ACOUSTICS AND ACOUSTIC MEASUREMENTS

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Contents

Summary

The contents of this article is concentrated on the criteria for evaluating noise which are needed to assess the influence of the acoustic energy on a human being and his ambient environment. Criteria for evaluation of noise are founded on the measurements of the fundamental acoustic quantities as the sound level and the equivalent continuous sound level. There is a review and discussion of some of the most important and of the most modern instrumentation for noise and vibration measurements. A very important task for acoustics in new millennium is prediction of noise as a planning tool, and long-term noise control programme which is briefly outlined in the last section of this article.

1. Introduction

Sound and vibration touches all of us. It affects our environment. It affects the safety of our vehicles. It affects the construction of our buildings. In fact, when you stop to think about it, sound and vibration is a major parts of our daily lives: it is all around us, permeating every aspect of our everyday world. And most important of all, it affects our quality of life.

A human is exposed to noise during daytime and night-time hours. During the day the noise can interfere with various activities (e.g. communication, efficiency of work) and very intense noise can even lead to hearing damage, affect the human organism as well as have negative psychological effects. During the rest-time period noise can disorder comfort and affect sleep. If the noise is more intense, it is normally more annoying, although there are a number of other attitudinal and environmental factors too that affect annoyance (see Effects of Acoustic Waves on the Human Beings).

There are a large number of ways to measure and evaluate noise, each normally resulting in different noise measures, descriptors, or scales. The different measures and descriptors mainly result from the different sources and the different researches involved in producing them. From these measures and descriptors, criteria have been developed to decide on the acceptability of the noise levels for different activities. These criteria are useful in determining whether noise control efforts are warranted to improve speech communication, reduce annoyance, and lessen sleep interference.

This article chiefly describes descriptors and rating methods used in establishing criteria for outdoor, indoor and industry noise, presents some of the most important acoustic formulas without derivation which are used for rating criteria, presents effects of acoustic waves on the human being, introduces the needed acoustical measurements and instruments, and indicates means of noise control (see Criteria for Evaluation of Noise).

The aim of acoustic noise measurement is to provide objective physical measurements of noise which can be compared with predetermined criteria in order to judge its acceptability. In order to ensure the quality and uniformity of the results of the measurement and monitoring as far as possible, the equipment specification and the measurement procedures are subjected to national and international standards of various severity depending on the application. (see Instrumentation for Noise Measurement)

2. Basis of Sound

The following text shortly presents an overall picture of engineering fundamentals involved in the study of noise. It is intended to provide an introduction to the analysis of sound and to its control wherever noise may adversely affect working and living conditions, and the comfort and health of people in modern society.

2.1. Generation of Sound

Sound requires a source, a medium for transmission, and receiver. The source is simply an object which is caused to vibrate by some external energy source. The medium is the substance which carries the acoustic energy from a source to any place in space. In this discussion the medium will generally be air. Figure 1 illustrates the generation of acoustic waves in the air by the vibrating object, where the sound pressure variation is periodic, one complete variation in pressure being called a *cycle*. The time for one complete cycle is called the *period* (T) of pressure oscillation.

