Sound, People and Buildings

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Introduction

Sound, according to physicists, is wave motion in an elastic medium (solid, liquid or gas); sound, according to animals with ears, is that which is heard; unwanted sound is noise. The purpose of this note is to sketch the properties of these three manifestations of sound, with particular attention to the properties relevant to the design and functioning of buildings. Little will be said, however, about buildings; attention will be focussed, rather, on the effects of sound on the inhabitants of buildings.

In this context it is the second and third manifestations of sound - the subjective impressions - that are of primary concern. But the complicated physiological and psychological processes thus involved are difficult to analyse and measure, and there is a tendency to replace subjective problems with physical approximations that employ purely physical measurements. The significance of these approximations will form an important part of the discussion. Another incidental objective will be to give precise meaning to the more common acoustical terms.

Physical Properties of Sound

Though most real sounds are rather complex, the basic theory is built around the concept of a simple disturbance that might be termed a "pure tone." If the pure tone is a sound wave in air it takes the form of a small sinusoidal fluctuation superimposed on the steady atmospheric pressure. A graph depicting such a sound wave is shown in Figure 1. It is characterized by its *amplitude* and by the *frequency* of fluctuations (usually in cycles per second [Hz]). The inverse of the frequency, the time for one cycle, is termed the *period*.

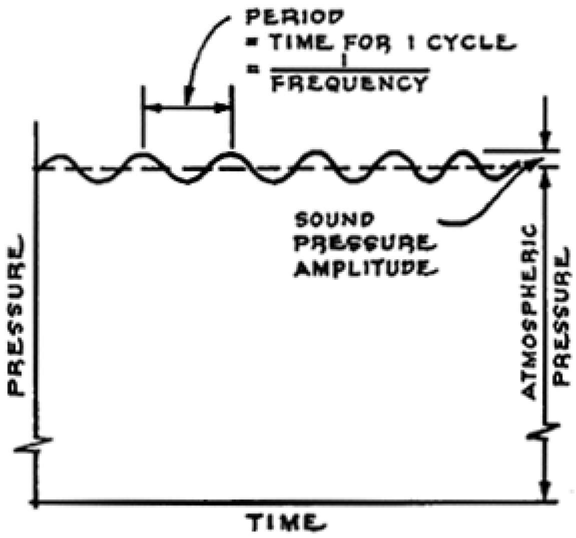

Figure 1. Pure sinusoidal wave in air.

Successive crests of a pure sinusoidal wave will travel a *wavelength*, apart in space, at a speed known as the *speed of propagation* or the *speed of sound*. It may readily be seen that the wavelength λ, the frequency f, and the speed of propagation v are related by the expression $v = f\,\lambda$. The speed of sound in air is about 350 metres per second. Wavelengths ranging from about a few millimetres to about 20 metres are of interest in acoustics. This wide range of wavelengths, encompassing the dimensions of people and most of their surroundings, does not lend itself to any of the simplifying assumptions of wave theory; although the simple principles of geometrical optics are of some help in dealing with high frequency (short wavelength) sounds.

Any complex sound may be completely described as the combination of a number of pure tones of various amplitudes, frequencies and phases relative to each other. Some musical tones (e.g. the flute) contain only a few components, for which the frequencies and phases have definite, simple relations. More complex sounds contain many components, which may not be systematically related in frequency and phase. The ultimate complexity is "white noise," a randomly constituted disturbance that contains all frequencies; the sound from a water-spray or a jet of air is an approximation of white noise. A simple sound may be described in terms of its pure-tone spectrum, i.e. in terms of its actual pure-tone components. A complex sound is usually described in terms of its "band spectrum," i.e. the distribution of sound pressures in a series of contiguous frequency bands (usually octaves, half-octaves, or one-third octaves).

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The decibel scale.

The decibel scale, which is almost universally used for describing the magnitudes of sounds, is derived from the way in which humans react to sounds. Roughly speaking, a given *ratio* of sound pressures produces the same subjective sensation of change regardless of absolute sound pressures, i.e., an increase of sound pressure amplitude from 1 to 2 microbars produces the same impression of change as an increase from 0.01 to 0.02 microbar. For this reason the procedure used for scaling sounds is based on ratios rather than on absolute sound pressures.

