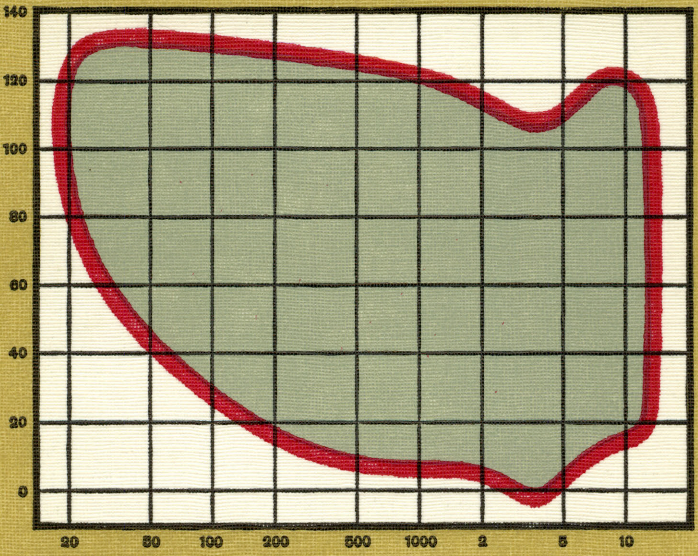

Application of B & K Equipment to

ACOUSTIC NOISE MEASUREMENTS

BRÜEL & KJÆR

The Application of the Brüel & Kjær Measuring Systems

to

ACOUSTIC NOISE MEASUREMENTS

by

Jens Trampe Broch

Dipl.ing. E.T.H.

July 1970

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ACOUSTIC NOISE MEASUREMENTS

Introduction.

Noise is often defined as *unwanted sound.* The degree of "unwantedness" is, however, a psychological question and may range from moderate annoyance to *various degrees of permanent hearing loss* and will, furthermore, be rated differently by different observers. It is therefore extremely difficult to answer the question: "What is gained by reducing this particular noise". However, it is generally recognized that the overall efficiency of human beings is considerably higher when they are performing their duties under satisfying and comfortable conditions than when they are constantly being "irritated" or annoyed by their surroundings. Also, a certain degree of environmental quietness is a desirable quality in itself. People in general do for instance, not like to live in the immediate vicinity of an airfield, of roads with heavy traffic or other more or less noisy places. The noise may thus in these cases affect the prices of the nearby land and bear considerable economic importance.

Furthermore, in choosing utility items, such as refrigerators, vacuum cleaners, washing machines, air conditioning systems, oil burners etc. the noiselessness of the items is definitely considered by the buyer. The control of noise is therefore important not only *from an annoyance and health point of view* but also *from an economic point of view.*

To be able to effectively control noise it is necessary that the noise be measured objectively, according to more or less internationally standardized procedures, and that the measured results are evaluated against predetermined criteria for acceptance. The intention of this booklet is to briefly describe some of the most important measurement methods and acceptance criteria in use today, and to aquaint the less experienced engineer with the use of Brüel & Kjær instruments for acoustic noise measurements. For a better understanding of the underlying principles it has, however, been deemed necessary in chapter 2 and 3 to review some physical aspects of sound signals as well as some fundamental psycho-acoustic facts about the hearing mechanism.

1. Précis.

In this précis it is intended to give a brief extract of the main subjects dealt with in the succeeding chapters. This should allow the more experienced noise measurement engineer to rapidly find the charts and data that he might need, and help the less experienced engineer to easily find the text that he would want to study a little closer.

Chapter 2 reviews briefly the basic characteristics of vibration and sound as related to acoustic noise measurements. It is stated that the origin of sound is mechanical vibration and that the propagation of such vibrations in elastic media takes the form of sound waves. Various quantities characterizing the magnitude of vibration (and thus sound) are defined, the most important of which is the RMS (root mean square) value because of its relation to the energy contents of the vibrations.

$$A_{RMS} = \sqrt{\frac{1}{T}\int_0^T a^2(t)\,dt}$$

Also the concepts of frequency and wavelength and their interrelation

$$\lambda = \frac{c}{f}$$

are discussed as well as the frequency composition of sound and noise in the form of frequency spectra. The statistical nature of noise is mentioned and the ability of the RMS value of the signal to remain an important descriptive quantity, even in this case, pointed out. Two "kinds" of sound waves, the plane sound wave and the free, progressive spherical wave are described and the important inverse-distance law for spherical waves derived:

$$p = (\text{const.})\,\frac{1}{r}$$

The types of sound fields most commonly encountered in noise measurement work are defined: The acoustic "near" field, the "far" field and the reverberant field, and an example of such fields produced by a noise source in a large "semi"-reverberant room given, Fig. 2.9. Mention is furthermore made of the most important condition necessary for an obstacle to produce sound reflections, i.e. that its physical dimensions should be of the order of magnitude of the sound wavelength or larger. Finally, numerical scales for noise measurements are discussed and it is shown that a direct measure of the sound pressure in terms of μbar (or N/m^2) is inconvenient, partly because of the wide dynamic range encountered in noise measurements and partly because the hearing mechanism reacts to relative quantities rather than to absolute quantities. Introduction is made to the decibel scale (dB scale) for sound pressure levels:

$$\text{S.P.L.} = 10\log\left(\frac{p^2}{p_o^2}\right) = 20\log\left(\frac{p}{p_o}\right)\text{dB}$$

and the reference sound pressure (p_o) of 0.0002 μbar (2×10^{-5} N/m^2) stated. This is the weakest sound perceived by the "average" person at 1000 Hz. Typical sound pressure levels encountered in practice are given in Fig. 2.10.

In Chapter 3 an outline of some of the known facts about the hearing mechanism and the human perception of sound is given. After a brief description of the functioning of the ear such psychoacoustical terms as loudness, loudness level, annoyance, and noisiness are "defined". Also, the concepts of critical frequency bands (Frequenz Gruppen) and the masking effect are discussed, as well as some aspects of the loudness of impulsive sounds. In section 3.6. various methods of loudness determination are described starting with the original, subjective method suggested by Barkhausen. The two internationally accepted methods of calculating loudness from measured sound pressure level data. suggested by E. Zwicker and S. S. Stevens respectively are also outlined, but a more detailed description of their use is delayed until Appendix C. Mention is furthermore made in section 3.7 of the PNdB concept often used in the description of aircraft noise.

Section 3.8 contains some internationally proposed noise control criteria based on so-called Noise Rating Numbers. The essence of this noise rating method may be extracted from Figs. 3.8 through 3.15, although for the less experienced engineer it might be advisable to study the complete text of this section specifically. It is concluded that noise with a noise rating number lower than N – 85 may well upset the speech intelligibility and cause annoyance, but only noise with a noise rating number higher than N – 85 might cause physiological hearing damage. The rating system also contains a method for evaluating intermittent noise exposures (Fig. 3.15).

Chapter 4 deals with various aspects of noise measurement instrumentation and measurement technique. It is stated that the "simplest" physical measure of a noise is its overall sound pressure level, but that such a measure would give little or no information as to the human perception of the noise. Even though a simple frequency weighting will not be sufficient, it might often, however, give an indication as to the noise perception, and commercially available sound level meters are therefore supplied with three internationally standardized weighting networks termed A, B and C. Measurements with these networks inserted should be reported in terms of sound level, dB (A), dB (B) and dB (C), respectively.

Also, it is pointed out that the result of a noise measurement in terms of dB (A) is often an approximate measure of the Noise Rating Number, N, discussed in chapter 3, section 3.8, – a relationship which is very convenient to apply in noise surveys. When a more thorough investigation of a noise problem has to be made the noise should be frequency analyzed.

In section 4.2 various kinds of noise measurement systems are outlined, starting with the battery-operated precision sound level meter and its octave filter set extension. Then follows a brief discussion on the use of mains operated amplifiers and analyzers, as well as read-out devices such as graphic level recorders, statistical distribution analyzers and analog voltage read-outs for analog-to-digital conversion of the measured results. The use of noise "monitoring" equipment of the noise limit exceedance type is also briefly described. Section 4.3 deals with the selection of a suitable measurement microphone. This choice may in some cases be rather complicated and to assist the reader the three charts given in Figs. 4.15, 4.16 and 4.17 have been prepared. It is concluded, however, that for general noise measurement purposes use should preferably be made of either the B & K Condenser Microphone Type 4131 or Type 4134. A wide range of microphone accessories extends the applicability of the microphones to various measurement situations.

A more detailed discussion on frequency analysis techniques, graphic level recording and statistical measurements as applied to noise problems is carried through in section 4.4, while section 4.5 deals with calibration of the equipment and performance checks. The latter is most readily made by means of the B & K Pistonphone Type 4220 which produces a very exact reference sound pressure level at the microphone diaphragm.

In section 4.6 influence of environmental effects, such as sound reflections and background noise, is described. It is found that when the noise field is diffuse the accuracy of the measured results will depend mainly upon the accuracy of the instrumentation used, while, if the noise contains one or two predominant frequencies, and the sound field consists of free, plane or spherical waves, serious measurement errors might be introduced due to reflections from the operator and measurement equipment. To take into account the effect of background noise when this is less than 10 dB below the noise being measured a correction curve is given in Fig. 4.36.

Section 4.7 gives an outline of the basic factors to be remembered when noise measurements are to be made, and it is recommended that this section is read in full. It is based upon the text of the preceding sections and is intended to serve as a reminder.

