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PHYSICAL FACTORS AND THEIR EFFECTS ON BIOLOGICAL OBJECTS

METROLOGICAL PROVISION OF INFRASOUND LEVEL MEASUREMENTS

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It is demonstrated that the response of the vibratory systems of living organisms to acoustic effects depends not only on the sound pressure level (which is predominantly subject to sanitary regulations), but also on the vibration velocity of the particles moving under the sound pressure gradient and the amplitude of their displacement from the equilibrium position. The conclusion is therefore drawn that to correctly regulate sound levels in the low-frequency region, it is necessary to measure simultaneously the sound pressure and the vibration velocity of the particles of the medium.

Acoustic fields occupy an important place among the physical fields that actively affect biological objects, man included. An acoustic signal, in the narrow sense means a sound, i.e., elastic vibrations and waves in gases, liquids, and solids, heard by the human ear. For this reason, the acoustic field and acoustic signals (sound) are primarily considered as a means of communication. Sound waves with frequencies below 16–20 Hz are usually referred to as infrasound. Acoustic waves with frequencies below 200–300 Hz, propagating in the earth's crust, are sometimes called seismoacoustic waves, and those with frequencies below 10–20 Hz (often less than 1 Hz) are known as seismic waves. The idea that the acoustic field is an environmental contaminant has originated comparatively recently. This particularly refers to acoustic signals in the frequency bands not perceived by the human ear. In this connection, the term "acoustic ecology" has in the last few years come to be used in increasing frequency when analyzing the ecological condition of the environment.

As a rule, acoustic ecology means a division of ecology dealing with studies into the effect of acoustic vibrations and waves on biological objects, ecosystems, and man, in particular.

In analyzing the effect of noise on the human being, a distinction should be made between the following two main irritation mechanisms: the direct action of sound on the organs of hearing through the intermediary of auditory cells and nerves and its indirect action, through the excitation of signals in nerve cells other than the auditory ones [1].

The fact that audible noise, vibrations, and infrasound exert, in the general case, a harmful effect on man has been noted by many investigators. Their combined effect is especially harmful.

In both cases, the excitation of the vegetative nervous system and/or the development of additional psychic reactions takes place. Characteristic of the vegetative nervous system is a precise correspondence between the noise and the reaction to it, whereas in the domain of psychics no such correspondence exists. What is worse is that discomfort manifests itself through the psychological state or (less frequently) through painful sensations of internal organs (usually in the low- frequency and infrasonic radiation regions). Pronounced psychic reactions start manifesting themselves at sound pressure levels of 30 dB(A). The decisive

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role in the sensation of comfort or discomfort in man is played by his attitude to the source of sound. For example, the sound of droplets falling from a tap or the tick of an alarm-clock may cause irritation, while a loud music may have a positive effect (joy, relaxation) on some persons and a negative effect on others.

However, sonic influence does not always cause a negative reaction. It has been known, for example, that music can help raise the productivity of monotonous labor. Noise has a positive effect on the process of concrete thinking and a negative one on abstract thinking. As the volume of sound increases, the productivity in that case first grows and then decreases.

Based on what has been said above, the World Health Organization (ISO) has defined acoustic noise as a sound that is appraised negatively and causes harm to health.

Nevertheless, with the former mechanism, there may develop sensations of discomfort unassociated, at first, with the presence of a sonic irritant. This is associated with the specific structural features of the human ear, particularly of the inner ear, a cavity located in a recess in the temporal bone. It contains a cochlea, a bony spiral, and a spiral plate that divides the cochlear canaliculus into two parallel cavities: the upper (vestibular) and the lower (tympanic) one. It is predominantly the lower cavity that transmits sonic information to the brain through the intermediary of a group of membranes and sound-sensitive (hair) cells. However, the excitation of the vestibular part of the ear at certain frequencies and some loudness levels of sound may lead to the excitation of some nerve cells unassociated with the sound-sensitive elements. What is more, waves incident upon the cranial bones cause vibrations therein and also excite nerve endings other than the auditory ones.

The sensation of discomfort may be caused by various sound levels, depending on the particular person, his (her) working conditions, and the previous history of his (her) psychic condition. In most cases, this sensation vanishes as the irritation source disappears. But sometimes there develop residual phenomena which either come to an end some time after the irritant is switched off or accumulate in the organism, though the external manifestation of discomfort has ceased, and eventually lead to irreversible changes therein.

