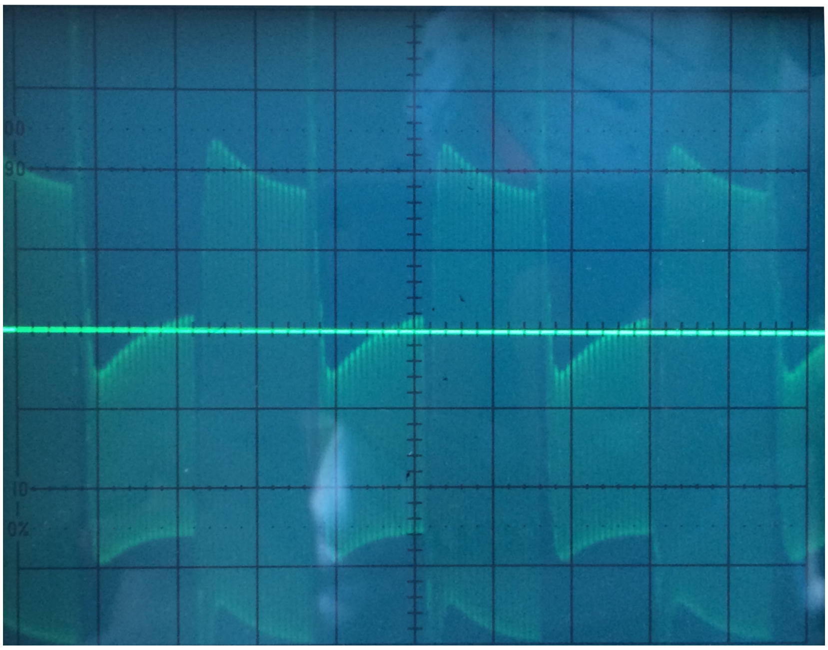


Figure 7. Amplitude-pulse modulation signal at carrier frequency of 100 kHz.

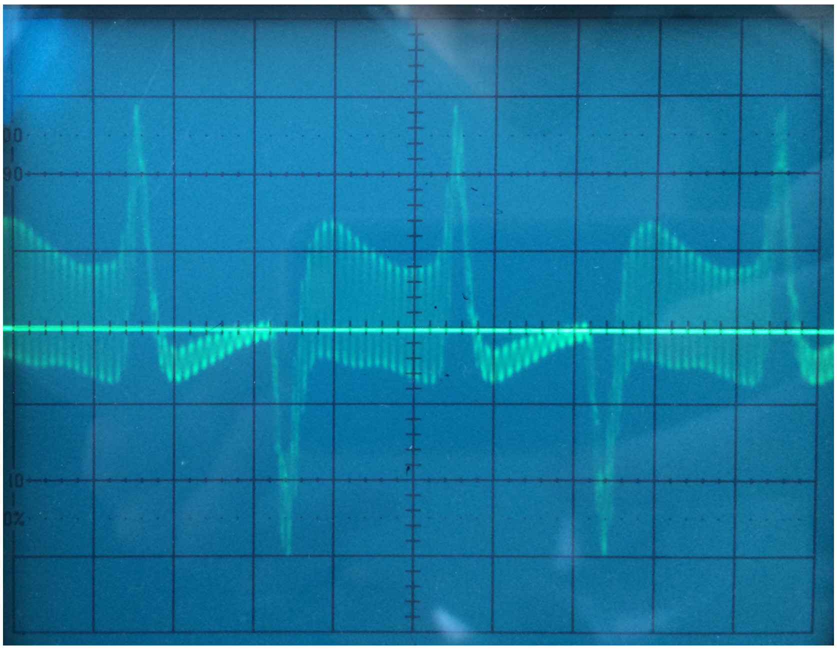


Figure 8. APM. The frequency of the carrier signal of 100 kHz.

