ACOUSTICS IN THE BUILT ENVIRONMENT

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Contents

Summary

The following discourse takes the reader through the basics of sound, the assessment of physical outdoor noise, to its final impact on the indoor acoustic environment. In the process details and formulations are presented which allow the reader to assess relevant problems and their degree of difficulty. References, both hard copy and internet based will allow the reader to develop further in their topic of interest.

1. Introduction

Acoustics (n, pl), A science that deals with the generation, transmission, reception, effect and control of sound.

Within the built environment the ultimate receptor of interest is the human while the measurement devices are typically electronic instruments from which one may measure directly or infer time related acoustic energy, thus of main concern are objective measures of subjective response. We begin however with an over view of basics.

1.1 Equal Loudness Level Phon and (A) and (C) Weighting

Frequencies associated with human hearing are about 20 Hz, (below which acoustic energy tends to be felt rather than heard), up to about 20 kHz,(above which the average human hearing mechanism is very inefficient).

Energy levels of interest range from “ The threshold of hearing 0dB” (energies just able to excite a good hearing mechanism) to “ The threshold of pain, 120 dB” (energies which induce a reaction of pain rather than hearing).

The human hearing mechanism responds differently to different frequencies when played continuously. Lines of equal perceived sound energy for pure tone frequencies are referred to as lines of equal Phon [1]. The Phon level is defined by a continuous reference sound level at 1 kHz at which a good hearing subject perceives a sound at other frequencies to be of equal loudness and a set of " Equal-loudness contours i.e. equal Phon" are developed.

Instrument weighting networks are constructed to mimic wide band lower Phon levels, (A), wide band medium Phon levels, (B), and wide band higher Phon levels, (C). In practice it has been found that measures employing the (A) level-weighting (based on the 40 Phon contour), correlate sufficiently well with subjective response that it is now adopted for many objective measures over all Phon levels and for many time varying noises for which statistic metrics are employed. The C weighting is sometimes incorporated into instruments as an approximation to Linear weighting at mid to higher frequencies. If a comparison between an A scale and C scale reading indicates a higher C scale value then it may be inferred that lower frequency energies are dominant.

1.2 The dB

The energy level at the Threshold of Pain is between twelve and fourteen million times that of the Threshold of Hearing so that for convenience acoustic measures are made by taking ten times the logarithmic ratio to base ten of the given energy level to the energy level at the Threshold of Hearing. Many measurement devices employ a single pressure-sensing microphone and an International reference pressure P_o of $2x10^{-5}$ pascals is prescribed.

For a number of wave types, the relationship between I and P^2 root mean square (rms) is

$$I = \rho_0 C_0 P_{rms}{}^2 \qquad (1)$$

where I is the Intensity W/m^2
ρ_0 is the density of air kg/m^3
Co is the velocity of sound in air m/s
In addition

$$Lp = 20\log_{10}\left(P/P_0\right).dB \qquad (2)$$

where P is the root mean square of the signal (Pascal)
Po is the reference pressure $2x\ 10^{-5}$(Pascal)
and Lp is The Sound Pressure Level

When an (A) scale weighting is introduced, the measure becomes dB (A)

1.3 The Sone

Complex sounds containing many frequencies at differing Phon levels cannot immediately be assessed for Loudness. For example an increase of 10 Phons at one discrete frequency compared to another is judged by many listeners to be a doubling of Loudness. A concept of relative loudness has been developed, one Sone is defined as the loudness experienced by a typical listener when listening to a tone of 1 kHz and a sound pressure level yielding 40 Phon. Levels relative to this standard are then judged as multiples of the 40 Phon reference. Then analogous subjective equal loudness contours are evolved for bands of noise and finally knowing the loudness to bandwidth, levels in one bandwidth may be added to the next to achieve an overall Sone level. The overall Sone Level may then be compared to a level achieved for another complex sound, typically suggesting which noise source warrants prioritized attention [2].

1.4 Bandwidths of sound, octave and third octave

Complex sounds typically contain many frequencies of interest and it is desirable to package their energies into a fewer number of convenient frequency bandwidths; the most common for subjective assessment purposes is the Octave bandwidth. An Octave bandwidth is defined by the relationship

$$f_c \times 2^{-\frac{1}{2}} < f_c < f_c \times 2^{\frac{1}{2}} \qquad (3)$$

where by international agreement the center frequencies f_c are:
31.5Hz , 63Hz, 125Hz, 250 Hz, 500 Hz, 1kHz, 2kHz, 4kHz, 8kHz and 16 kHz.