A particular problem, the treatment of which has been delayed until section 4.8, is that of signal storage and conversion i.e. the use of magnetic tape recording. After a brief discussion on which of the two main analog recording principles, F.M. and direct recording technique, that would be the most suitable one to use in a particular noise measurement situation the problem of absolute calibration of the tape is considered. It is pointed out that the B & K Pistonphone Type 4220 also in this case, provides an excellent acoustic reference signal. Also the possibilities of frequency and time transformations offered by speed changes in the tape transport system are described, and finally an example is shown of the analysis of transient noises by means of the tape loop technique.

Section 4.9 concludes the chapter with some remarks on analog-to-digital transformation of measurement data, and a method of transformation is mentioned which at the same time acts as a log converter (linear to logarithmic data conversion). In Chapter 5 some commonly experienced noise measurements are exemplified. The measurement techniques described are based on international standard recommendations and general noise control practice.

It has not been possible, however, within the scope of this booklet to go into detailed discussions on particular problems. Each section is, on the other hand, followed by a selected bibliography where a more thorough treatment of the subject can be found.
Finally, Chapter 6 summarizes various standards, available in different countries, which may be helpful in the solution of particular noise measurement problems. A closer study of this chapter is generally recommended.

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2. Some Physical Properties of Noise.

2.1. Characteristics of Vibration.

Acoustic *noise* is *sound* (even though unwanted) and sound is, physically speaking, *mechanical vibrations* in gaseous, fluid or solid media. Such vibrations are characterized by their *frequency* (or, as in the case of noise, frequencies) their *amplitude* and their *phase**).

As is outlined in the next chapter, not all mechanical vibrations can be perceived by the hearing mechanism of the human ear. Firstly, the vibrations have to be of a certain magnitude to be audible and secondly the frequency has to be within certain limits. Audible vibrations are found within a certain area, called hearing range. This area varies from person to person and will also depend on the person's age, possible hearing loss, physiological conditions etc.

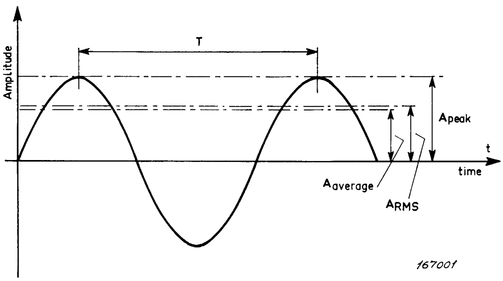

Fig. 2.1. Example of a sinusoidal vibration with indication of the peak, the RMS and the average absolute value of the signal.

The simplest vibration is a pure tone which consists of a *sinusoid,* Fig. 2.1, with the frequency: $f = \frac{1}{T}$. To characterize the magnitude of this vibration several quantities may be considered, which, in this case, all will have a certain mathematical relationship to each other. The RMS (root-mean-square) value is the most commonly used because of its direct relation with the energy content of the signal in linear systems. It is defined as:

$$A_{RMS} = \sqrt{\frac{1}{T}\int_0^T a^2(t)\,dt.}$$

Other important characteristic magnitude values are:

$$A_{|average|} = \frac{1}{T}\int_0^T |a|\,dt$$

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*) As a noise signal is, in general, composed of a great number of frequencies combined in random phase, the phase characteristics of the noise is normally not important.

and A_{peak}, which is the maximum amplitude value that the signal reaches within the period of time T.
For a pure sinusoid and *only* a pure sinusoid the relationship between the various values are:

$$A_{RMS} = \frac{\pi}{2\sqrt{2}} A_{|average|} = \frac{1}{\sqrt{2}} A_{peak}$$

$$\left(= F_f \, A_{|average|} = \frac{1}{F_c} A_{peak} \right)$$

The factors F_f and F_c mentioned above, called "form factor" and "crest factor" respectively, give an indication of the wave shape of the signal. For sinusoids:

$$F_f = \frac{\pi}{2\sqrt{2}} = 1.11 \ (\simeq 1 \text{ dB}) \text{ and } F_c = \sqrt{2} = 1.414 \ (= 3 \text{ dB})$$

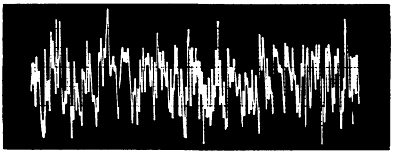

Fig. 2.2. Example of a sound signal as commonly encountered in daily life. Note the random distribution of amplitudes.

Most sounds met with in daily life are not purely sinusoidal vibrations. Very often they vary with time, both in frequency and in magnitude, see Fig. 2.2. Simple mathematical relationships between the various characteristic values do not exist for such complex signals and to characterize the magnitude of the signal it has been found convenient to introduce the concept of *amplitude density* instead of amplitude, because the different possible amplitude values occur with a certain "density" when the phenomenon is studied statistically over a certain period of time. The concept of amplitude density corresponds to the concept of probability density in statistics.
As is shown in Appendix A, however, *the quantities A_{RMS} and $A_{|average|}$ as defined above, retain their importance even when measuring statistical sound signals such as noise.* The peak value, A_{peak}, on the other hand, has no direct meaning in this case because theoretically it may become infinite, and in practice it will depend greatly upon the instrument meter circuit used in the measurement.
It was stated above that the "simplest" type of signal is the sinusoid, but that most sounds occurring in practice have a much more complex waveshape than the sinusoid. Now FOURIER has shown that any finite signal, no matter how complex, may be looked upon as a combination of a number (possibly an infinite number) of sine waves. These components of the signal constitute the signal *spectrum*. In the case of a pure sine wave the spectrum consists of one single line only, Fig. 2.3a).

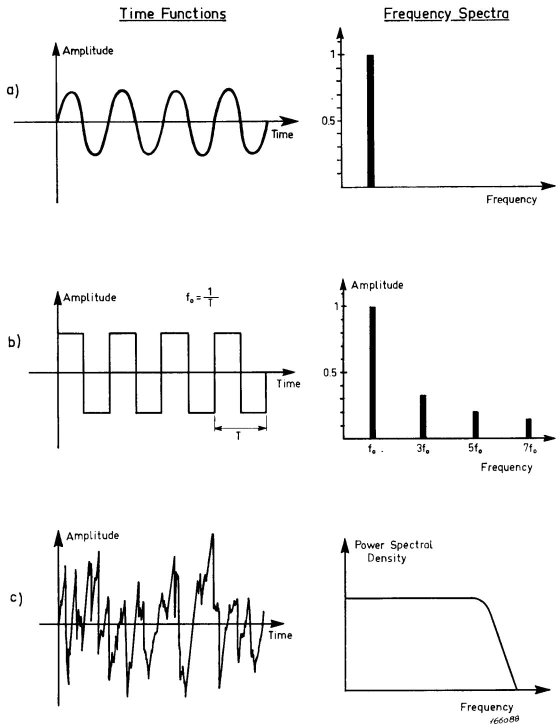

Fig. 2.3. Examples of sound signals and their frequency spectra:
a) A pure tone (sine wave).
b) A complex but periodic signal.
c) A complex non-periodic signal (random noise).

If the wave-shape is a little more complex but repeats itself periodically with time the spectrum consists of a number of discrete lines which are harmonically related to each other, Fig. 2.3b). Finally, statistically distributed signals, such as noise, show continuous frequency spectra, Fig. 2.3c).

Obviously much can be learnt about the nature of a sound signal if it is broken down into its constituent sine components, i.e. if it is *frequency analysed.* Various aspects of frequency analysis techniques as commonly used in the fields of sound and vibration measurements are described in Chapter 4 of this booklet and also, more specifically, in a separate publication*).

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*) "Application of B & K Equipment to Frequency Analysis and Power Spectral Density Measurements". Brüel & Kjær, Denmark.

2.2. Sound Wave Propagation and Reflection.

If a medium, for instance air (or water), is set into vibration the vibrations propagate away from the place of their origin. Perhaps the most commonly visualized phenomenon of propagation of vibrations is the occurrence of water waves. However, every elastic medium is capable of propagating mechanical vibrations in a similar manner.

Physically the propagation may be thought of as the transfer of momentum from one molecule to the next. Due to the elastic bonds between the molecules the motion of one molecule will, more or less, follow that of the "preceding" one.

This transfer of momentum takes time so that the motion of the molecules at a particular point of observation will occur with a certain time lag with respect to the motion of the molecules at the place where the vibration originated, i.e. the vibrations propagate with a certain *speed*. The speed of propagation is a physical property of the medium and in air it is approximately 344 m/sec (1,127 ft/sec) at normal temperature 20°C (68°F).

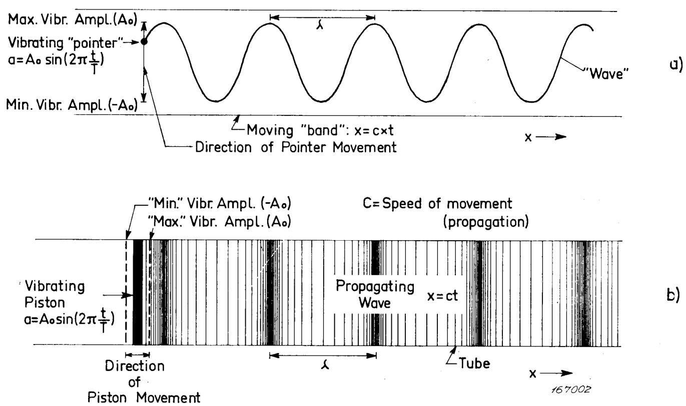

Fig. 2.4. Illustration of how vibrations are "transformed" into waves

a) A vibrating "pointer" writes on a "band" which moves in the x-direction with a speed c.

b) A vibrating piston "radiates" the vibrations into a tube in the form of compressions and rarefactions. The compressions and rarefactions propagate in the x-direction with a speed c (sound waves).