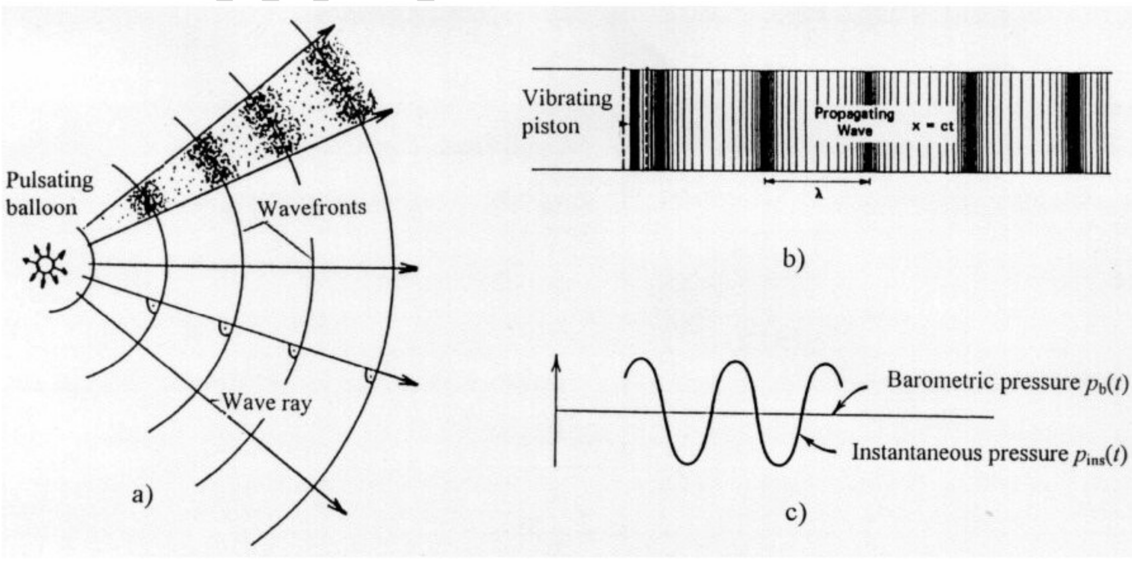

Figure 1. The generation of spherical sound waves (a), plane sound waves (b) and superimposition of the sound pressure to the barometric pressure (c)

The speed of elastic waves is related to two properties of the medium: elasticity and density. The speed, in meters per second, at which a sound wave travels through a media is the **speed of propagation**, *c*.

The distance between successive waves of the same sense is called the **wave-length** of sound in the medium and is usually denoted by λ, in meters, and is given by

$$\lambda = cT \tag{1}$$

The **frequency** *f*, in Hertz, is defined as the number of cycles per unit time, *T*, i.e.:

$$f = \frac{1}{T} \tag{2}$$

The **sound pressure** variation with time is given by the expression

$$p(t) = p_0 \sin(\omega t + \varphi) \tag{3a}$$

or with respect to barometric pressure $p_b(t)$ (see Figure 1)

$$p(t) = p_{ins}(t) - p_b(t) \tag{3b}$$

where

p_0 is amplitude of sound pressure fluctuation in Pa;
ω is frequency of sound pressure fluctuation in rad/sec;
φ is phase of the sound signal;
$p_{ins}(t)$ is instantaneous pressure.

In practical application is used r.m.s value of sound pressure which is given by the expression

$$p = p_{rms} = \sqrt{\frac{1}{T}\int_0^T p^2(t)\, dt} \tag{4}$$

If

$$y(t) = y_0 \cos\omega\left(t - \frac{x}{c}\right)$$

is the displacement of the particle in the medium, then the **particle velocity** (*acoustic velocity*) is given by the equation

$$v(t) = v_0 \sin\omega\left(t - \frac{x}{c}\right)$$

In practical application is used r.m.s value of the particle velocity, v.

In freely propagating sound waves, where the pressure and velocity reach simultaneous maximum, it is necessary to evaluate the conditions that relate sound pressure and particle velocity. The term **acoustic impedance** (characteristic impedance) is defined by analogy with electrical systems as

$$Z_a = \frac{p}{v} = \pm \rho\, c \tag{5}$$

2.2. Sound Intensity, Sound Power and Sound-Energy Density

The ***sound intensity***, I, is defined as the average rate of flow of sound energy (power) passing through a unit of area of the medium that is perpendicular to the direction of sound propagation per unit time, in watt per square meter (Figure 2). It is different for various types of acoustic field.