A narrower bandwidth is typical for engineering purposes and the Third Octave is usually chosen.

The Third Octave Bandwidths are defined by the relationship

$$f_c \times 2^{-\frac{1}{6}} < f_c < f_c \times 2^{\frac{1}{6}} \qquad (4)$$

Where by international agreement the center frequencies f_c are:
25 Hz, 31.5 Hz, 40 Hz, 50 Hz, 63 Hz, 80 Hz, 125 Hz, 160 Hz, 200 Hz, 250 Hz, 315 Hz, 400 Hz, 500 Hz, 630 Hz, 800 Hz, 1 kHz, 1.25 kHz, 1.6 kHz, 2 kHz, 2.5 kHz, 3.15 kHz, 4 kHz, 5 kHz, 6.3 kHz, 8 kHz, 10 kHz, 12.5 kHz, 16 kHz and 20 kHz.

Instruments capable of narrower bands of measurement, to fractional frequencies exist.

1.5 Addition , subtraction and average of dB

dB addition or subtraction of two sound pressure levels is achieved via:

Sound Pressure Level (addition)

$$L_P = 10\log_{10}\left(\left\{P_1^{\,2} + P_2^{\,2}\right\} \big/ P_0^{\,2}\right) \qquad (5)$$

Sound Pressure Level (subtraction)

$$L_P = 10\log_{10}\left(\left\{P_1^{\,2} - P_2^{\,2}\right\}\Big/ P_0^{\,2}\right) \tag{6}$$

Where $P_1 > P_2$.

Expressed in terms of Sound Pressure Levels throughout,

Sound Pressure Level (addition)

$$L_P = 10\log_{10}\left(10^{\frac{L_{P_1}}{10}} + 10^{\frac{L_{P_2}}{10}}\right) \tag{7}$$

Sound Pressure Level (subtraction)

$$. \ L_P = 10\log_{10}\left(10^{\frac{L_{P_1}}{10}} - 10^{\frac{L_{P_2}}{10}}\right) \tag{8}$$

Where $Lp_1 > Lp_2$

The relationships above show that a sound pressure level added to another of equal magnitude yields a 3dB increase and a difference of 10 dB or greater between two levels causes a negligible change to the higher level.

The average of dB is the average energy related content i.e.

$$L_{P_{avg}} = 10\log_{10}\frac{1}{N}\sum_{i=1}^{N}10^{L_{P_i}/10} \tag{9}$$

See reference [3], “ Working in dB”.

2. External Propagation

Several factors affect the propagation of sound in the atmosphere. If the dimension of the source is small with respect to the distance of the receiver then the source appears as a point and sound intensity decreases as the square of the radius i.e. 6dB decrease for doubling of distance. If the source appears as a line e.g. a line of vehicles, then intensity dispersion as a function of radius occurs, i.e. 3dB decrease for doubling of distance. As the distance from the source increases, the line source tends to a point. Also as distance to the source increases, atmospheric absorption becomes important.

2.1 Atmospheric absorption and dispersion

Atmospheric absorption and dispersion is a complicated function of relative humidity or precipitation, air density (temperature) and frequency, higher frequencies being most affected, see reference [4].

The terrain over which the sound travels also influences the intensity loss with distance with respect to a surface source and receiver. For example propagation over a lined surface e.g. concrete, exhibits less attenuation with distance than propagation over grass or snow, through trees or bushes. Each of these features is also a complex function of frequency and ground type.

Weather conditions will also influence propagation. Wind will effect the propagation by causing more energy to flow downwind than upwind. Over varying ground surfaces the wind increases as a power law with respect to height and surface type, thus a shadow zone upwind with a reinforcement downwind often occurs; thus for outdoor measurement it is better to measure down wind, as a worst case occurrence.

Temperature gradients in the atmosphere can also influence the propagation of sound causing a shadow effect some distance away from the source when a normal temperature decrease with height is encountered.

However, in the event of a temperature inversion, i.e. temperature increase over a limited height within the vicinity of the earth's surface, sound reinforcement, typically at distances greater than one kilometer can be encountered.