If the propagation had taken place with an infinite speed the vibrations at every point of observation would, *at any instant,* have been the same (except for attenuation and divergence effects). Due to the finite speed, however, the propagation takes the form of a *wave* where the time scale of the original vibration is "transformed" into a length scale. For the particular case of sinusoidal vibrations this is demonstrated in Fig. 2.4.

The "transformation" scale is given by the speed of sound in the medium in question, and one *wavelength,* λ, corresponds to one period of vibration, T, i.e. $\lambda = cT$, where c is the speed of sound. More often this relationship is given in the form of an equation connecting the wavelength to the vibration frequency. Remembering that the frequency, f, is related to the period, T, by $f = \frac{1}{T}$ (p. 8), then:

$$\lambda = \frac{c}{f}$$

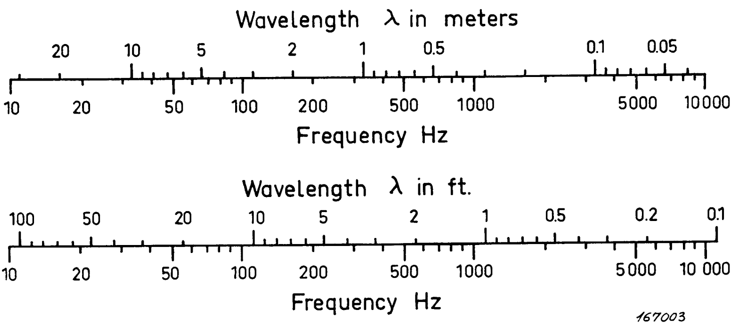

Fig. 2.5. Wavelength in air versus frequency under normal conditions.

In Fig. 2.5 this relation is plotted for sound in air under normal conditions (20°C), and for most sound measurements it is very convenient to keep in mind the order of magnitude of the wavelengths. This will be further emphasized later in the text.

In a gaseous medium such as air, the propagation of mechanical vibrations takes place in the form of *density variations* in the direction of propagation (longitudinal waves), see Fig. 2.4b). The most common method of measuring these density variations is to measure the associated variations in pressure i.e. to measure the *sound pressure.* Some times it might be desirable to measure not only the sound pressure but also the *particle velocity* of the vibrating gas particles, for instance when a determination has to be made in the "near" field*) of the *noise power* emitted from a machine. In most cases, however, the noise power may be measured by other methods (see chapter 5), and the measurement of particle velocity has not, so far, gained any widespread usage.

If the sound propagates in one direction only it is said to propagate as a *plane, free progressive wave* or shortly as a *plane wave.* Except for transmission losses in the medium (and dispersion) the RMS value of the sound pressure

*) The acoustic "near" field of a sound source depends upon its sound radiating characteristics and is the field close to the source where the particle velocity does not necessarily have the direction of travel of the wave.

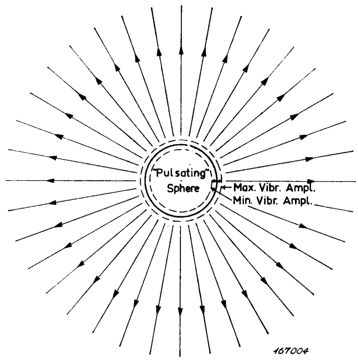

Fig. 2.6. Illustration of how sound waves propagate away from a "pulsating" (vibrating) sphere.

would then be the same everywhere along the direction of propagation. An approximation to this simple kind of wave is obtained very far away from a sound source when this is placed in an acoustically free field*), a situation which is practically never met in normal noise measurement work.

Another type of wave, however, which is relatively frequently found in practice, at least to some approximation, is a *free spherical progressive wave,* or just *spherical wave.* Such waves are thought of as waves propagating radially away from a small "pulsating" sphere (a "point"-source), see Fig. 2.6. Without going into details of the exact theory, a very important and simple relationship between the noise emitted from such a source and the sound pressure excisting at a distance, r, from the source can be derived.

Assuming that the emitted noise power is E, this spreads out from the source in the form of spheres with continuously increasing radius, r, Fig. 2.7. Thus the noise power passing through the surface of a sphere of radius, r, must, in a nondissipative medium equal the emitted power, E, divided by the area of the surface ($A = 4\pi r^2$):

$$I = \frac{E}{4\pi r^2}$$

Now, at a sufficient distance away from the source, this "average noise intensity", I, is also proportional to the square of the sound pressure, p, at r, whereby:

$$p = (\text{const.})\,\frac{1}{r}$$

This relationship is the socalled *inverse – distance law* (sometimes also called the "inverse – square law", for obvious reasons), and governs the free sound radiation in the acoustic "far" field**) of a sound source.

*) An acoustically free field is a field without any sound reflecting obstacles.

**) The acoustic "far" field is the sound field far enough from the source that the particle velocity is primarily in the direction of propagation of the sound and the acoustic intensity is proportional to the sound pressure squared.

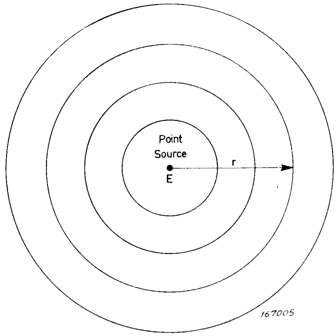

Fig. 2.7. Sketch illustrating the concept of spherical wave "fronts" (see also Fig. 2.6).

So far two regions of radiation from a sound source have been briefly mentioned, the acoustic "near" field and the acoustic "far" field with no sound reflecting obstacles. As soon as one, or more, sound reflecting objects are introduced in the field, however, the wave picture changes completely due to the reflections. This is easily understood as there is now not only one progressive wave present, but also a reflected wave travelling more or less in the opposite direction to the original one. *The sound pressure at a certain point in the field is then at any instant the combination of the pressure due to the original wave and the pressure(s) due to the reflected wave(s).*

Before discussing a little further the effects of reflection, the conditions necessary to obtain a reflection at all should be briefly mentioned. If for instance an object which is very small compared with the sound wavelength is placed in the sound field (see Fig. 2.5) no real reflection of the wave is produced. To produce a reflection which effectively interferes with the sound field, the dimensions of the reflecting object in the directions perpendicular to the direction of travel of the original sound wave must be of the order of the sound wavelength, or larger. The amount of reflection also depends upon the sound absorbing properties of the object. Thus, *both the physical dimensions and the sound absorption of an obstacle affects its reflecting properties.*

Returning to the effects of reflections upon the "original" sound wave one of the most important effects with regard to noise measurements is the production of a so-called *diffuse sound field.* A diffuse sound field is a field where a great number of reflected waves, from all directions, combine in such a way that the average sound energy density is uniform everywhere in the field. An approximation to this kind of field exists in large, reverberant rooms, and the way in which it is achieved is demonstrated in Fig. 2.8.

To illustrate the importance of the above described kinds of sound fields with respect to noise measurements, assume that a noise producing item is placed in a room. The sound pressure level set up around the item as a

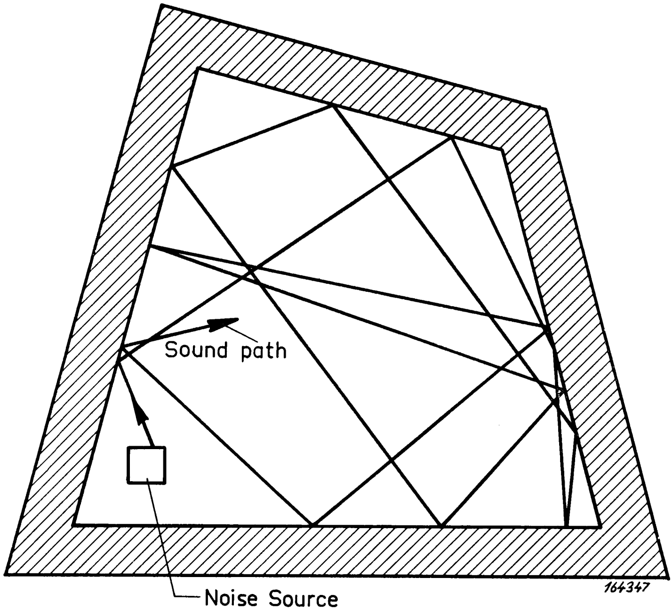

Fig. 2.8. Illustration of how sound "diffuseness" is obtained.

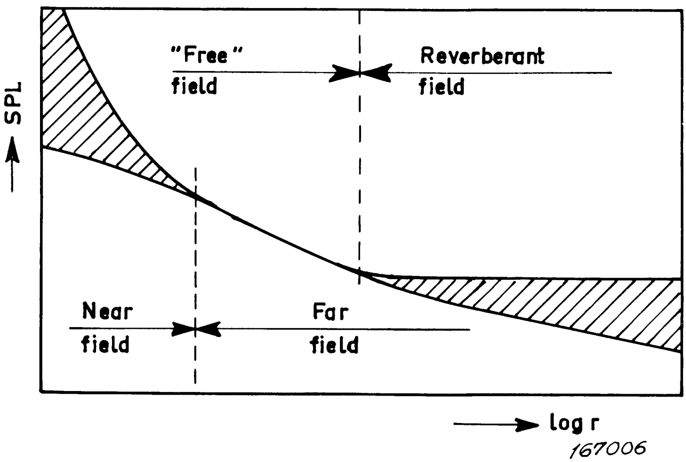

Fig. 2.9. Sketch illustrating the variation of sound pressure level in a room as a function of distance from a noise source. The shaded areas indicate regions of level fluctuating with distance (F. M. Wiener).

function of distance might then be of the type shown in Fig. 2.9. In both the regions marked "near" field and "far" field the direct sound from the noise source is predominant, while in the region marked "reverberant" the effects of reflections dominate and cause the field to approach what has been termed a diffuse field. Whenever noise measurements are made indoors it might be helpful to keep this picture in mind.