For a *free sound field* in which the sound wave arrives only from the direction of the source

$$I = \frac{p^2}{\rho\, c} \tag{6}$$

For a *diffuse sound field* in which there is equal probability of sound arriving from any direction, the net intensity is zero. However, the intensity of sound passing through a plane of unit area from one side only is

$$I = \frac{p^2}{4\rho\, c} \tag{7}$$

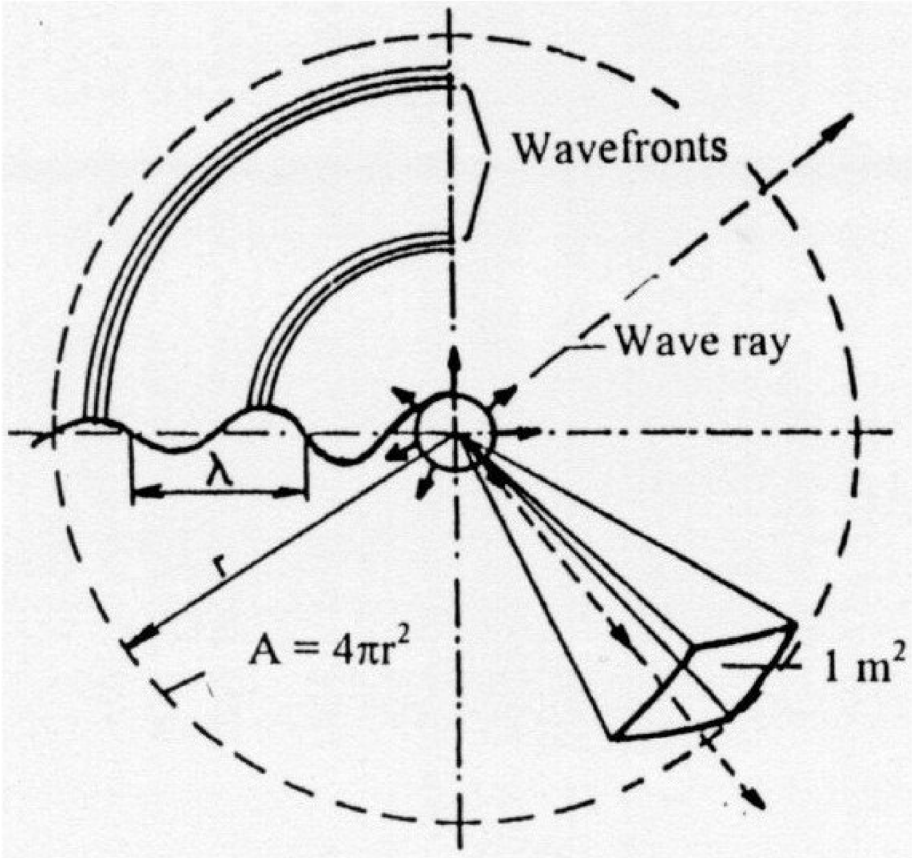

Figure 2. The flow of sound energy through an area of the medium.

Any source of noise has a characteristic sound power, a basic measure of its acoustic output. Sound power on the other hand is a fundamental physical property of the source alone, and is therefore an important absolute parameter which is widely used for rating and comparing sound sources. The ***sound power***, *W*, is defined as the average rate of flow of sound energy (power) passing through an area, *A*, of the medium that surrounds the source per unit time, in watts (Figure 2.).

$$W = IA = \frac{p^2}{\rho c} A \qquad (8)$$

The sound energy contained in a unit volume of the medium is a fundamental parameter of any type of acoustic field. ***Sound-energy density***, *w*, is energy stored in a small volume of medium, and is related to the acoustic pressure by the following expression

$$w = \frac{p^2}{\rho c^2} \qquad (9)$$

The unit is joule per cubic meter.

2.3. Frequency Spectra of Sound

An acoustic spectrum plot is a graphical display of the frequency characteristics of a sound. If a piston moves with simple harmonic motion a sine wave is produced (see Figure 1). Such disturbance is characterised by a single frequency (Figure 3a). If the piston moves irregularly but cyclically, so that is produces the wave-form shown in Figure 3b, the resulting sound field will consist of a combination of sinusoids of several frequencies. However, most sounds heard in everyday life contain a multitude of frequencies. Sounds such as the running of water from a tap, traffic noise, fan noise, jet noise, etc., contain a continuous spectrum of frequencies (Figure 3c). Such information is helpful in establishing the frequency distribution of sound energy. Spectrum analysis is also important to designers for avoiding harmful or annoying sounds that might otherwise be present in a finished product.