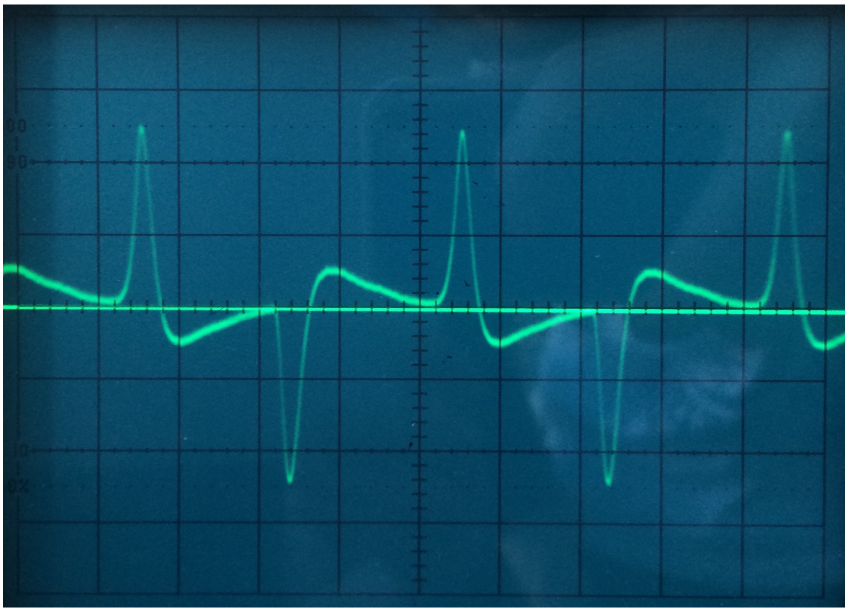


Figure 9. APM. The frequency of the carrier signal of 450 kHz.

Pulse durations in Fig. 9 is noticeably less than in Fig. 6.

3.3 Installation for laboratory research

In the future, it is planned to conduct experiments on other environments where the conversion effects are most likely to be not as effective, and acoustic signal multiplication will be required.

Many substances in states when the conducting properties of the medium correspond to dielectric ones can be classified as low absorbing media. This is analytically determined by the ratio between the values of the real and imaginary components of the complex dielectric constant. The same can be said about complex conductivity.

For most substances, this state is reached only in a certain frequency domain, due to dependence of the dielectric constant and conductivity on the electromagnetic wave frequency. Note that low conducting media, including soil, water and saline solution

(Chou et al. 1980), have non-linear current-voltage characteristics, which allows us to assume that the spectrum part of the output signal is in the low frequency range. This provides the so-called signal path-demodulation (Chou et al. 1980; Barinov, Prokopov & Zheleznyak; 2015).

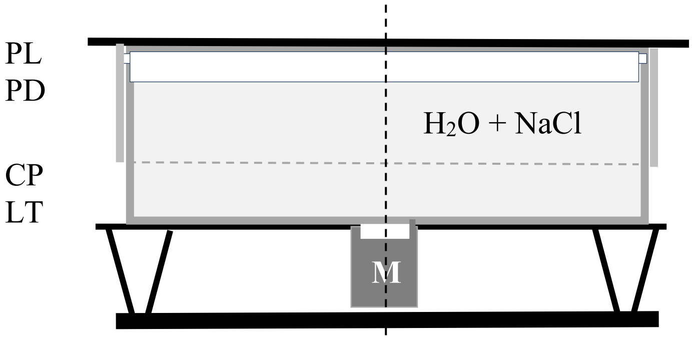
Medium interface also has a significant nonlinearity, which is not discussed here. In this paper, it is proposed to use water, solution of sodium chloride in water, and, in particular, a model of saline as the test medium: H_2O — 1,000 g, NaCl — 9 g. According to the "salinity", the saline model corresponds to sea water and, to some extent, blood plasma (Chou, Guy, Galambos 1982; Barinov, Tambovtsev & Kydyrbaeva 2015). Table 4 shows the electrical parameters of the medium (Grudinskaya 1975).

Table 4. Properties of liquid mediums.

Medium type	Wave length λ, m	Transmittivity, ε	Conductivity, γ, Cm/m	Media type	Wave length λ, m	Transmittivity, ε.	Conductivity, γ, Cm/m.
Fresh water	≥1 0.1 0.03 0.003	80 75 65 10	10^{-2}-$3\cdot10^{-2}$; 1-2; 10-20	Sea water	≥1 0.1 0.03 0.003	75 70 65 10	1–6 1–6 10-20 10-20

The scheme of the laboratory bench is presented in Fig. 9. Petri dish (PD) is placed between the charge plates (CP) of flat capacitor (C). The microphone (M) is fed to the bottom of PD through a hole in the bottom CP. Everything is placed on the laboratory table (LT). In the Petri dish there is solution of sodium chloride in water from low concentration to concentration of saline: H_2O (99.1%) + NaCl (0.9%).