2.3. Physical Level Scales for Noise. The Decibel.

In the previous sections a physical description of vibrations and waves has been given. It was stated that vibrations propagate through elastic media in the form of waves, and that the most important quantity characterizing the magnitude of a vibration (and a wave) is its RMS value (A_{RMS}). However, no numerical *magnitude scale* was assigned to this value and it is the purpose of this section to introduce such a scale.

The quantity normally measured when dealing with acoustic noise is the RMS *sound pressure.* Because the weakest sound pressure that is perceived by a person as sound is a very small quantity, use has conveniently been made of the so-called CGS-system in scaling sound pressures. Thus, as the sound pressure is the force per unit area caused by the sound wave (vibration) the unit is dyne/cm^2 = microbar (μbar)*).

Now, even though the weakest sound pressure perceived as sound is a small quantity, the range *of sound pressure* perceived as sound is extremely *large.* The weakest sound pressure to be detected by an "average" person at 1,000 Hz has been found to be 0.0002 μbar (2×10^{-5} N/m^2). On the other hand, the largest sound pressure perceived without pain is of the order of 1,000 μbar, i.e. the scale of sound pressures covers a dynamic range of around 1 : 1,000,000! The use of sound pressures in μbar directly as a measure in sound measurements is therefore not too convenient. Also, as is explained in the next chapter, the hearing mechanism responds to changes in sound pressures in a relative manner rather than in an absolute way. It is therefore more convenient to use a *relative scale* of sound pressure than the above described absolute scale. Such a scale is the decibel scale (dB-scale).

The decibel is defined as ten times the logarithm to the base ten of the ratio between two quantities of power. As the sound power is related to the square of the sound pressure a convenient scale for sound (noise) measurements is defined as:

$$\text{Sound Pressure Level} = 10 \log \left(\frac{p^2}{p_o^2} \right) = 20 \log \left(\frac{p}{p_o} \right) \text{dB.}$$

where p is the sound pressure being measured and p_o is a reference sound pressure, normally taken to be 0.0002 μbar. It should be noted that the term *level* has been introduced in the above equation. This indicates that the given

*) In changing from the CGS-system to the more generally accepted MKS-system of units, 1 μbar = 0.1 Newton/m^2 (N/m^2).

Sound pressure in bar	Sound level in dB		Environmental conditions
		140	
1 mbar	134		Threshold of pain
		130	
			Pneumatic chipper
		120	
100 μbar	114		Loud automobile horn (dist. 1 m)
		110	
		100	
10 μbar	94		Inside subway train (New York)
		90	
			Inside motor bus
		80	
1 μbar	74		Average traffic on street corner
		70	
			Conversational speech
		60	
0.1 μbar	54		Typical business office
		50	
			Living room, suburban area
		40	
0.01 μbar	34		Library
		30	
			Bedroom at night
		20	
0.001 μbar	14		Broadcasting studio
		10	
0.0002 μbar			Threshold of hearing
		0	

Fig. 2.10. Some commonly encountered noise levels (sound pressure levels).

quantity has a certain *level above a certain reference quantity (0.0002 μbar = 2×10^{-5} N/m^2).*

The use of decibels reduces the scale of sound pressures of 1 : 1,000,000 to sound pressure levels of 0 to 120 dB, 0 dB indicating the reference level and 120 dB indicating the "maximum" level. This is a much more convenient scale to use as will be clear from a look at the table given in Fig. 2.11, and from the brief description of the hearing mechanism given in the next chapter.

A table and procedures for converting power (intensity) ratios and sound pressure ratios into dB and vice versa are given in Appendix B.

3. Psycho-Acoustics and Noise Criteria.

3.1. The Ear and the Hearing Mechanism.

The perception of sound by the human ear is a very complicated process. Even though the basic works of Helmholtz, v. Békésy, Fletcher and a number of other investigators have greatly helped to clarify its functioning, many details are still not completely understood. It is therefore quite natural that a variety of methods have, in the course of time, been devised which try to relate physical measurements of sound to the human perception. The purpose of this chapter is to outline the main methods of loudness determination in use to-day, to briefly explain the background on which they are based, and to summarize certain noise criteria which may guide the practicing noise abatement engineer in his work. As a logical starting point some of the known facts about hearing should be briefly reviewed.

The human ear consists of three "main" parts, the outer ear, the middle ear and the inner ear, see Fig. 3.1. The outer ear "matches" the impedance of the ear-drums to the air, a matching which is remarkably good at 800 Hz and remains fairly good even at higher frequencies. Only at frequencies below some 400 Hz is the matching rather poor.

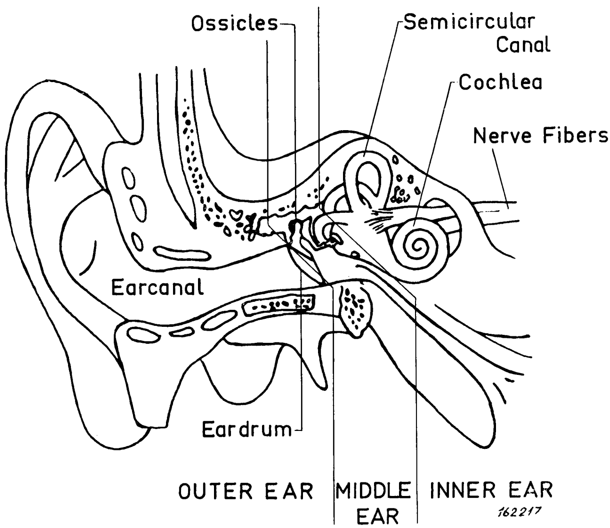

Fig. 3.1. Drawing illustrating the three "main" parts of the ear: The outer ear, the middle ear, and the inner ear with cochlea.

The vibrations of the ear-drum are mechanically transferred via the middle ear to the inner ear. Because the inner ear is filled with lymph, there is a further impedance "matching" here. At the same time the amplitudes of the ear drum are transformed to the much smaller vibration amplitudes but higher pressures in the inner ear. The perception of the sound by the nerves finally takes place along the basilar membrane of cochlea in the inner ear. Here also a sort of frequency analysis of the sound is made. Sounds of various frequencies set the basilar membrane into "maximum" vibrations at different distances from the oval window. The "maxima" are rather broad and the lower frequency maxima occur furthest away from the oval window, see Fig. 3.2.

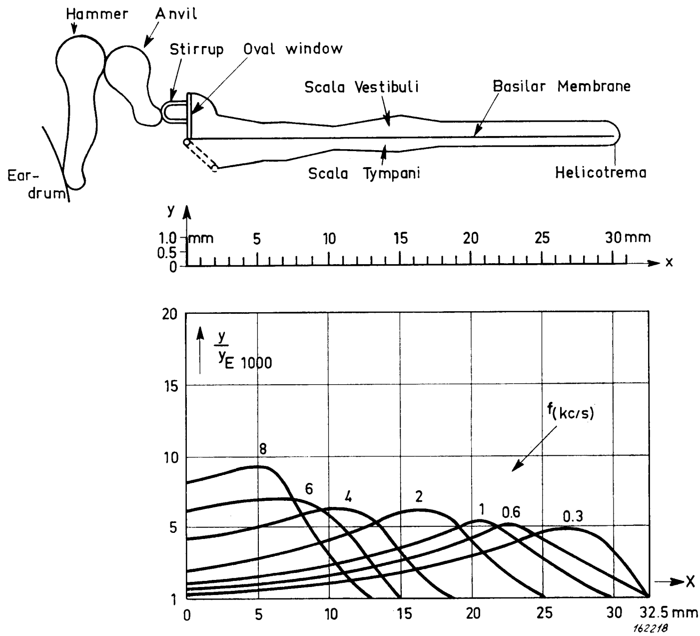

Fig. 3.2.

a) Sketch of the "folded out" cochlea.
b) Drawing indicating the vibrations of the basilar membrane during sound reception.

Because the maxima are relatively broad the complete frequency analysis performed by the hearing mechanism, which is a very selective analysis, cannot be accounted for by the formation of these maxima only. It has therefore been suggested that only a "preliminary" analysis is made along the basilar membrane and then a more selective analysis is performed in the nervous system itself. Later measurements seem to confirm this hypothesis.

The shape and amplitude of the nerve pulses produced in the organ of Corti along the basilar membrane are independent of the excitation amplitude. Only the number of pulses depends upon the excitation. However, as soon as the nerve is excited it will be "blocked" for a certain time interval during which it is completely insensitive to further excitation, and a maximum of about 150 pulses per second has been observed for the strongest excitations. To produce a single pulse a certain excitation level has to be exceeded, and in this way the "limits of hearing" may be explained, at least to a certain extent.