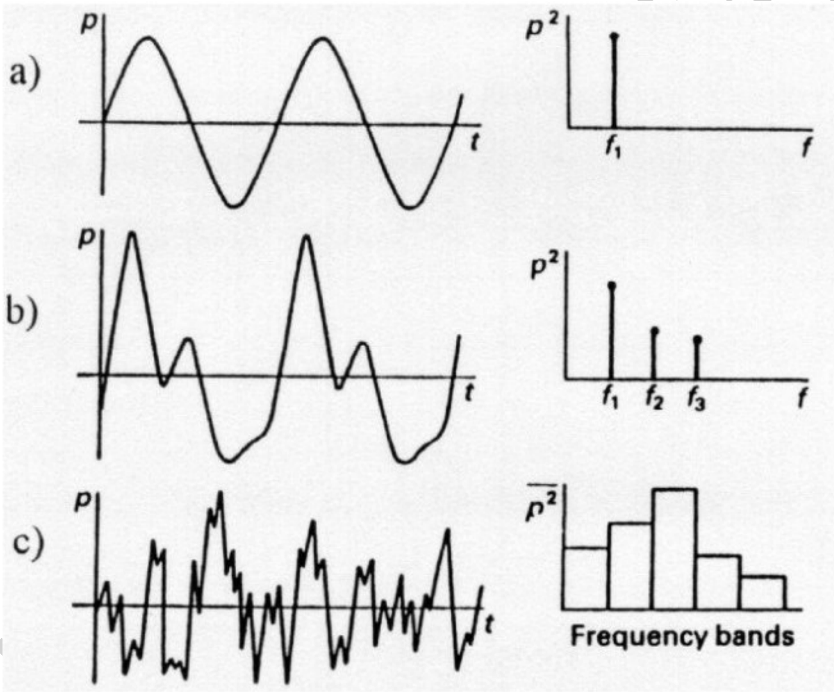

Figure 3. Sound signals and their spectra. a) pure sinusoid; b) combination of three sinusoids; c) random noise

2.4. Levels and Decibels

The sound pressure oscillation that ears of human beings are capable of hearing generally represent very small pressure variation about the atmospheric pressure. From hearing tests it has been agreed that the lowest audible pressure from 1000 Hz pure tone corresponds to 20 μPa. On the other hand, the pressure associated with the sensation of pain is approximately 200 Pa. For intensities range, it is approximately from 10^{-12} W/m^2 to 10 W/m^2, respectively. The range of the sound power outputs of a few regularly encountered noise sources are indicated in Figure 4. This demonstrates well the problems of magnitude and dynamic range which are always involved when making noise and acoustic measurements. The use of a logarithmic scale compresses the range of numbers required to describe this wide range of sound pressure (intensity). A second reason is that humans judge the relative loudness of two sounds by the ratio of their intensities, a logarithmic behaviour (Weber-Fechner physiological law). The argument of the logarithm is dimensionless, and the scale is said to give the level of the sound in decibels (no physical unit).

