3. FUNDAMENTALS OF SOUND AND HEARING

A significant part of the incoming information is perceived by our ears and then processed by hearing. Sound processing and transmission is, therefore, one of the important areas of telecommunication systems. To be able to design equipment used in this field, one must become well acquainted with the physical properties of sound and with the psychophysical characteristics of the ear. This chapter describes physical parameters of the sound, quantities which handle the physiological characteristics of hearing, artificial sound field and the sound perception and reproduction techniques.

3.1. Physical Aspects of Sound

Sound is the mechanical vibration of an elastic medium. Influenced by an outer force, the particles of the elastic material are displaced and because of the elastic force and the inertness they begin to vibrate. Vibration propagates in solids, liquids and gaseous materials, as well. As the human ear perceives generally airborne sounds, the generation, propagation and perception of airborne sound is of essential importance.

Airborne sound appears as the fluctuation of air pressure. Sound pressure can therefore be regarded as an alternating component superposed to constant (or very slowly varying) atmospheric pressure (see Fig. 3.1.). Air pressure $P(t)$ in a given point of space can be expressed as the sum of the atmospheric pressure P_0 and of the sound pressure $p(t)$.

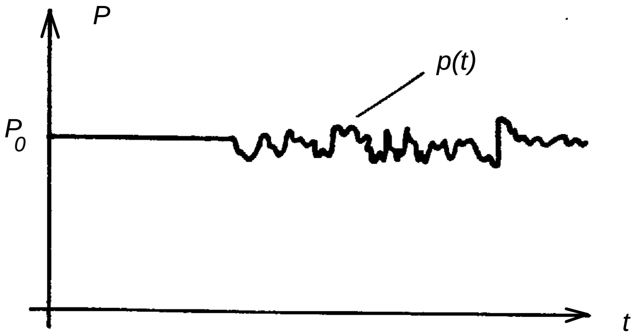

Figure 3.1. The Air Pressure

$$P(t) = P_0 + p(t) \qquad (3.1)$$

In the following discussion we will examine only sound pressure. To characterize the magnitude of sound, the effective value of sound pressure is used. The standardized unit of sound pressure is the Pascal (1 Pa = 1 N/m^2). (Atmospheric pressure is about 100.000 Pa).

Sound pressure is measured by microphones. Instead of its actual value, sound pressure is usually given in dB being compared to certain reference pressure. 20 *m*Pa is used as reference, since this is the level of the 1 kHz sinusoidal sound just yet audible by the average human ear. The sound pressure level can therefore be given as

$$\mathrm{SPL} = 20 \lg p/p_0 \qquad (3.2)$$

Pressure difference generated in one point of the space tends to equalize towards the adjacent parts. During this process, particles of the air are displaced generating thus a new pressure difference in the neighbouring space.

So the sound pressure variation propagates in the form of sound waves. The distance between two points having the same phase of the sound wave is called the *wavelength*. The product of the frequency and the wavelength is equal to the *propagation velocity* of the sound wave:

$$c = f \cdot l \tag{3.3}$$

The propagation velocity of the sound is 340 m/sec.

If the sound source is concentrated in a single point and if there is no obstacle in the surrounding field then the sound waves are spherical. Far enough from the source, the curvature of the sphere can be neglected and the wave is supposed to be plain (Fig. 3.2.). For plain waves the ratio of sound pressure and particle velocity is constant:

$$\frac{p}{n} = r_0 c = 410 \frac{\mathrm{kg}}{\mathrm{m}^2 \cdot \mathrm{s}}, \tag{3.4}$$

where ρ_o is the air density.

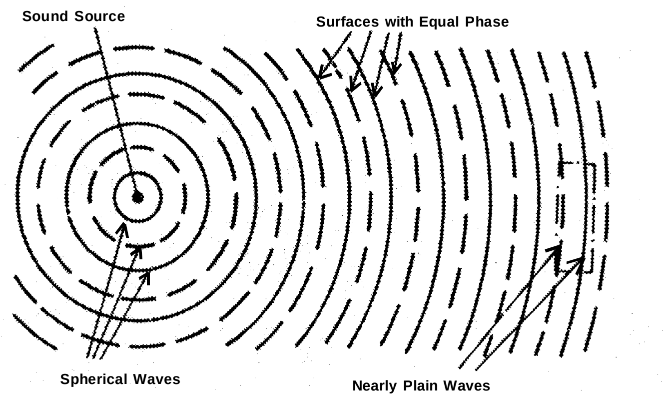

Figure 3.2. Spherical and Plane Waves

Sound can also be characterized by the acoustic power which comes through a unit of area. This quantity is called *sound intensity* and its value can be expressed as the product of sound pressure and particle velocity:

$$\mathrm{I} = \mathrm{p.v} = \mathrm{p}^2/(r_o\ \mathrm{c}) \tag{3.5}$$

Intensity is usually given in related form in dB, too. The reference is the same as for sound pressure. It can be seen easily that the reference value is I_o= 1 pW/m^2 which is the intensity of a just yet audible 1 kHz tone. Intensity can, therefore, be expressed as