By and large, the action of acoustic waves on the human organism is very like that of radioactivity or X-rays, though with somewhat different results. For this reason, when establishing standards for the maximum permissible acoustic signals and noise, account should be taken not only of the "loudness" and frequency band of the sonic radiation, but also of the time during which man is exposed to a given impact, the regularity of the latter, and so on.

According to the established standards, there are three different criteria by which noisiness is estimated:

— loudness level of sound;
— sound pressure level;
— ultimate spectrum curves.

It is taken at present that the loudness levels of sound in the frequency band over 60 Hz that are harmful to the human organism have been fixed relatively correctly. Sanitary standards have been established for the permissible noise levels in buildings and residential areas in this frequency band.

In addition to hearing sensations, the following main functional changes under the effect of sound waves of certain intensity may develop.

Temporary deafness and sometimes even rupture of the tympanic membranes occurs upon a high-intensity acoustic irritation arising instantaneously (e.g., upon an explosion).

Temporary elevation of the threshold of audibility occurs upon the action of a sound of sufficiently high intensity causing a contraction and even total blockage of the blood vessels in the inner ear and a disturbance of metabolism and fatigue of the auditory cells (a reduction of the sensitivity of the organs of hearing).

Partial deafness (an irreversible loss of hearing) occurs upon a long-duration exposure to a high-intensity sound. Partial deafness as a professional disease manifests itself in the frequency band 2–6 kHz, because most of industrial noises have a maximum intensity in this band.

The auditory nerve fibers reach as far as the medulla oblongata where the irritation is transmitted further. As a result, an isolated irritation of the ear may be accompanied by a complex reaction.

Increased breathing rate following the action of a noise.

Reaction of the vegetative nervous system to changes in the blood circulation system. The reaction to a sound appears in the form of an insignificant reduction of the blood pressure, some increase in the pulse rate, and to a much greater extent, contraction (spasm) of blood vessels at sound intensities of over 70 dB(A).

In addition to the reaction to noise intensity, a linear relationship has been found to exist between the peripheral resistance and the bandwidth of noise. This relationship is due to the fact that the auditory nerve fibers are tuned to a certain frequency, so that the reaction to sound intensity within a narrow frequency band is predominantly governed by the number of hearing pulses per unit time.

The vegetative reactions caused by acoustic irritation are independent of the habituation factor.

Dilatation of the pupils, which depends on sound intensity and from 75 dB(A) proceeds in a nonlinear fashion. As a result, there may be a reduction of the depth of focus.

Psychic reactions. The scale of the results of the action of noise on man as a function of its intensity includes four ranges.

Range I (30–65 phons) is the range of purely psychic reactions.

Range II (65–90 phons) causes, in addition to psychic reactions, also vegetative reactions.

Range III (90–120 phons) is characterized by possible irreversible changes in the human psyche, strong vegetative reactions, and also damages to the inner ear.

Range IV (120 phons and more) exceeds the threshold of pain.

The effect on the psyche increases with the increasing frequency and loudness of sound and the decreasing frequency band of noise, although noise does not always cause a negative reaction,

A long-duration exposure to a noise with an intensity in excess of the maximum permissible value may cause organic damages. Most frequent are pathological alterations in the peripheral circulatory system. It is believed that the irritation threshold of the vegetative nervous system is approximately 70 dB(A) when staying wide awake and around 55 dB(A) when in sound sleep. A moderate-level noise, no more than 35 dB(A) in intensity and containing no discrete components exceeding this value by more than 10 dB, may be even favorable for normal sleep.

Infrasound may exert a very substantial effect on man, on his psyche in particular. To illustrate, cases of suicide under the influence of a high-power infrasonic source have been reported time and again in the literature. It is therefore important to reveal minor sources as well.

Subject to consideration are natural (native) and artificial (man-made) sources of infrasound.

The natural infrasonic sources include earthquakes, volcanic eruptions, thunderclaps, storms, and winds. No small part in their development is played by the turbulence of the atmosphere. For example, the mistral (a cold north or north-west wind in the south of France) produces an infrasound with a frequency of 0.6 Hz. The natural infrasound produced during storms was used in Japan to give warning of tsunamis in good time (model Sofer sound detectors).