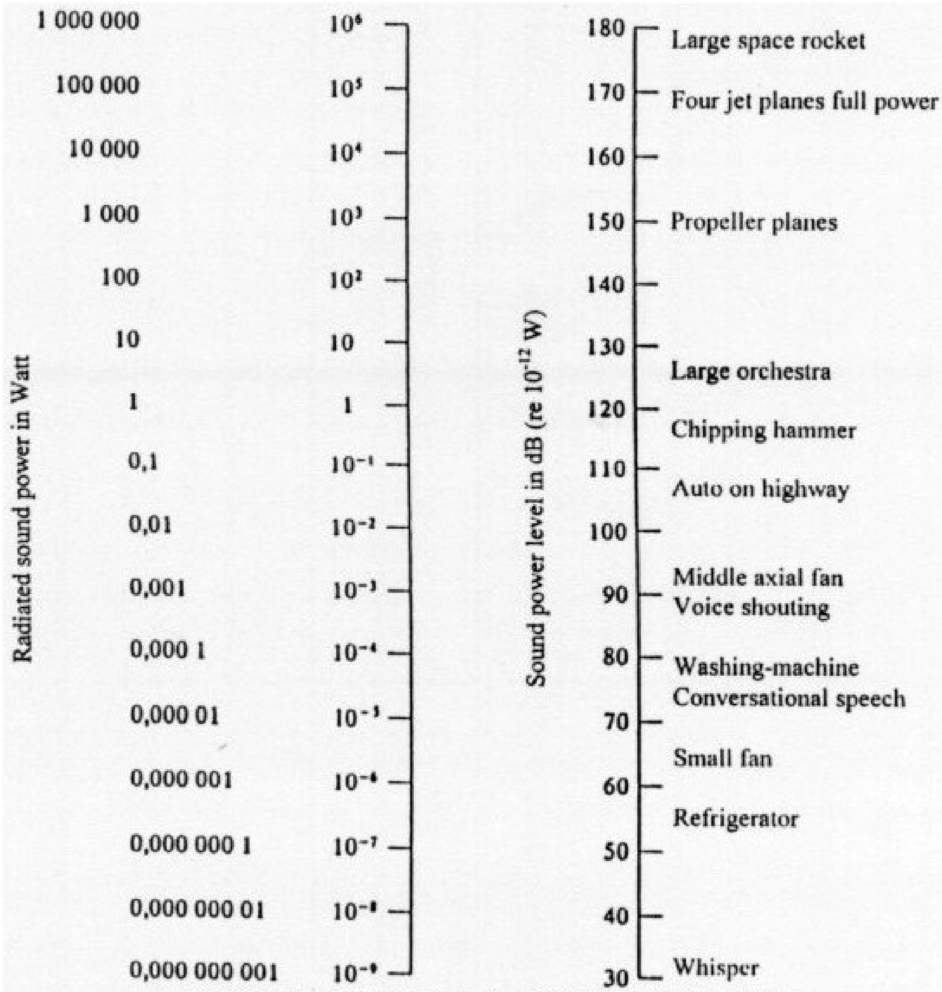

Figure 4. Sound power output of some typical noise sources.

The ***decibel*** of the quantity A relative to the reference quantity A_0 is defined as

$$L = 10 \log \frac{A}{A_0} \quad \text{dB re } A_0 \tag{10}$$

The decibel is used in environmental noise pollution as a measure of sound power level, sound intensity level and sound pressure level. Note that in each case the term level is synonymous with the decibel.

The ***sound power level***, L_W, is defined as

$$L_W = 10 \log \frac{W}{W_0} \quad \text{dB re } W_0 \tag{11}$$

where

W is the sound power in watts of a given source;
W_0 is the reference sound power, in accordance with international agreement is 10^{-12} W.

The **sound intensity level**, L_I, is defined as

$$L_I = 10 \log \frac{I}{I_0} \quad \text{dB re } L_0 \tag{12}$$

where

I is the sound intensity in watts per square meter in the given point of interest;
I_0 is the reference sound intensity, in accordance with international agreement is 10^{-12} W/m^2.

The ***sound pressure level***, L_p, is the most common level used in practice which is measured directly on a sound level meter. Since the acoustic pressure squared is proportional to the sound intensity (6) the sound pressure level is defined as

$$L_p = 10 \log \frac{p^2}{p_0^2} \quad \text{dB re } p_0 \tag{13}$$

where

p is the acoustic pressure at Pascal in the given point of interest;
p_0 is the reference acoustic pressure, in accordance with international agreement is $20\ \mu\text{Pa}$.