$$L_I = 20 \lg I/I_0 \tag{3.6}$$

3.2. Physiological Characteristic of the Human Hearing

Human hearing is limited both in frequency and amplitude. According to the test measurements carried out on a very large amount of people, levels of just audible sound pressures were determined. The average of the measured values is called the *threshold of* *audibility*. The threshold of audibility is strongly frequency dependent. The ear is most sensitive in the range of some few kHz, below and beyond this range the sensitivity is smaller (see Fig. 3.3.) It can be seen that the range of the audible signals is between 20 Hz and 20 kHz. Too loud sounds cause pain, the lowest of such a sound pressure is called the ***threshold of pain***. Musical sounds and the speech are within these limits. It can also be seen that the frequency range and the amplitude range of music are remarkably greater than that of speech.

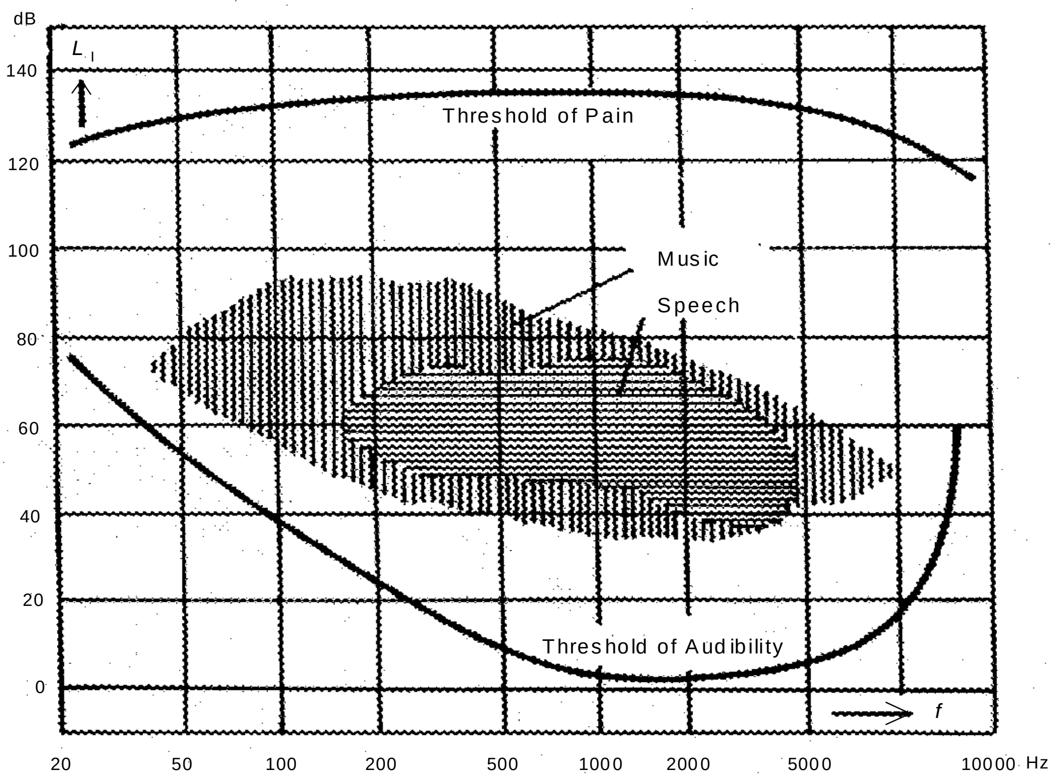

Figure 3.3. Limits of Human Hearing

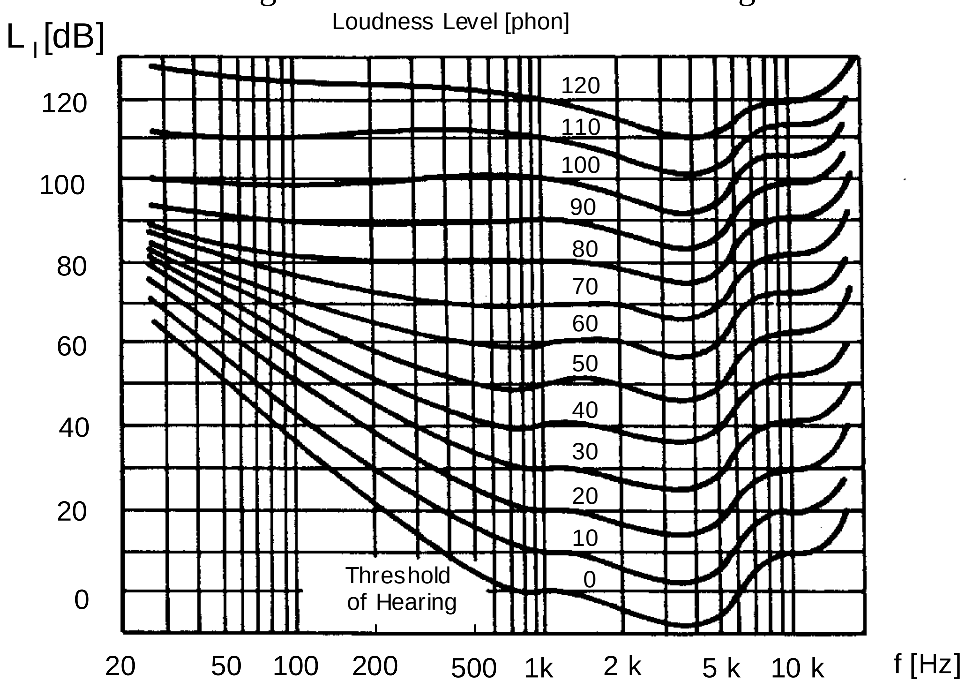

Figure 3.4. Equal Loudness Level Contours

For the subjective judgement of the sound level, the term of *loudness level* was introduced. Loudness level of an arbitrary sound is as many *phon*-s as many dB-s is the sound pressure level of the 1 kHz tone of the same loudness. (In the loudness evaluation test, the listener alternately listens to and compares the measured sound with the reference sound which can be varied by himself until the two sounds are judged to be equal.)

Connecting the points with the same loudness along the frequency axis, we obtain the so called Fletcher-Munson curves (see Fig. 3.4.). Loudness level of a sound at a given frequency and pressure level can be read as the value of L_N belonging to a certain curve on the diagram. Loudness is thus suitable for the comparison of sounds with different frequencies.