The complete hearing process seems to consist of a number of separate processes which, in themselves, are fairly complicated so *no simple and unique relationship exists between the physical measurement of a sound pressure level and the human perception of the sound.* The loudness of a certain pure tone may for example, be judged to sound different to that of another pure tone, and different again from a combination of tones, even if the sound pressure level is the same in all cases.

3.2. Loudness and Loudness Level.

The human perception of the loudness of pure tones of different frequencies has been investigated by a number of experimenters over the past decades and various sets of equal loudness level "contours" have been proposed. Such curves are the outcome of a great number of psychoacoustical experiments and will, of course, be valid only when certain experimental conditions are fulfilled. For example the observer should face the sound source, the source as well as the observer are to be placed in an acoustically free field. The observer should be in "normal" physiological and psychological condition and he should be unable to "see what he is doing" and thereby try to influence the measured result etc.

A set of equal loudness level contours which has been internationally standardized is shown in Fig. 3.3. The figure shows how *the loudness level of pure tones* with constant sound pressure level (SPL) vary with frequency. The decibel scale used on the Y-axis (ordinate) is well known to electronic engineers and is, as explained in the previous chapter of this booklet, a logarithmic, relative scale. It has been chosen partly on the basis of Weber-Fechner's basic psychophysical law*) and partly for convenience because of the great dynamic range of the human perception of sound (1 : 1,000,000).

On the other hand if the physical intensity of a sound is increased so that the sound appears twice as loud to the observer the increase is not equal to a factor of two on the decibel scale. Over most of the audible range the increase is approximately equal to 10 dB, see Fig. 3.4.

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*) The Weber-Fechner law states that the change in response to a certain change in excitation is inversely proportional to the absolute excitation before the change. Mathematically this can be written $\frac{dR}{dE} = \text{Const.} \times \frac{1}{E}$.

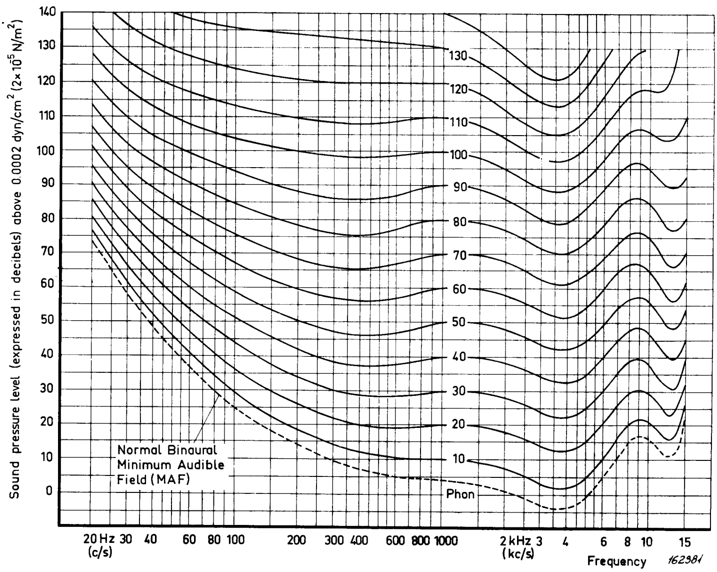

Fig. 3.3. Normal equal loudness contours for pure tones. They can be applied when:

a) The source of sound is directly ahead of the listener.
b) The sound reaches the listener in the form of a free progressive plane wave.
c) The sound pressure level is measured in the absence of the listener.
d) The listening is binaural.
e) The listeners are otologically normal persons in the age group 18 to 25 years inclusive.

The *loudness,* as perceived by the human, is measured in *sones* and, as stated above a *two fold change in loudness equals a change in sound intensity of 10 dB (phon).* This relationship has been internationally standardized in the form given in Fig. 3.4.
From the above discussion it is seen that the relationship between frequency and the human perception of pure tones can be given in the form of Fig. 3.3 while the relationship between the loudness level and the human perception of loudness can be found from Fig. 3.4. By combining the two sets of information it is possible, if desired, to construct a set of loudness curves for pure tones.

3.3. The Critical Band Concept.

Now, if a number of pure tones are combined into a complex sound, not only the loudness and pitch determine the human perception of the sound, but a third factor, the timbre enters the picture. The timbre depends upon the harmonic content of the sound and its transient behaviour (and thus also to

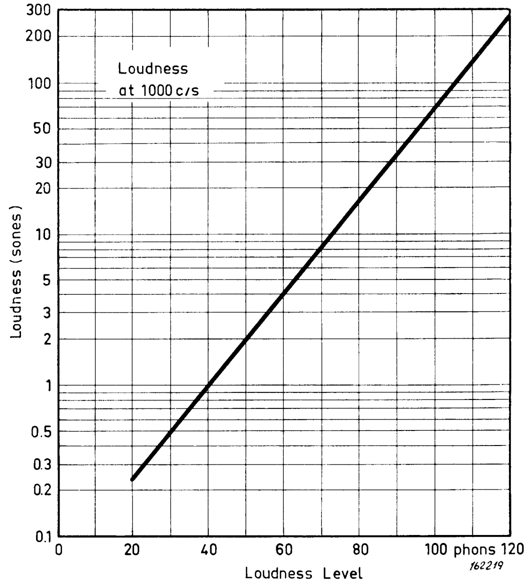

Fig. 3.4. The relationship between the loudness in sones and the loudness level in phon. According to the I.S.O. Recommendation ISO/R 131-1959 the relationship may be written as $S = 2^{(P-40)/10}$ for loudness levels between 20 phon and 120 phon.

a certain extent upon the phase relationship between the various components of the sound). A great amount of research work has been done in trying to make possible the measurement and/or calculation of this effect so as to take it into account during noise measurements. Investigations have shown the existence of certain "critical" bands of frequencies (German: Frequenz-gruppen), and also that a definite relationship exists between these bands and the previously mentioned vibration maxima on the basilar membrane. Based on these results the "main" audible frequency range has been oivided into 24 critical bands, see table Fig. 3.5.

Critical Band (Bark)	1	2	3	4	5	6	7	8
Center Frequency (Hz)	50	150	250	350	450	570	700	840
Bandwidth f (Hz)	100	100	100	100	110	120	140	150
Critical Band (Bark)	9	10	11	12	13	14	15	16
Center Frequency (Hz)	1000	1170	1370	1600	1850	2150	2500	2900
Bandwidth f (Hz)	160	190	210	240	280	320	380	450
Critical Band (Bark)	17	18	19	20	21	22	23	24
Center Frequency (Hz)	3400	4000	4800	5800	7000	8500	10500	13500
Bandwidth f (Hz)	550	700	900	1100	1300	1800	2500	3500

Fig. 3.5. Table of critical bands (Frequenz-gruppen).

One critical band corresponds to a distance of 1.3 mm along the basilar membrane and is defined as 1 Bark. *Within one critical band the loudness of the sound is mainly proportional to the RMS value of the sound pressure, while the loudness of the various bands add together according to a somewhat different scheme.*

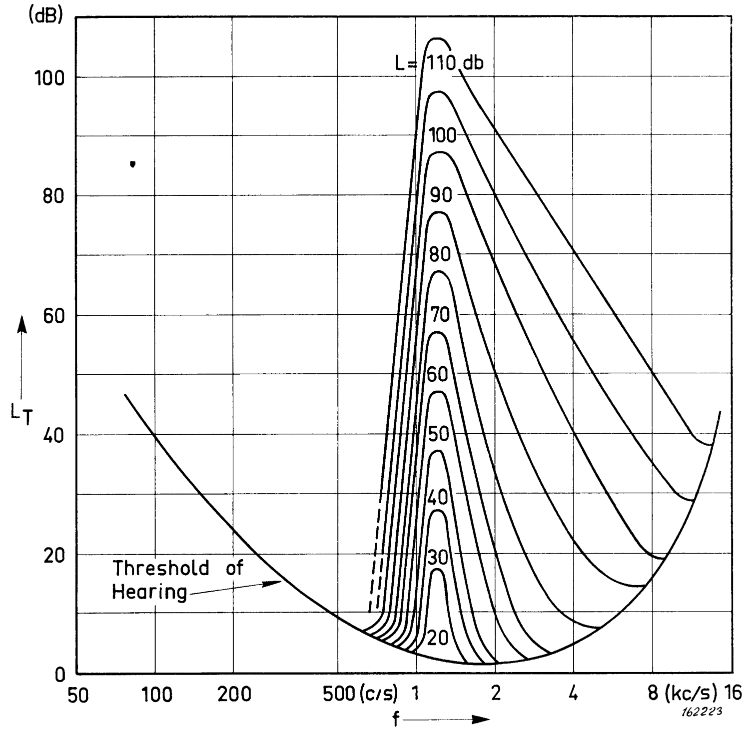

Fig. 3.6. Masking effect of narrow band noise with a center frequency of 1,200 Hz. The parameter is the RMS-value of the noise band (E. Zwicker).

3.4. Masking.

If the ear is simultaneously exposed to two different sounds it is a general experience that when one of the sounds is very loud the second sound is "drowned" and cannot be heard. This phenomenon is called masking, and the very loud sound is said to mask the other sound. The masking effect is explained as a shift in hearing threshold caused by the loudest sound and depends upon the frequency difference between the two sounds. The shift in hearing threshold is greatest around the frequency of the masking tone and is different for pure tones and for bands of noise of the same overall level, a difference which may, at least to a certain extent, be explained on the basis of beats between the tone being masked and the masking tone. Fig. 3.6 illustrates the shift in hearing threshold due to masking with respect to both level and frequency. The masking effect plays a very important role in the calculation of the loudness of a sound from sound pressure level measurements.