2.2 Velocity of sound with temperature

The velocity of sound varies with temperature approximately in accordance with the relationship:

$$C = C_0 (1 + T/273)^{1/2} \qquad (10)$$

where C is the velocity of sound m/s

Co is the velocity of sound at O ^{o}C [approx. 331.6 m/s]

T is the absolute temperature deg. K

When measuring the sound pressure level a correction with respect to atmospheric pressure is required particularly at low or high atmospheric pressures; the correction is 20 log (Pa/Po), where Pa is the actual barometric pressure and Po is the normally assumed value, 1013 mbar.

It is good practice during measurement to record both atmospheric temperature and barometric pressure.

2.3 Barriers

Barriers are intentional or accidental partitions interposed between the source and receiver. In the simplest effect they cause an elongation of the source to receiver path thus introducing an artificial diminution with distance; they also create a shadow zone particularly at high frequencies in their immediate receiver side vicinity. A typical intentional barrier is a solid fence, brick, concrete or metallic wall; earth burms are also used to good effect, particularly if in addition trees or bushes are planted on them. The maximum attenuation realized by barriers is typically about 15 dB so that the mass of the barrier need not be chosen as dense, a direct transmission loss of about 25 dB being sufficient for the construction [5].

The effect of barriers is frequency dependent, with marked shadow zones being evident at high frequencies. At low frequencies for which the barrier height or width is similar to the wavelength of sound, little attenuation effect is realized.

3. Community Sources of Sound

Community noise [6] is recognized as a major cause of disturbance, having influence on communication, hearing loss, annoyance response, and effects on sleep and general social behavior. Many outdoor noise types typically transportation, construction noise or the noise of general human activity assault the built environment to cause disturbance, while with occupational noise we are generally concerned with the prospect of causing hearing loss.

Transportation noises, road traffic, trains or aircraft, requires the assessment of a time variant signal hence some form of statistical analysis. In all cases a time variant dB (A) measure is considered and measures of average energy, background and peak approximation is determined.

3.1 L_{Aeq}, (T), Ln and Ldn

The time average level of energy for a series of discrete samples is defined as: -

$$LA_{eq}, T = 10\log_{10}\frac{1}{N}\sum_{i=1}^{N}10^{L_{Pi}(A)/10} \qquad (11)$$

Where N is the number of discrete samples separated by a small time interval DT, and NxDT = T.

That is, the height of the equivalent rectangle having the same area as the time variant signal, Lp (A), over the time T. Time periods may be divided between day and night i.e. LAeq, 15hrs between the hours 07 00 and 2200 hrs, and LAeq, 9hrs between the times 2200 to 0700 hrs. For discrete sampling devices, the time interval of samples typically should not exceed 15 minutes. The maximum value of Aeq, 15hrs, LAeq, 9hrs and a peak value LAeq, 1hr occurring between those intervals would then be proscribed for standards dealing with roads or intended roads of stipulated type [7].

Statistical measures also applicable to road traffic noise assessment is the dB (A) measure exceeded for 10, 50, and 90 percent of the time, referred to respectively as L_{10}, L_{50}, and L_{90}. L_{90} is often taken as a measure of the background noise and L_{10} taken as a measure of the peak noise values.

A day/night level Ldn is often employed to register a worse situation during nighttime for given sound pressure level. This measure is defined as:

$$L_{dn} = 10\log_{10}\left(\frac{1}{T}\int_{0}^{T} w(t)10^{L_A(t)/10}dt\right) \qquad (12)$$

Where w(t) = 1 during the period 7am to 10 pm
and w(t) = 10 during the period 10 pm to 7am

3.2 Road traffic, Railway and Aircraft Noise

Models exist to predict the sound pressure level LAeq at distances from roads given the traffic flow rate, the speed of vehicles, the proportion of heavy vehicles, the nature and path of the road, and the overland propagation surface including barriers. Variations in traffic speed as might arise due to traffic lights could also be accommodated. Ref. [8] describes a simple predictive model.

Railway noise depends primarily on the speed of the train, number and type of power units, wagons [9], gradients and rails. The measurement of Impact sounds within the vicinity of stations or marshalling yards need also to be considered. High-speed trains are in a special category when traveling at high speeds where they more closely relate to low flying aircraft.