The HF electrical signal from the GSS generator is supplied to capacitor C. From the acoustic microphone M the signal is amplified and fed to the oscilloscope OS. The laboratory bench is placed in a sound protected casing.



PD — Petri dish, d = 8 cm
CP — charge plates
M — microphone
LT — laboratory table

Figure 10. The laboratory bench (placebo liquid).

The microphone is located in the center of the Petri dish through a hole in the bottom charge plate of the capacitor. The top charge plate is glued to the lid of the dish.

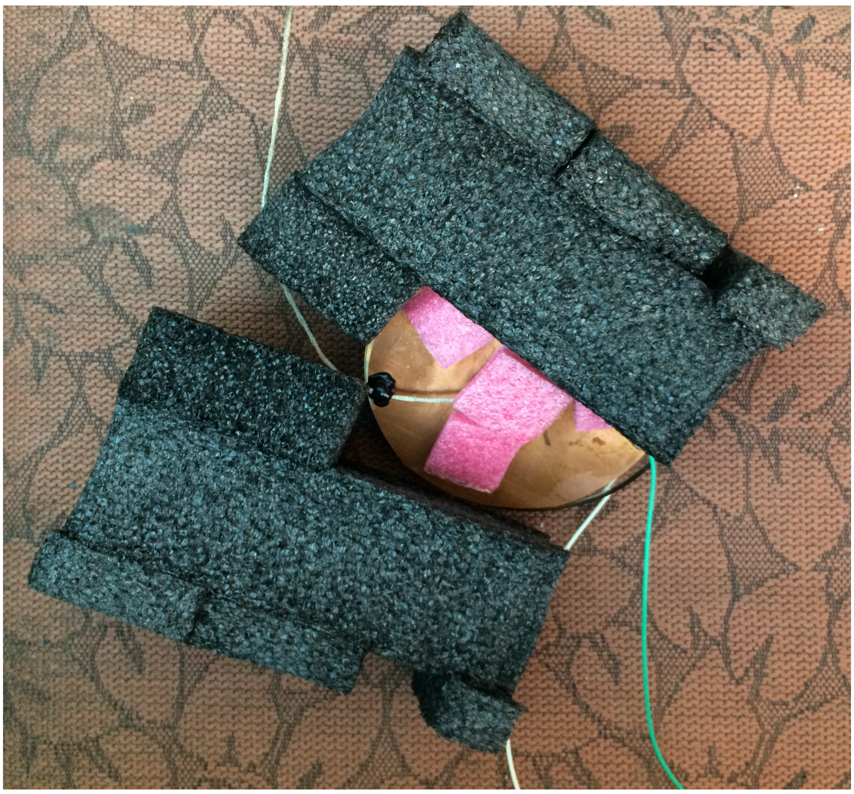


Figure 11. The Petri dish is placed in a sound protected casing.

3.4 Additional analysis

Shortly after the experiment was done and all parameters were measured, we started to prepare the basement for the next study. We applied the principles of mathematical analysis to our results. Here we observe the oscillogram and amplitude specter of first signal which we have received during experiment. This will form the basis of following publication (Tambovtsev & Tambovtsev 2019) regarding physical nature of the Frey Effect obtained in a practical way.

Here below we directly quote our recent comments on the experiment:

"Without a signaling device, the screen shows the AM signal image, if the carrier frequency is below 6 MHz – the upper limit of the oscilloscope range frequency). As the experiment shows, the UHF electroacoustic effect is best observed at the resonant frequency F_C of the piezo signaling device – this is also the modulating signal frequency: $F_C = F_R = 2.5$ KHz In the first experiment, the carrier frequency $F_S = 100$ KHz."

The result is shown on the photo (see Fig. 12). On the oscilloscope screen, the signal received during the conversion contains HF and LF components of the signal spectrum. The LF component is associated with the signal conversion effect. The sound is reproduced at the resonant frequency of the signaling device.

"The HF component is preserved due to the fact that the boundary frequency for the oscilloscope is as follows: $F_{GR} = 6$ MHz, which is much higher than 100 KHz – the carrier signal frequency".

Next, we observe and show the difference in the laboratory equipment "perception" using two different frequencies – one of them is significantly larger than another.