The arithmetic of acoustics and electro-acoustics is facilitated by using not merely ratios but logarithms of ratios, so that the process of multiplication or division of ratios is converted to the addition or subtraction of logarithms. This utilizes the property of logarithms

that $\log (ab) = \log a + \log b$ and $\log (a/b) = \log a - \log b$.

Finally the decibel scale emerges: *the sound pressure level*, in decibels, corresponding to a sound pressure P is given by

$$20 \log (P/P_o)$$

where P_o is the standard reference pressure of 0.0002 microbar (approximately the minimum level of audible sound).

It follows from the properties of logarithms that the difference in sound level between two sound pressures P_1 and P_2 becomes

$$20 \log (P_1/P_o) - 20 \log (P_2/P_o) = 20 \log (P_1/P_2).$$

The first term in this equation might, for example, represent the sound pressure level in a room containing a sound source, and the second term might be the resulting level in an adjacent room; then the right hand member would represent the sound reduction (in decibels) provided by the separating wall.

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A few concrete examples may further illustrate the use of the decibel scale: two equal sound pressures differ in level by 0 dB; a factor of two in sound pressure is equivalent to 6 dB; a factor of 10 in pressure is 20 dB. One decibel is approximately the minimum change in a pure 1000-cycle tone that can be detected subjectively under laboratory conditions; more generally, the minimum detectable change in complex sounds under ordinary listening conditions is about 3 dB.

Thus far it has been implied that sound consists of continuous steady tones. On the contrary, such important categories as speech and music consist largely of transient sounds lasting a small fraction of a second. The proper perception of such sounds requires that they retain their characteristic shape until they reach the listener. In speech, for example, the chief contribution of consonants is to the shape of beginnings and endings of the adjacent vowels. This is an important consideration in the design of large rooms, where the listener receives the direct sound plus a series of slightly delayed reflections.

Subjective Properties of Sound

Only a portion of what the physicist terms sound can be heard by humans. Figure 2 shows the range of sound levels and frequencies that can be perceived. The lowest contour represents the *threshold of audibility*, i.e., the lowest level of sound that can be heard. It will be noted that the ear is most sensitive in the frequency range 1000 to 2000 cycles per second [Hz], where the minimum level is approximately 0 dB. Perhaps not coincidentally, this is also the frequency range most important for speech communication.

The highest contour, approximately 130 dB, is the *threshold of pain*, at which sound ceases to be heard and becomes a tickling or painful sensation. The range of frequencies perceived as sound extends from about 18 to 18000 cycles per second [Hz]. Continuous exposure to a sound pressure level higher than 80 to 90 dB, may ultimately produce permanent impairment of hearing. This is an occupational hazard in many industrial plants.

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The subjective quantity corresponding to the sound pressure level is the *loudness level* in *phons*. The decibel and phon scales correspond for 1000-cycle pure tones, and the relationship for pure tones at other frequencies is shown by the "equal-loudness" contours of Figure 2. For a complex sound the sensation of loudness is dependent in a very complicated way on the frequency components it contains the subjective impression of pitch is closely related to frequency for a pure tone, but is again very complicated for more complex sounds.