3.5. The Loudness of Impulsive Sounds.

It is at present generally assumed that the ear responds to the sound *energy* as averaged over a certain time. This assumption is not new and a number of experimenters have in the course of time, tried to determine the effective averaging time of the ear. Partly because of the lack of accurate experimental conditions and partly because of variations in the spectra of the pulses used in the various experiments the data obtained by different investigators are not very consistent, Fig. 3.7.

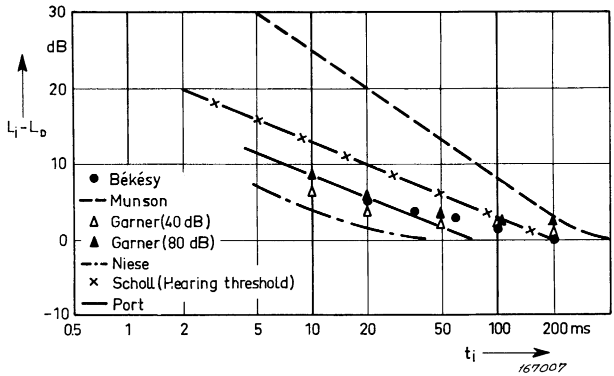

Fig. 3.7. Comparison of measured results on the loudness of impulsive sound as reported by various investigators. (E. Port).

To better understand Fig. 3.7 it should be mentioned that the curves given here were obtained by comparing subjectively, i.e. by means of psycho-acoustical experiments, the loudness of pulses of different duration with that of "steady" sounds. The sound pressure level difference $L_I - L_D$ (in dB) between the impulse "level" L_I*) and that of the "steady" sound, L_D, which was judged to be equally loud, is used as ordinate in the figure. The abscissa (X-axis) is simply the duration of the pulse in milliseconds. It is seen that as long as the duration of the pulse is longer than a certain amount the pulse is judged to have the same loudness as that of the "steady" sound

*) As impulse "level", L_i, was here used the level of the signal from which the pulse was "cut out".

($L_I - L_D = 0$). However, for pulses shorter than this duration the "level" of the pulse has to be increased to give the same loudness sensation as the "steady" sound. The "breaking point" then corresponds to the effective averaging time of the ear, and because the ear is assumed to be an energy sensitive device, the *increase in pulse intensity* has to compensate for the *decrease in pulse duration. This means that to sound equally loud the intensity of a pulse, which is shorter than the effective averaging time of the ear, should be doubled when the pulse duration is halved.* Because so many psychological factors affect the results of more complicated psychoacoustical experiments no general agreement as to the absolute value of ear averaging time has been reached to date. The results plotted in Fig. 3.7 as well as the above brief discussion are deemed, however, to give the reader an idea of how the ear is assumed to respond to impulsive types of sound, and to the expected order of magnitude of the response time involved.

3.6. Methods of Loudness Determination.

The historically first method of determining loudness was devised by Barkhausen and consisted in a subjective comparison of the loudness level of a given sound with that of a 1,000 Hz tone of known sound pressure level. The loudness level scale obtained in this way was graduated in *phon.* This unit has later been generally accepted as a measure of loudness level and the phon scale corresponds at 1,000 Hz, and *only* at 1,000 Hz, to the decibel scale commonly used for the measurement of sound pressure levels. As explained below, and further detailed in Appendix C, the "unit" phon is often accompanied by an index or subscript indicating whether the loudness level in question was determined subjectively (Barkhausen method) or according to some known method of calculation.

In older German litterature the expression "DIN-Phon" is sometimes found, an expression which was invented to distinguish the results obtained from measurements according to the German standard DIN-5045 from that obtained according to the Barkhausen method. In DIN*)-5045, and various national standards in other countries, it is recommended to insert a set of frequency weighting curves in the noise measurement equipment. This frequency weighting, when used according to the recommendations, was then assumed to approximate the ear's response to sound and the result of such a measurement assumed to give an indication of the loudness level.

From the preceding discussion on the hearing mechanism, however, it is readily understood that a simple frequency weighting of the sound, such as prescribed in these standards, could not possibly give a correct measure of the loudness level in all cases. Later psychoacoustical experiments also verified this (although in certain cases a remarkably good correlation has been found). It was thus agreed internationally *not to accept measurements*

*) DIN = Deutsche Industrie Normen.

made with a simple frequency weighting network as a measure of loudness level, but, in general, to use the result of such measurements merely for comparison purpose. This will be further discussed in chapter 4.
In search of methods that would allow a determination of the "subjectively felt" loudness level from objectively measured sound pressure level data two procedures have been internationally recommended. One of these, which is due to the German scientist E. Zwicker, is based on the critical band concept and integrates the excitation along the basilar membrane taking due account of the masking effect. The integration is made graphically from preprinted forms and instead of exact critical bands, use is made of "corrected" one third octave bands as commonly available in commercial frequency analyzers (B & K Type 2112).
A second method is due to the American scientist S. S. Stevens and makes use of 1/1 octave frequency bands. By comparing measured results with subjective judgements and taking some of the known facts about hearing, such as masking, into account Stevens has arrived at a very simple, easy-to-use method of loudness calculation.
Both methods are explained in more detail in Appendix C and an example of their use given. Even though the two methods are basically different they both seem to give remarkably consistent results so that the actual method chosen for practical calculations may be regarded mainly as a matter of taste and convenience. The results of such calculations should, however, be given in phons (GF), phons (GD) or phons (OD)*) to distinguish them from the loudness in phons obtained subjectively by the original Barkhausen method.

3.7. Annoyance and Noisiness. The PN-dB Concept.

The preceding sections of this chapter have been concerned with the hearing mechanism and the determination of *loudness.* Even though many details of hearing are still not well understood the concept of *loudness* seems to have been fairly well agreed upon and seems to be predictable from the measurement of sound pressure levels. The concepts of *annoyance* and *noisiness,* on the other hand, have not yet been so firmly established and seem, at least at present *not* to be predictable from measured physical data, at least not in any general sense. Annoyance has a great many psychological aspects which makes it difficult to define and "measure" in any simple manner. An attempt to define and measure the slightly simpler, but still very difficult concept of noisiness has been made in conjunction with the assessment of aircraft noise and a "scale" graduated in PNdB (perceived noise level) has been introduced. This will be further discussed in chapter 5 of this booklet. It should, however,

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*) Phons (GF) = phons ("Gruppen", Frontal sound), obtained by means of Zwicker's method.
Phons (GD) = phons ("Gruppen", Diffuse sound), obtained by means of Zwicker's method.
Phons (OD) = phons (Octave, Diffuse sound), obtained by means of Stevens' method.

be borne in mind that *the PNdB concept does only have a meaning in conjunction with aircraft noise.*

Certain general trends in the annoyance effects of acoustic noises might be found even though they can not be physically "scaled". When the physical intensity of a noise becomes greater it is for instance normally judged to be more annoying i.e. certain aspects of annoyance seem to be connected simply with the *loudness* of the noise. Also, a great number of psychoacoustical experiments seem to agree in that *high-pitched* (high frequency) noise is more annoying than low-pitched noise, the "high" frequencies here ranging from around 1,500 Hz and upwards (to around 10,000 Hz). Furthermore, if the noise is *intermittent,* like for instance the fly-over of aircraft at various time intervals, or irregular or rythmic, it may also be considerably more annoying than a "steady" noise of the same physical intensity (or even the same loudness). Finally, the *localization* of the noise source seems to play a not unimportant role with respect to its annoying effect. If the noise source is fixed at a certain place, which can be readily localized by listening, the noise it produces is generally less annoying than if it moves or cannot be localized (reverberant noise). To reduce the annoyance effect of a noise source in a large, reverberant room it might therefore be useful to cover the walls of the room with a certain amount of sound absorbing material, a measure which also automatically reduces the sound pressure level in the room.

3.8. Some Noise Control Criteria.

The effects of noise on a person may range from "mild" annoyance and speech interference to permanent hearing damage. In the course of time various noise rating methods have been suggested and a number of different criteria for "tolerable noise levels" have been proposed. A general trend in these proposals has been to emphasize an attenuation of the higher frequencies which is in line with the statements made in the above section on annoyance. A set of so-called noise rating curves which have been found very useful in conjunction with certain tables on "tolerable noise levels" is given in Fig. 3.8. With these curves as a basis a complete scheme of noise rating has been built up as explained in the following:

The sound pressure level of the noise in question is measured in 1/1 octave frequency bands*) and plotted in Fig. 3.8a). A *noise rating,* N, is then assigned to the noise, the rating number being that which is marked on the curve that lies just above the 1/1 octave spectrum, see also Fig. 3.9. This number should now be corrected according to Fig. 3.8b) and compared with the values given in the tables and curves of Fig. 3.10 through 3.15. The actual table or curve used must be selected according to the noise criterium which is found to be the most relevant one with respect to the noise problem at hand.