Artificial infrasonic sources are more diverse. These are primarily explosions, atomic ones included, heavy gun-shots, vibrations of buildings and other structures, presses, ventilation systems, vibrations of various vehicles, etc. Artificial infrasound sources are usually characterized by distinct frequencies and strongly differ from one another in both frequency and intensity.

The data available on the physiological action of infrasound are contradictory. But it is considered an established fact that the effect of infrasound on man is associated with the resonance of internal organs [2]. Some authors point out three essential resonances at frequencies of 5, 10, and 15 Hz. Various organs have different natural frequencies. As can be seen from Table 1, falling within the infrasonic range are the resonances of the organs located in the abdominal cavity, and so the effect of infrasound on man is primarily associated, as in the case of seasickness, with disturbances in the gastrointestinal tract: nausea, vertigo, and sensations of fear and horror.

In the range 7–13 Hz, the effect of infrasound on the human organism may be due to the fact that infrasound is synchronized with the alpha rhythm of the brain, but there is no sufficient information on this matter. It is also possible that the effect is associated with the bioacoustic resonance phenomenon.

As the wavelength of infrasound in much greater than the size of man, the latter is subject to infrasound on all sides simultaneously. This is essential for all air inclusions in the human body, for example, in the inner ear and lungs.

In the case of resonance, great periodic displacements of organs and tissues may take place, the motions of all organs being in phase. At high intensities (over 170 dB) infrasound may cause ruptures and bleeding in the lungs.

Table 1

Organ	Frequency, Hz
Head	30
Thorax	60
Spinal column	8
Abdominal cavity	4–8
Pelvis	4–6

Table 2

Level	Intensity, dB	Effect
1	190–150	Mortal
2	150–140	Psychic changes (permissible exposure for no more than 2 min.)
3	140–120	Physiological disorders
4	under 120	Weak (physiological disorders are possible in the course of long-duration exposure)

It is known that four levels of action of infrasound exist in man (Table 2).

Some similarity was reported [3] between the effects of alcohol and infrasound on human beings. Attention is given to the fact that the harm caused by infrasound depends not only on its level, but also on its frequency.

As noted earlier, the main specific feature of the action of infrasound on man is that it cannot be directly perceived by the organs of hearing. This causes the danger of the use of infrasonic sources as mass-destruction weapons.

Of all the obvious effects detected in volunteers exposed to infrasound, we note the following:

— changes in arterial pressure and heart beat rate (7–10 Hz);

— disturbance of the vestibular functions of the brain (20 Hz and less);

— disturbance of vision (40–60 Hz);

— disturbance of the functioning of the gastrointestinal tract, nausea, vomiting, vertigo;

— development of sensations of fear and horror.

People over 50 years of age are especially sensitive to low-frequency sound.

An acoustic field is customarily characterized by the sound pressure $P(t)$ and the velocity $V(t)$ with which the particles of the medium vibrate as a result of changes in the density of the latter. A distinction is made between the sound level in terms of pressure, i.e., $P^2 = \langle P(t)^2 \rangle$, where the symbol $\langle \cdot \rangle$ denotes averaging over time no shorter than the period of vibrations, and in terms of vibration velocity, i.e., $V^2 = \langle V(t)^2 \rangle$.

In acoustics, the sound pressure level L_P is customarily measured (in decibels) relative to some level P_0 taken to be the zero level (zero level in acoustics is usually taken to be the conventional audibility threshold of the human ear, $P_0 = 2 \times 10^{-5}$ Pa):

$$L_P = 20 \log(P/P_0) = 10 \log(P^2/P_0^2). \tag{1}$$

The sound level in terms of vibration velocity, L_V, is determined in a similar way:

$$L_V = 20 \log(\rho c V/P_0) = 10 \log[(\rho c V)^2/P_0^2]. \tag{2}$$

Here ρ is the density of the medium and c is the sound velocity therein.

Away from the source or in a plane wave, these levels are usually equal, i.e., $L_P = L_V$, and so it does not matter which field characteristic is measured. For this reason, all the health regulations (especially in Russia) known to us are aimed at controlling the sound pressure level.

At present there is no special state standard covering the infrasonic region of frequencies, except for one section of State Standard GOST 12.1.003-76, which prohibits even a short-term stay in areas with a sound pressure level in excess of 135 dB in any octave band.