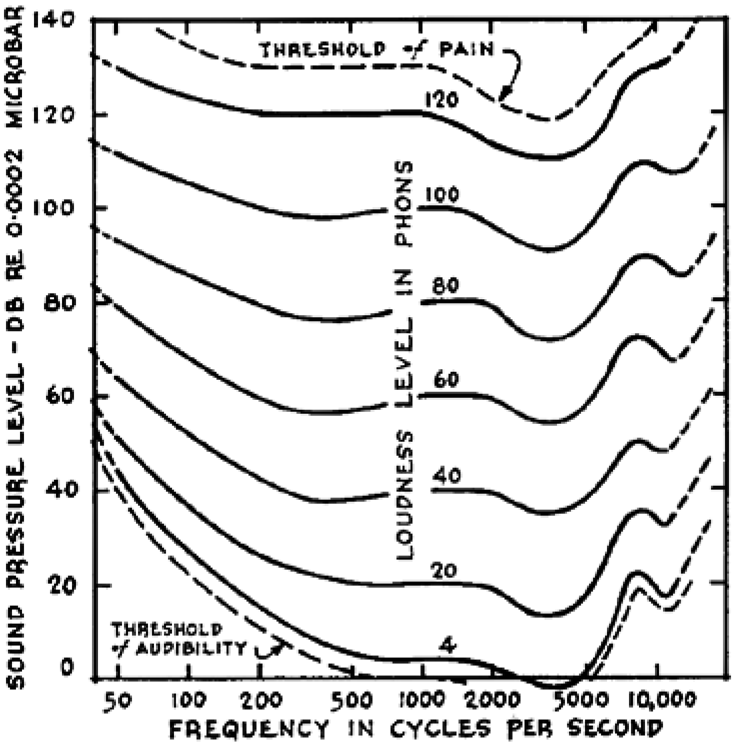

Figure 2. Range of sound levels and frequencies perceived by humans. The curves are equal-loudness contours for pure tones.

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It is usual to describe complex sounds by one of various physical approximations to the subjective impression. The simplest is provided by the A, B and C weighting networks on an ordinary sound level meter. The three networks vary the sensitivity of the meter with frequency in approximately the same way as, the ear sensitivity varies, following the 40-, 70 and 100-phon equal-loudness curves, respectively (see Figure 2). For pure sounds or sounds containing a reasonably uniform distribution of frequencies the use of the correct network provides an approximate measure of loudness level. The technique, though simple, has several limitations of which the most obvious is that to obtain a meaningful measure of the loudness level one must know which network to use, and this in turn depends on the loudness level. Because of these problems it is customary to refer to all measurements made with the sound level meter simply as *sound levels*. The unqualified term means C-scale measurements, which are approximately equivalent to sound pressure levels.

The A network, which emphasizes the speech range, is also used widely as a measure of the loudness of speech or, alternatively, the loudness of noise that might mask speech. By extension, it is sometimes used as a measure of the noisiness or annoying effect of sound.

A more sophisticated way of analysing a complex sound is first to determine its band spectrum level and then to calculate one of the several parameters that have been identified with subjective reactions to sound. Of these the most important is the loudness level. About a dozen procedures have, over the years, been developed for calculating loudness; the two currently accepted methods provide good approximations of subjective loudness ratings for most complex sounds. Their greatest weakness is in dealing with sounds that have strong pure-tone components in combination with a uniform spectrum.

It is an interesting point of semantics that the subjective rating of "noisiness" is different from "loudness," noisiness being more strongly dependent on high frequency sounds than loudness. A procedure similar to the loudness calculation, but giving more weight to high frequencies, has been developed for calculating the *perceived noise level*, expressed in PNdB.

Another procedure is to compare the band spectrum with a family of standard noise curves known as *noise criteria* (NC curves). These were developed primarily to assess the problem of speech communication in noisy environments. Figure 3 shows the family of NC curves and their effect on speech communication. The method of comparing a given spectrum with the NC curves is not carefully defined. A conservative procedure would be to choose the NC curve that lies on or above the given spectrum in each band, but minor overlaps are usually tolerated except in the bands important to speech. Since the frequency range of importance in speech is also the most sensitive range for the ear, the NC ratings are sometimes used as a rough measure of loudness, or noisiness.

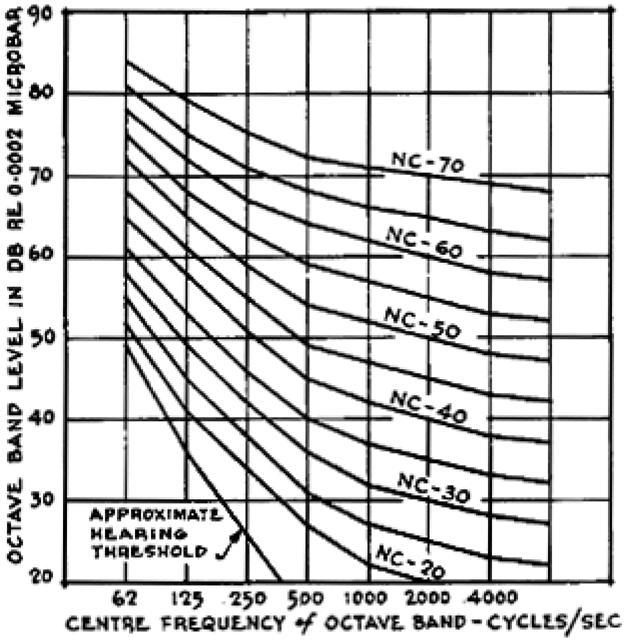

Figure 3. Noise criteria and office communication.