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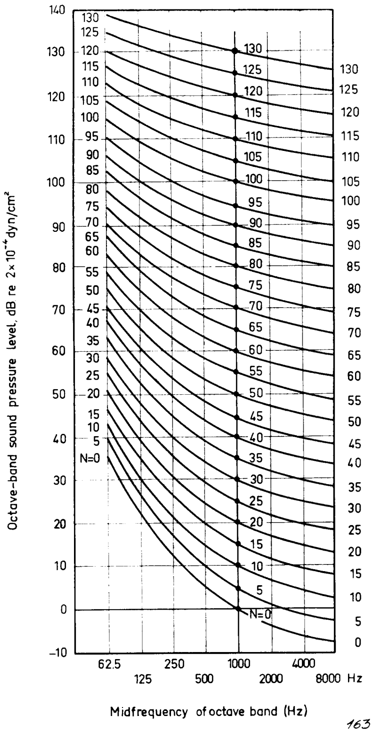
*) For measurements of 1/1 octave sound pressure levels the reader should consult chapter 4.



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a) b)

	Criterion
broadcasting studio	15
concert hall, legitimate theatre 500 seats	20
class room, music room, TV studio, conference room, 50 seats	25
sleeping room (see corrections below)	25
conference room 20 seats or with public adress system, cinema, hospital, church, courtroom, library	30
living room (see corrections below)	30
private office	40
restaurant	45
gymnasium	50
office (type writers)	55
workshop	65
Corrections for dwellings	
a) Pure tone easily perceptible	— 5
b) Impulsive and/or intermittent	— 5
c) Noise only during working hours	+ 5
d) Noise during 25 % of time	+ 5
6 %	+10
1.5 %	+15
0 %	+20
0.1 %	+25
0.02 %	+30
e) Very quiet suburban	— 5
suburban	0
residential urban	+ 5
urban near some industry	+10
area of heavy industry	+15

Fig. 3.8. Proposed Noise Rating Curves and table of "corrections" to be applied under certain specified circumstances (C. W. Kosten and G. J. Van Os).

Even though the application of the tables and curves should be quite self-evident some explanatory notes might be useful:

Noise levels below some *N 85* might interfere seriously with the intelligibility of speech and be very annoying, but they do not cause hearing damage. Whenever such questions as speech intelligibility or annoyance are disputed the tables given in Figs. 3.10 through 3.13 might be consulted.

Noise levels above *N 85* might cause *hearing damage* ranging from a temporary shift in hearing threshold (TTS) to a permanent hearing loss. The curves shown in Fig. 3.14 indicate a relationship between the time that a person is exposed to noise of a certain level and the corresponding shift in hearing threshold at 2,000 Hz. A temporary threshold shift of 12 dB is here assumed

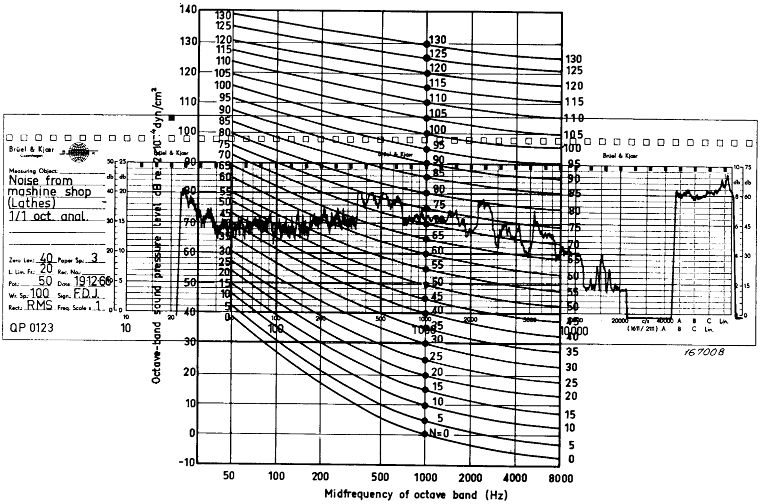

Fig. 3.9. Example of use of the Noise Rating Curves. The Noise Rating Number is here N 80.

Column 1	Column 2		Column 3	
Noise Rating Number	Distance at which every-day speech of conversational voice level is considered to be intelligible		Distance at which everyday speech of raised voice level is considered to be intelligible	
	(m)	(ft)	(m)	(ft)
40	7	23	14	46
45	4	13	8	26
50	2.2	4.4	4.5	15
55	1.3	4.1	2.5	8.2
60	0.7	2.3	1.4	4.6
65	0.4	1.3	0.8	2.6
70	0.22	0.74	0.45	1.5
75	0.13	0.41	0.25	0.82
80	0.07	0.23	0.14	0.46
85	--	--	0.08	0.26

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Fig. 3.10. Table of Noise Rating Numbers for intelligibility of speech communication.

Column 1	Column 2
Noise Rating Number	Quality of telephone communication
50	satisfactory
60	slightly difficult
75	difficult
above 75	unsatisfactory

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Fig. 3.11. Table indicating the quality of telephone communication for various Noise Rating Numbers.

Noise Rating Number	Example for type of room
20-30	Bedroom, hospital room, television studio, living room, theatre, church, cinema, conference room, lecture room
30-40	Larger office, business store, department store, meeting room, quiet resturant
40-50	Larger resturant, secreterial office (with typewriter), gymnasiums
50-60	Larger typing halls
60-70	Workshops

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Fig. 3.12. Table of suggested Noise Rating Numbers for Acoustic adequacy of rooms.

CORRECTED NOISE RATING NUMBER	ESTIMATED PUBLIC REACTION
range	
below 40	no observed reaction
40-50	sporadic complaints
45-55	wide spread complaints
50-60	threats of community action
above 65	vigorous community action

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Fig. 3.13. Public reaction to noise in residential districts.

to be permissible and should be applied as a criterion with respect to hearing damage. If, for instance, the noise rating number assigned to the noise in question is N 110 no person should be exposed to this noise for more than 10 minutes. Similarly, if the noise rating number is N 100 the maximum permissible time of exposure is some 25 minutes.

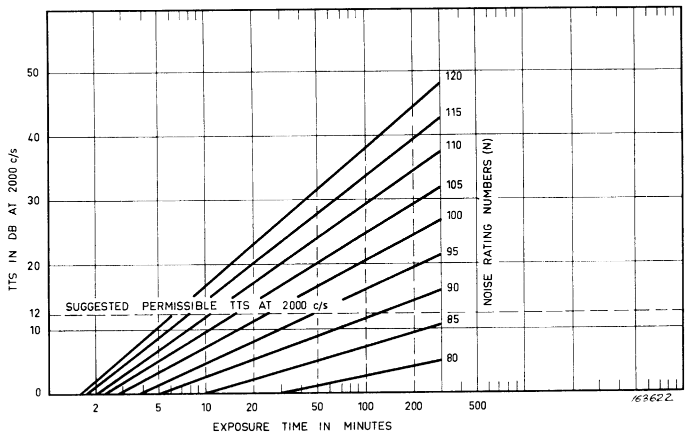

Fig. 3.14. Noise Rating Numbers for short term noise exposure (Glorig, Ward and Nixon).

In cases where the noise is not "steady" but is more or less periodically interrupted i.e. intermittent noise, the curves shown in Fig. 3.15 might be applied. Here the abscissa (X-axis) is graduated in minutes that the noise is on, while the ordinate (Y-axis) is graduated in minutes that the noise is off. The curves drawn in full correspond to various noise rating numbers as marked in the figure, and the dashed curves indicate the number of on-off switchings of the noise permitted per day (exposure cycles per day).
As an example of the use of the curves assume that a noise with a noise rating number of N 105 is on for 10 minutes. It should then be followed by (at least) 50 minutes "off-time". Eight such cycles are "permissible" per day. On the other hand, if the noise rating number of the noise is N 100, a 10 minutes "on time" need only be followed by an 8 minutes "off-time" and some 25–30 cycles might be "permitted" per day.
Before closing this brief description of a noise rating system it should be mentioned that the frequency bands of greatest importance with regard to the conservation of hearing, are the octave bands centered at 500, 1,000 and

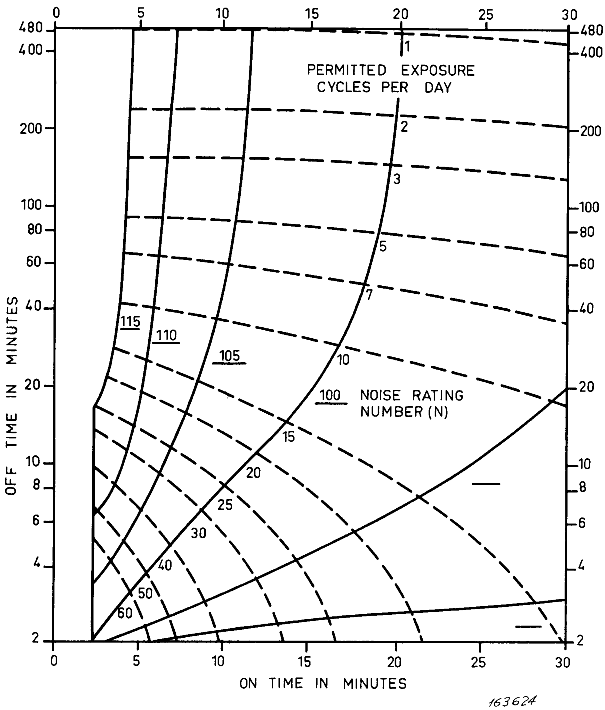

Fig. 3.15. Noise Rating Numbers for intermittant noise exposure (Glorig, Ward and Nixon).

2,000 Hz. The noise level in these frequency bands should therefore be most seriously considered when the noise at hand is investigated with a view to possible hearing damage.

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4. Measurement Instrumentation and Technique.