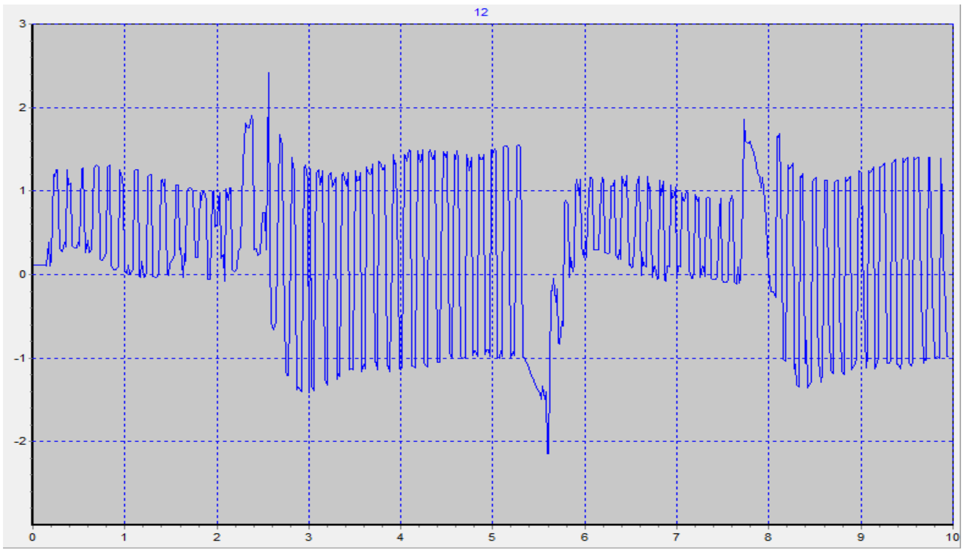


Figure 12. Oscillogram of the signal with carrying wave F_C = 100 kHz with sensitivity 0.5 V per scale.

“In the following experiment, a symmetrical AM signal is applied to the piezo signaling device. Carrier frequency F_C = 450 MHz. The oscilloscope does not reproduce the HF component due to frequency limitations of the oscilloscope and, of course, there is a capacitor shunting of the signaling device. The LF signal has a repetition rate 2.5 kHz, but the third harmonic is also expressed. The constant component is absent due to the fact that there is no detection effect. The sound reproduced by the signaling device does not change as compared with the first experiment, since the sound is reproduced at a resonant frequency. In the third experiment, a symmetrical APM signal is applied to the piezo signaling device. Carrier frequency F_C = 450 MHz“.

The result is shown on the photo (see Fig. 13). The oscilloscope does not reproduce the HF component. The signal spectrum is enriched with odd harmonics. The signaling device sound, in comparison with the first experiments does not change, – the sound is reproduced at the resonant frequency of the detector.

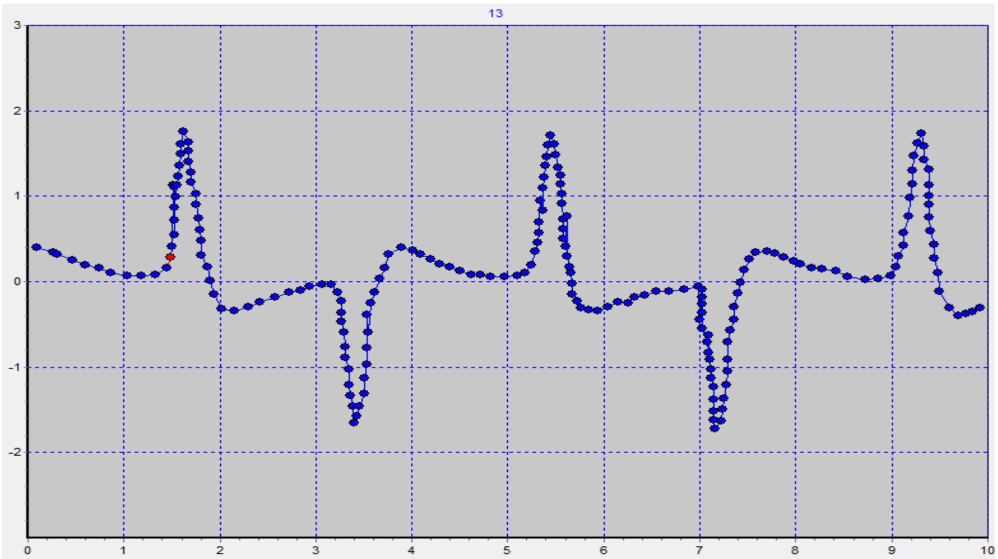


Figure 13. APM. Signal waveform (F_C = 450 MHz).