There is a considerable spread in the permissible sound pressure values: a number of health regulations exist for the permissible levels of infrasound and low-frequency noise in residential areas (San-PiN 42-128-4948-89), at workstations (GOST 3223-85b 23337), etc. In the case of higher frequencies, the controlled parameter is the pressure level in octave and 1/3-octave frequency bands or the integral intensity of sound in terms of sound pressure in the frequency band of interest.

However, as applied to infrasound, this approach cannot be considered fully objective for the following reasons. For infrasound, a relation between pressure and vibration velocity in the low-frequency and infrasonic bands where the length of the wave being excited is long is generally not unique.

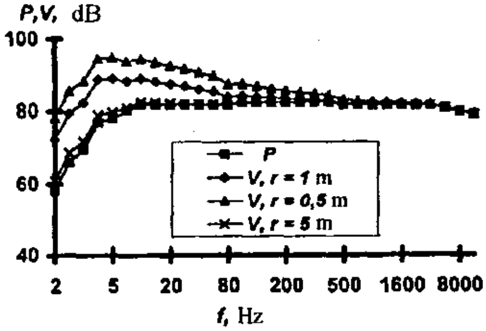

Fig. 1

Figure 1 presents as an illustration the frequency dependence of the radiation level calculated by formulas (1) and (2) at a distance of 0.5, 1, and 5 m from the loudspeaker installed in the sound-proof chamber of the Department of Physics of Moscow State University. One can easily see a noticeable discrepancy at low frequencies between the levels measured by different types of sound detectors. Approximately the same discrepancy must be observed when taking measurements with different types of microphones, for example, a carbon and a band type: the band microphone is sensitive to the pressure gradient in the sound wave, whereas the carbon type is sensitive to the sound pressure level.

Of particular interest is the problem of regulating the levels of low-frequency noises of aero- or hydrodynamic origin (noise produced in a narrow section of a subway during the passage of a train through it, the noise produced by jet and propeller engines, etc.). In this case, the effect on instruments sensitive to a sound pressure gradient or vibration velocity is greater by 20–40 dB than that on their counterparts sensitive to a sound pressure level.

Note also the possibility of the development of small-size standing infrasonic waves, or waves close to the standing type, in pipes, tunnels, cars, and other enclosed spaces of small size. In this case, the human organism and instruments may also be subjected to a strong action of infrasound in those regions where the measured sound pressure is close to zero, because sound pressure gradient or vibration velocity in these regions usually reaches its maximum.

Furthermore, subject to multiple reflections from the walls and various objects in enclosed spaces, sound waves produce a multiple-travel echo (reverberation phenomenon) with complex sound pressure and vibration velocity distributions.

It should be noted at the same time that the response of vibratory systems, including those of living organisms, to acoustic stimuli depends not only on the sound pressure level, but also on the vibration velocity of the particles of the medium, which move under the action of the sound pressure gradient, and the amplitude of their displacement from the equilibrium position.

Investigations have shown that the organs of hearing of a fairly great number of biological objects prove to be sensitive just to the vibration velocity or the sound pressure gradient in the sound wave. In some cases, the magnitude of these parameters also governs the amplitude of forced vibrations of the internal organs in man and animals.

Based on the literature results of sound level measurements in the low-frequency and infrasonic regions and on our many years experience, we believe that to correctly regulate the levels of sound in these frequency bands, it is necessary to measure simultaneously the sound pressure and the vibration velocity of the particles of the medium or the sound pressure gradient in the sound wave. As a result, it becomes possible to characterize acoustic fields not only by sound pressure level (1), but also by vibration velocity level (2), as well as by the following parameters: sound intensity (strength) I (in W/m^2) determined in terms of sound intensity in a plane sound wave at which an acoustic power of 1 W is transmitted through a surface of 1 m^2 in area normal to the direction of the wave propagation and given by

$$I_p = P^2/\rho c, \quad I_v = \rho c V^2;$$

the Poynting vector, i.e., the product $P(t)V(t)$; and the acoustic energy flux $W = \langle P(t)V(t)\rangle$ characterizing that part of the wave energy which is transferred in space (in a standing wave, the power flow of sound is zero).