Aircraft noise assessment, particularly about airports depends upon the aircraft types, numbers of take offs and landings, the proscribed flight paths, time of day and environmental conditions. Methods in aircraft noise assessment are presented in reference [10].

3.3 Occupational noise exposure

In occupational noise exposure of primary concern is the avoidance of noise levels which may cause hearing damage over the short or long term. Predictions are usually based upon the equal energy hypothesis, that is, equal amounts of sound energy above a certain level will produce equal amounts of hearing impairment, regardless of how the sound energy is distributed in time.

The base level recommended for tolerable noise exposure for an eight hour time weighted average is 85 dB(A) with a 3 dB(A) exchange rate for each halving of time from eight hours, that is:

$$T = 480/(2^{[L-85]/3}) \qquad (13)$$

Where T is exposure time in minutes
L is level dB(A), L> 85 dB(A)

Noise dose meters are available to assess time varying levels of sound, where the "Dose" yields the actual exposure relative to the allowable exposure, and for which 100% and above represents exposures that are hazardous. The noise dose is calculated according to the formula:-

$$D = [C1/T1 + C2/T2 + \ldots + Cn/Tn].100 \qquad (14)$$

Where Cn = Total time of exposure at a specified noise level
and Tn = exposure time at which noise for this level becomes hazardous

For workers whose noise exposures equal or exceed 85 dB(A), the National Institute for Occupational Safety and Health (NIOSH) [11] recommends a hearing loss prevention program that includes exposure assessment, engineering and administrative controls, proper use of hearing protectors, audiometric evaluations, education and motivation, record keeping, and program audits and evaluations.

3.4 Ear protection

Ear protection can be employed to ameliorate exposure to otherwise hazardous levels. The U.S. Environmental Protection Agency requires that a laboratory derived rating, the noise reduction rating (NRR) be affixed as a label to each hearing protector sold in the United States. NIOSH recommends that the NRR be " derated" by subtracting from the NRR 25%, 50% and 75% for earmuffs, formable earplugs, and all other earplugs, respectively. An "Effective Noise Level" is then established by subtracting derated NRR from C-weighted noise exposure levels, or subtracting derated NNR minus 7dB from A-weighted noise exposure levels.

4. Noise Intrusion

4.1 Noise intrusion at the façade

External sound impacts the façade of a building, causing it to vibrate and act as a sound source to the inner building. An estimate of the sound energy transmitted by this mechanism can be made if the Sound Reduction Index (R) of the façade is known or if a field measurement is taken [12]. R is the ratio of Energy incident on the source side surface W_1 to the energy propagated to the reception side surface W_2, expressed in dB. Predictions of the source side energy may be made employing predictive models or physical measures of the incident sound Pressure Level L_1. The sound pressure level at the façade may be assumed 3dB higher than free field source propagation because of a pressure doubling at the façade by way of a reflected wave.

4.2 Sound reduction index

The energy on the reception side is usually deduced in acknowledge of the Sound Pressure Level on the reception side L_2. The relationships between W_1, W_2 and L_1, L_2 yield:

$$R = L_1 - L_2 + 10\log_{10}(S/A) \qquad (15)$$

Where S is the area of the façade or panel in question, and A is the equivalent Sound Absorption Area in the Reception Room, in square meters, known as metric sabins.

With the advent of Intensity Measuring Devices, it is possible to measure W_2 directly by integration of the panel surface intensities, obtained either by scanning or by a point-to-point procedure [13]. This technique offers the prospect of avoiding flanking transmission and of detailing specific transmission paths.

4.3 The simple wall

A simple wall or façade is found to admit sound energy in four successive frequency

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NOTE: Web sites listed above are current at the time of writing. They can be exploited for numerous additional entries regarding noise, its effects, measurement and problem resolution.

Biographical Sketch

Dr. Richard Guy received a Master of Science degree in Acoustics from the Institute of Sound and Vibration Research, Southampton University, England (1971). He received his Ph.D. from the Acoustic Research Unit of Liverpool University, England, (1975). Since that time he has been working in the area of sound transmission in Buildings and the Surrounds. He has published extensively in learned journals and via conference presentations. His research continues at the Department of Building, Civil and Environmental Engineering of Concordia University, Montreal, Canada where he holds the position of full professor.