"The Fourier discrete transformation method was used to calculate the spectra of the converted signals (Tambovtsev, Zhelyeznyak & Kopyrkin, 2018). In processing, the signal period is divided into 36 discrete values. The Kotelnikov theorem allows us to obtain the spectrum from the values $N < 36/2$, i. e. $N_{max} = 17$. Fig. 14 and Fig. 15 show the spectra of the received signals in the relative coordinates. The first maxima in the spectrograms correspond to the resonant frequency of the piezo signaling device: Fs = 2.5 kHz"

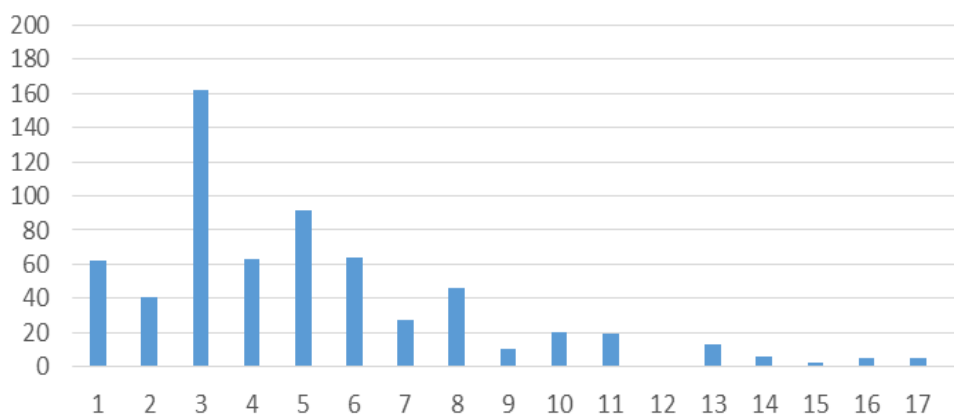


Figure 14. Amplitude spectrum of converted AM signal. F_C = 450 MHz, Fs = 2.5 kHz.

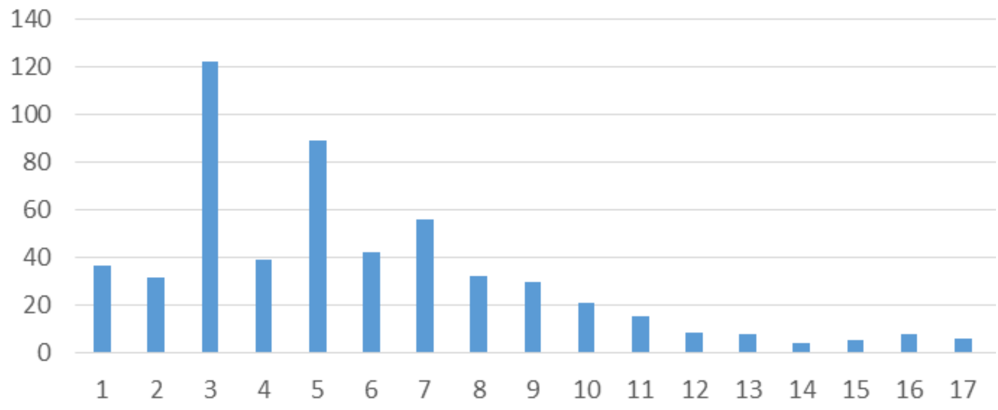


Figure 15. Amplitude spectrum of the converted APM signal. Here: F_C= 450 MHz, pulse repetition rate Fs = 2.5 kHz.

"The amplitude spectra (Fig. 14 and Fig. 15) show that the odd harmonics (No. 3 and No. 5) are larger in magnitude than the fundamental frequency amplitude — the effect of non-linear distortion of the signaling substance. For the APM signal, the 7th and 9th harmonics also appear, which is associated with nonlinear distortions and the nature of the HF signal spectrum. The appearance of even harmonics is explained by the quality of oscillogram digitization relative to the time coordinate: a slight offset reproduces the action of the DC component."