From the standpoint of protection against low-frequency noises by way of localization of their sources, this method seems very promising, for it enables one to solve the above inverse problem of acoustics on the basis of measurements taken in a region of space whose size is much smaller than the wavelength of interest. This idea was first advanced by the employees of the Chair of Acoustics of the Department of Physics of Moscow State University as far back as the 1960s. At the present time, this approach has been predominantly implemented in hydroacoustics (in the Russian literature, it is referred to as the method of vector-phase measurements (vector-phase method)). It has not yet been recognized in aero- and architectural acoustics in Russia, but is known to be used elsewhere (e.g., by the Brel & Kjaer Company) to localize low-frequency noise sources. Nevertheless, statistical data on the simultaneous measurement of absolute infrasound levels in terms of sound pressure and vibration velocity are very scarce, and there are no international standards for the permissible infrasound levels.

The importance of distinguishing between such characteristics as I_p and W can be illustrated using, as an example, our measurements of noise levels in the infrasonic range in a high quality car at various driving speeds on city streets.

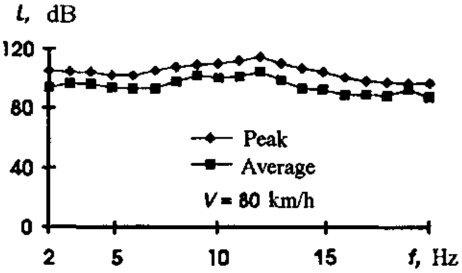

Fig. 2

In measuring acoustic noise fields, we used a method based on simultaneous measurement, in a small region of space, of sound pressure, the projections of its gradient onto three mutually orthogonal directions in space, and a phase difference between them. As indicated above, the latter makes it possible to determine the sound intensity and acoustic energy flux in various directions and, if necessary, individual sound pressure levels. The advantage of the method is the fact that it is possible to take measurements in restricted volumes, determine noise levels in the presence of an additional disturbance, localize sound sources, and find the directions of the acoustic energy flux which may differ between different frequencies. All this is of interest in working out measures to combat noise. Our sound pressure detector was a Brel & Kjaer microphone. The pressure gradient sensor was a three-component vector detector 190 mm in

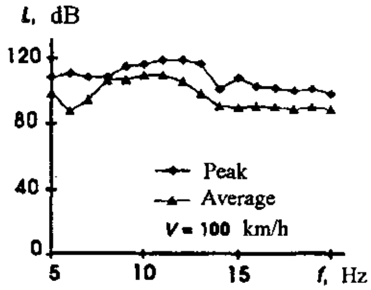

Fig. 3

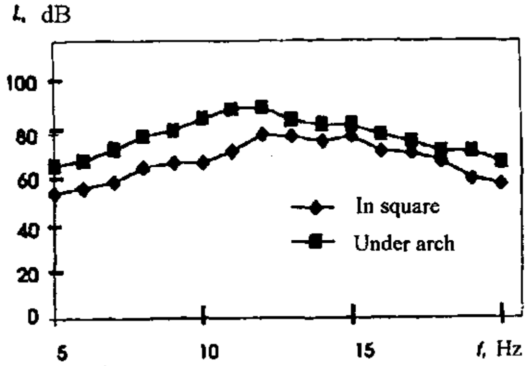

Fig. 4

diameter developed at the Department of Physics of Moscow State University. The sound pressure and vector detectors were elastically suspended from a special framework. The resonance frequency of the elastic suspension in air was below 2 Hz. The results of our experimental measurements of noise levels in the car are presented in Figs. 2 and 3 for two driving speeds in street traffic.

One can see an increased infrasound level in the range 8–16 Hz (Fig. 2) and a resonance frequency region in the range 8–14 Hz (Fig. 3), where the noise reaches substantial levels and may have an adverse physiological effect on man in the course of long driving hours. In Fig. 4, one can see a substantial elevation of the infrasound level in the car when riding under an arch of a building in comparison with the level measured when riding across a square.

At the same time, the spectral levels measured with a microphone and a vector detector and reduced to equivalent sound pressure levels (e.g., by formulas (1) or (2)) proved to be different, the difference being dependent on the location of the detection system inside the car, which pointed to the development of almost standing waves. The difference between the levels reached 15 dB.

It should be noted that while measuring the noise in the car, we obtained data which allowed us to determine the direction toward the noise source and give recommendations on this basis as to the measures necessary to reduce noise in some high quality cars.

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