Relations among acoustic pressure, sound intensity and sound power given by equations (6) and (8) predetermine relations among sound pressure levels, sound intensity levels and sound power levels. Substituting expression (6) for the intensity term in equation (12) obtains

$$L_I = L_p - C_1 \tag{14}$$

where C_1 depends on the temperature and barometric pressure and for normal conditions (t = 20°C and p_b = 1013 hPa) is 0,128 dB. Thus for far field and free progressive waves the sound intensity level and the sound pressure level are, for all practical purposes, equal in magnitude to each other, i.e.

$$L_I = L_p \tag{15}$$

When the intensity is uniform over an area A, the sound power and sound intensity are related by expression (8). Since $W_0 = I_0 A_0$ where A_0 is a reference area of 1 m^2, (11) becomes

$$L_W = L_I + 10 \log A \tag{16a}$$

or in accordance with to (15)

$$L_W = L_p + 10 \log A \tag{16b}$$

From these relationships it is possible calculate the sound power level of a sound source emanating free progressive spherical waves if the sound intensity level or the sound pressure level is measured and if the surrounding surface of the source is known. This is the basis for one of the methods used to establish the sound power level of a source.

If the area A equals 1,0 m^2 then $L_W = L_p$.

2.5. Levels of Multiple Sound Sources

Often it is required to estimate the total sound pressure level from many sources when the sound pressure levels of each source is known. In general, the phases between sources of sound will be random and such sources are said to be incoherent. Incoherent sounds add together on a linear energy (sound pressure squared) basis. Thus the ***total sound pressure level***, L_T, for n incoherent sources is

$$L_T = 10 \log\left(\sum_{i=1}^{n} 10^{0,1 L_i}\right) \tag{17}$$

where

L_i is the sound pressure level of the individual sources.

2.6. Octave Band and Fractional-Octave Band Analysis

The human ear is sensitive to sound in the frequency range from approximately 16 Hz to 16 kHz. Since it is almost always impractical to measure the sound pressure level at each frequency in this range, the measurements are made over an interval of frequency which is called the bandwidth and is specified by an upper and lower frequency limit, f_{i+1} and f_i, respectively, called *cut-off frequencies*. In acoustics the frequency bandwidths are usually specified in terms of octaves and one-third-octaves. However, in special cases also the different fractional-octaves can be used. An ***octave*** is defined as an interval of frequency such that the upper frequency limit is twice the lower limit, that is $f_{i+1} = 2f_i$.

The general relationship between the upper and the lower cut-off frequencies is given by

$$f_{i+1} = 2^n f_i \tag{18}$$

where n is the number of octaves, either a fraction or integer. For example, n = 1/3 specifies one-third-octave bandwidth. The ***mid frequency*** f_c of n-octave band is the geometric mean of the frequency band given by

$$f_{ci} = \sqrt{f_{i+1} \cdot f_i} \tag{19}$$

The ***octave band*** sound pressure level in decibels represents a measure of the mean-squared pressure of the sounds within the particular frequency band. For the one-third-octave there are three times as many data points, which provides a finer filtering process of the sound. As already mentioned, the frequency on the abscissa axis is represented by a logarithmic scale. Also, as a matter of convention, the octave and fractional octave band decibel levels are plotted at the corresponding mid-frequency.

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Biographical Sketch

Stanislav Ziaran obtained the Dip.Eng, PhD and Assoc. Prof. degrees from the Slovak University of Technology - Mechanical Engineering Faculty of Bratislava in 1971, 1978 and 1988 respectively. He is working at the university in the department of Applied Mechanics as a lecturer. He is lecturing Statics, Dynamics, Noise and Vibration Control, Protection of Humans against Noise and Vibration. His thesis concerned studies of the noise control of a car engine. Half year he acted as a visitor student at the University of Southampton Institute of Sound and Vibration Research in England. He is the author and co-author of over 16 textbooks and monographs of theoretical mechanics, acoustics and mechanical vibration for students and also for practice and author and co-author of over 60 professional journal and conference papers. He has solved more than 40 sponsored research projects for the professional community. His current research interests include industrial and communal noise control, transmission of vibroacoustic energy through structures. Currently, he is Chairman of the Technical Committee Noise and Vibration of the Slovak Organization for Standardization and chairman of the Technical Committee for Noise and Vibration Control of the Acoustical Society of Slovakia.