NC Curve	Communication application
20-30	Very quiet, suitable for large conference rooms
30-35	Communication in normal voice at 3 to 10 metres
35-40	Communication in normal voice at 2 to 4 metres
40-50	Communication in raised voice at 2 to 4 metres
50-55	Communication in raised voice at 1 to 2 metres

Basic Properties of Noise

Finally, it is necessary to come to grips with the distinctions between sound and noise. Any sound within the region of perception may in some circumstances be noise. The upper levels may be precisely assessed in terms

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of pain, impairment of hearing or interference with speech communication. This leaves the vague, indefinable, but nonetheless important category of annoying or disturbing sounds.

Few sounds are intrinsically unpleasant. They become so if they intrude sufficiently on a listener's consciousness to distract him from his own pursuits. The listener must first be able to hear the intruding noise above the other ambient noises in his own environment. In addition, it must attract his reluctant attention. This requires that the sound have some special character, usually denoting a specific activity. Speech sounds are particularly troublesome if they are intelligible or nearly so. Sudden impacts, startling or alarming sounds, and sounds with marked pitch or rhythm (even, for example, a dripping faucet) are particularly distracting and therefore annoying. Similarly, a single identifiable source of noise is more troublesome than the same level produced by a random assortment of many noises from many sources.

Sounds that are suitably random and meaningless sometimes serve the useful function of masking other sounds that would be distracting. The most acceptable form a masking sound can take is white noise, perhaps suitably tailored to mask a particular intruding sound. More commonly, there are residual sounds such as ventilating and air-conditioning noises that in this way justify their existence. The widespread use of background music in restaurants and other public areas is an example of the use of meaningless noise to protect people from their neighbours. Unfortunately, some of the purveyors of background music misunderstand its function and use a collection of musical cliches that is itself annoying.

The level of masking noise must be adjusted very carefully. To fulfil its masking function it should equal or exceed the level of the intruding noise in each octave band (better, in each third-octave band). On the other hand, it must not be so high that it interferes with the occupant's normal activities. In offices the upper limit is usually set by the communication requirements (using perhaps the NC curves discussed earlier). In dwellings the problem is made more difficult by the wide range of desirable activities and desirable sound conditions, from very noisy to very quiet. In the latter case the best that can be said for masking noise is that it is a lesser evil than noise from neighbours.

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Sound in Buildings

In previous sections the problems of architectural acoustics have been hinted at in the course of a fairly abstract examination of sound and its effects on people. At this point, still with no attempt to delineate all the acoustical problems, a brief look will be taken at the propagation of sound in buildings.

In unconfined space sound travels radially from the source, diminishing by 6 dB for each doubling of distance from the source. If the source is contained in a room the sound at any point consists of the direct sound plus an infinite sequence of reflections from the room boundaries. The level due to these reflections, which constitute what is known as reverberant sound, depends on the nature of the boundaries and furnishings in the room: if they are made of materials that absorb most of the sound that reaches them the reverberant sound level may be low. Such absorption treatment is appropriate in rooms such as general offices and restaurants, which contain many unrelated noise sources. On the other hand conference rooms and auditoriums intended for the propagation of one particular sound to many listeners must be designed so that most of the original sound is distributed usefully to all parts of the room. In this case little absorbing material is used, because the reflected sound is needed to reinforce the direct sound.

Of the sound that reaches the boundaries of the source room a small fraction is transmitted into and through the structure to the adjoining parts of the building. This transmitted sound constitutes a major nuisance in such occupancies as apartment buildings.

Thus the nature of the sound within a building depends very much on the nature of the building: specifically, on the degree to which sound is reflected from, transmitted through, or absorbed by the various boundary and separating surfaces.

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