To evaluate the resulting level of simultaneous sounds, the term *loudness* has been introduced. Loudness is denoted as N and its unit is called *son*. If the loudness level is greater than 40 phon then the loudness can be computed as

$$N = 2^{\frac{L_N - 40}{10}} \qquad (3.7)$$

Masking is another term related to the simultaneous presence of two different sounds. Masking means covering the weaker sound with a stronger sound when each has a different frequency. Masking has been examined for sinusoidal sounds and for narrow- and broadband noises, respectively. Fig. 3.5. shows the increase of the audibility threshold caused by 1 kHz narrow-band masking noises. As it can be seen in the figure, high frequency sounds are easier to mask.

Spatial parameters of sound are also very important. First of all, *direction of the sound* has to be mentioned. In the horizontal plane, the sound is localized by the difference of the sound pressures at our ears. At low frequencies the phase difference is detected while on higher frequencies a difference in intensity arrises due to the shadowing caused by the head. To perceive direction in the vertical plane, the head has to be moved up and down.

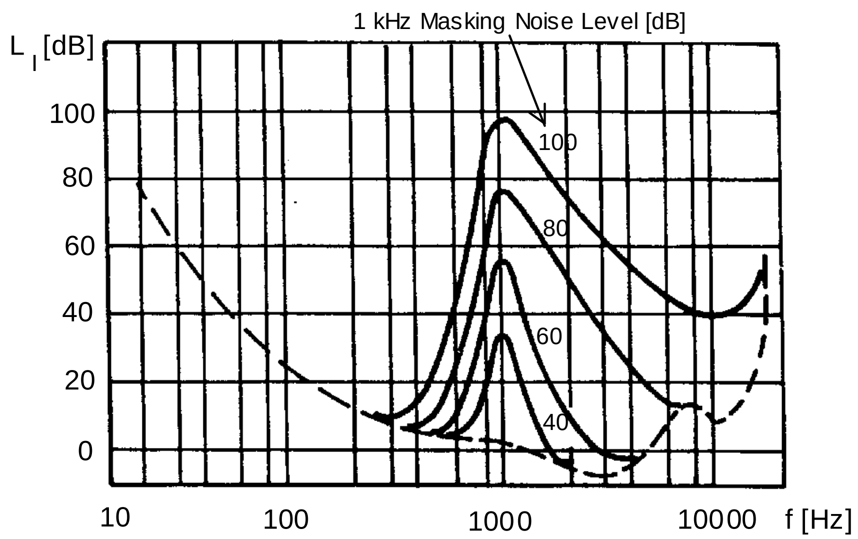

Figure 3.5. Masking

Control questions

1. How can sound be characterized physically?
2. What are the limits of hearing?

3. What are the psychophysical characteristic of the sound?

Exercises

1. How many dB is the sound pressure level of 1 Pa?
2. What are the loudness values of sinusoidal sounds of frequencies 110, 200 and 2000 Hz, if their intensity is 60 dB?
3. Determine the entire loudness of the previous three sounds!

References

[1] Valkó I. Péter: Az elektroakusztika alapjai. Akadémiai kiadó. 1963.
[2] Ivar Veit: Mûszaki akusztika. Mûszaki Könyvkiadó. 1977.
[3] Tarnóczy Tamás: Teremakusztika I. Akadémiai Kiadó. 1986.