4. IMPACTS ON FUTURE mmWAVE BASE-STATIONS

The human auditory response to pulses of radio frequency energy, commonly referred to as radio sound, is an extraordinary phenomenon. MW-induced sounds are similar to other common sounds, such as clicking, humming, hissing, knocking, or tweeting. MW-sounds can be characterized by low intensity and can be heard only in a quiet environment. Location of the conversion of radio frequencies into acoustic energy is located inside, at the cochlea periphery, and detection of MW-induced sound in humans and the MW-induced auditory responses in animals are similar to detection of acoustic noise. To hear sounds, people must be able to hear high frequency acoustic waves in the 5 kHz band and above. Impacts of pulsed high-frequency fields should be in the MHz and GHz range. The auditory phenomenon depends on the energy in a single pulse, and not on the average power density. Guy et al. (1975) found that the hearing threshold at 2,450 MHz was associated with energy density of 40 $\mu J/cm^2$ per pulse, or pulse energy absorption of 16 μJ/g. The converting mechanism of modulated HF signal to an acoustic LF signal has not yet been studied and is presented in the form of hypotheses. The laboratory tools development is required for the physical study of the phenomenon, which is the subject of the work. Trial or criterion measurements which confirm existence of the effect under investigation were carried out on laboratory benches. It should be noted that the mechanism of LF electrical signal event is also of interest.

Also, taking into account recent applications of the Frey Effect (Hambling 2008; Skopec 2018) we have to revise past statements regarding the impact of effect on human. At first it was considered that human perception threshold is significantly higher than usual radio frequency influence and the any possible relation between microwaves influence and human health were not provable. Even more, it was considered as actual hearing but later it turned out to be the thermoelastic delusion. But now we have proofs that Frey effect phenomenon (Skopec 2018) can be applied to create devices that can cause permanent damage to mental condition and even physical hearing. And this technology is dangerously close to current high-speed communication systems. In theory, even base-stations can partially act as Microwave Sonic Weapon (Skopec 2018).

5 CONCLUSION

Due to extremely low absorption power of the converter (less than 0.1 W), the effect of nonlinear polarization conversion of the modulated HF signal into the low-frequency one on the ferroelectric converter is obtained. This opens up opportunities to study all MW and acoustic-dependent effects in many fields of science (primarily in telecommunications, ecology and physiology) from a completely new angle. This is a new range of research, which lies beyond the physical perception of sound and concerns a very topical theme of high-frequency radiation influence on the human body and definition of a dangerous radiation threshold with which new generation networks can be connected (5G, etc.). Development of new methods of microwave therapy combining tissue heating with volume massage due to excitation of wave processes in the tissues of the human body can be among the possible application areas of the microwave effect of spectral converting of a radio signal into an acoustic one.

Creation of influence means on the unorganized crowd is also interested. The project MEDUSA–2008 (an abbreviation of Mob Excess Deterrent Using Silent Audio) (David Hambling 2008) explores use of radio sound to excite loud “screams” in the mind that destabilize the psychological state of people. Also the United States had developed even more dangerous, military Microwave Sonic Weapon (2018) that can permanently destabilize psychical condition of human or even make them deaf; and also this weapon itself allows to communicate in a special way as minor implication of it. This proofs that there is a potential and existing research trend in this field but currently the real, useful and positive impacts of effect are not studied enough. Also it should motivate us to aware and re-connect all effects of high frequency and electromagnetic influence that we absorb every day from high-speed (4G, 5G) connection, Wi-Fi access points, cell-phones and laptops. It is highly possible that on this stage of technology development the summary effect of technologies that we use every day could be measured and related to the impacts on mental condition and anxieties of people. But as it was mentioned in introduction, the Frey effect study intersects with many other fields of science and medicine which makes it complex to research and apply.

These are the reasons why this research thesis paper offers and demonstrates the simple ways to model experiments for further researches of the Frey effect. The microwave hearing effect can be used in several important areas, for example, in hearing aids of a new type, and in the tasks of wireless information transmission. It is already obvious that you can create devices for scaring birds, rodents and people with the use of it and inbounds it is already naturally related to humans whose have sensitive audible perception. From technical perspectives of implication, there are recent researches of the Frey effect started to imply alternatives to Near Field Communication through ultrasound channel (Asyaev, Bagaev, Saidov 2019) disregarding the chips or operation systems of the devices. As we may see, the possible use of Frey effect is revealing during the natural growth of technologies and the interest in this study was only increasing by the time and according to the amount of contributions made by scientists and engineers during past years.

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