4.1. What Type of Measurement is Required?

In the preceding chapter, section 3.8, a set of noise rating criteria was described. Now, what kind of noise measurements are necessary to make proper use of these criteria? And, if it is found that some action has to be taken to reduce the noise, what kind of measurements should then be made? These are two of the basic problems in noise measurements and their proper solution often leads to the most efficient and time saving methods of noise control. To answer the questions, however, a certain knowledge of the various types of noise measurement equipment available as well as of the technique involved in using the equipment are necessary. It is the intention of this chapter to try to supply the reader with the necessary information both on the instrumentation and on the technique, but before going into details some preliminary considerations should be pointed out.

The "simplest" physical measure of a noise would be to determine its overall sound pressure level. On the other hand, such a measurement would give no indication of the frequency distribution of the noise, neither would it give any information as to the human perception of it. In practice therefore such a measurement would be more or less meaningless. By relatively simple means, however, it is possible to give a noise measuring instrument certain characteristics which make the measured results much more useful. This has been done with the now internationally standardized *precision sound level meter.* The sound level meter is supplied with a set of *frequency weighting networks,* the characteristics of which have been termed A, B and C, see Fig. 4.1. The characteristic marked C shows only little dependence on frequency over the greater part of the audible frequency range, while the characteristic marked A, has a very pronounced frequency dependency for frequencies below some 1,000 Hz. By comparing the frequency characteristic A in Fig. 4.1 with the equal loudness level contours for pure tones shown in Fig. 3.3 a certain resemblance can be found between these and the "inverted" A-characteristic. Even though the human perception of sound is much too complicated to be even approximated by a simple frequency weighting like that described by curve A of Fig. 4.1*) a certain guidance with regard to noise problems may in many cases be obtained from measurements with an instrument containing the A-characteristic. On the other hand, to distinguish between the physical measurement of sound pressure levels in decibels (dB) (no frequency "weighting"), the subjective measurement of loudness level in

*) See chapter 3.

phons and measurements made with one of the standardized frequency characteristics A, B or C inserted it, has been internationally agreed that the result of the latter kind of measurement should be termed *sound level* and stated in decibels with an indication of which of the three weighting curves was used. *If, for example, the noise in question is measured with the A-weighting curve inserted the result should be given in terms of sound level measured in dB (A).* Similarly, if the noise is measured with the B or C weighting curve inserted the results should be given as dB (B) or dB (C), respectively.

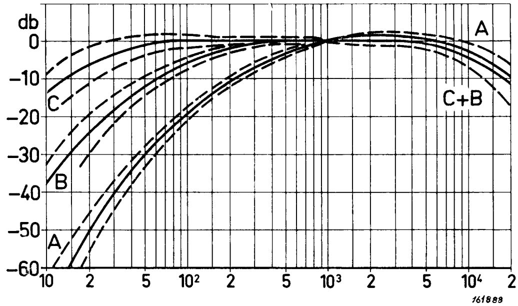

Fig. 4.1. The internationally standardized weighting curves for sound level meters. The tolerances allowed for "precision sound level meters" are also shown.

Now, it was stated above that a certain guidance with regard to noise problems might be obtained from a measurement of the dB (A) value of the noise. This is due to the fact that in many cases a representative noise rating number, N, (see chapter 3, section 3.8) might be assigned to the noise from a "simple" measurement with the A weighting curve inserted. *It has been found that an approximate noise rating number will be of the order of the dB (A) value.* If the noise rating number determined in this way exceeds the one which, in a given situation, would be desirable a more thorough investigation of the noise should be made. Such an investigation is, however, considerably more time consuming than a measurement of the sound level (in dB (A)), and the above mentioned "rule" is therefore of considerable value in noise surveys.
Should it be decided that a more thorough investigation is required the next step would then normally be to perform a *frequency analysis* of the noise, i.e. to perform a more detailed analysis of its frequency composition. As most noise criteria are given in terms of octave band sound pressure levels a suitable bandwidth for the analysis would be 1/1 octave*). Some further discussion on frequency analysis technique and application is given in section 4.4.

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*) In some cases where a loudness determination according to the method suggested by E. Zwicker (chapter 3, section 3.7) is desired use should be made of 1/3 octave bands.

The measurements mentioned so far actually provide, in brief, an answer to the first question raised at the beginning of this chapter. In answering the second question it might be generally stated that a more detailed frequency analysis, in terms of 1/3 octaves or even narrower frequency bands, is needed.
From the detailed frequency spectrum of the noise the most relevant sound attenuation measure may then normally be deduced, as pointed out in section 5.2.

4.2. Some Basic Measurement Systems.
In trying to decide what would be the most suitable measurement instrumentation for the noise problem at hand not only the two basic questions raised in the previous section are important but also questions as to the nature of the noise arise and might influence the choice of instrumentation. The noise might be more or less wideband, random noise, it may contain discrete tones, it might be of an impulsive character, it may be a "steady" noise or of a transient or intermittent nature. All these factors will influence the instrumentation to a greater or lesser extent, and so will the environmental conditions such as temperature, humidity, wind etc.
Finally the noise measurements may be of an investigating or a monitoring type. In the first instance the various instrumentation systems available have a great many common characteristics, while in the latter case a wide variety of systems may be deduced depending upon the purpose of the monitoring.

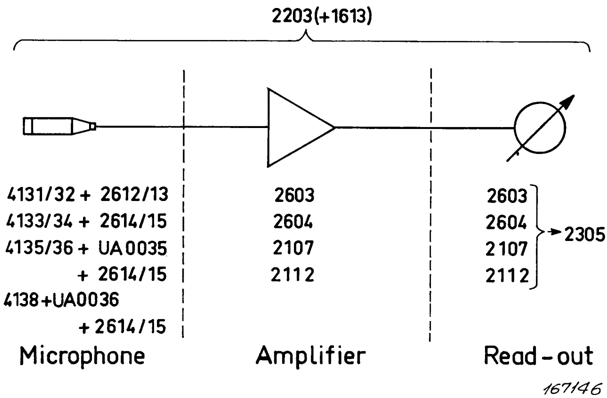

Fig. 4.2. Basic noise measurement system.

Some examples of specific noise measurements and monitoring are given in chapter 5 while this chapter deals mainly with more fundamental questions in the selection of instrumentation and measurement technique.
Fig. 4.2 shows, in the form of a block diagram, the basic elements of a noise measuring system. It consists of a *microphone, a special amplifier* or frequency

analyzer and a *read-out* or monitoring unit. The simplest practical realization of such a system is the previously mentioned sound level meter, and in Fig. 4.3 is shown the Brüel & Kjær *Precision Sound Level Meter Type 2203.* This instrument fulfills the requirements of the I.E.C.*) Recommendation Publication

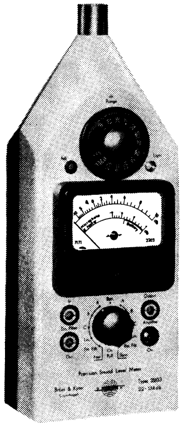

Fig. 4.3. Photograph of the Precision Sound Level Meter Type 2203.

179 and is a rugged, battery-operated, easy-to-handle instrument. The microphone used is of the *precision condenser microphone* type and a wide variety of microphone accessories such as wind screens, random incidence correctors, nose cones, extension connectors and adaptors for special microphones are available. Even though the basic instrument, as shown in Fig. 4.3, may be used directly in almost any noise measurement situation, certain applications will undoubtedly also require the use of some of the more specialized accessories. This is further discussed in the next section of this booklet.

The amplifier in the Precision Sound Level Meter is supplied with the standardized A, B and C weighting networks, and provision is made for the insertion of more specialized, external filters, for instance the *Octave Filter Set Type 1613.* A special feature of the instrument is that the Octave Filter Set can be connected mechanically directly onto the Precision Sound Level Meter, see Fig. 4.4.

In this way a very compact and easily portable 1/1 octave band analyzer is obtained. Also, the output from the amplifier is available on a set of output terminals allowing the noise signal to be recorded or monitored on an external recording device if desired.

The built-in read-out unit consists of an RMS rectifier and a meter circuit the dynamic characteristics of which are specified in the international standard.

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*) I.E.C. = International Electrotechnical Commission.

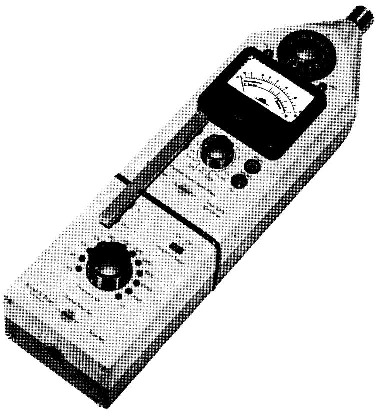


Fig. 4.4. Photograph of the Precision Sound Level Meter Type 2203 with connected Octave Filter Set Type 1613.

Fig. 4.5. Carrying Case KE 0011 with the Percision Sound Level Meter and various accessories for precision noise measurements (Sound and Vibration Set Type 3501).

Two different meter damping characteristics, termed "Fast" and "Slow" respectively are thus available, the "Slow" characteristic being used when the reading obtained with the "Fast" characteristic fluctuates too much (more than some 4 dB) to give a reasonably well-defined value of the sound level. To allow for easy transportation of the instrument and accessories a *Carrying Case KE 0011* has been designed, see Fig. 4.5.

If measurements are to be carried out over longer periods of time, or automatic frequency analysis recording is desired, the battery-operated Precision Sound Level Meter Type 2203 should preferably be substituted by mains driven equipment and some sort of a recording device added to the read-out.

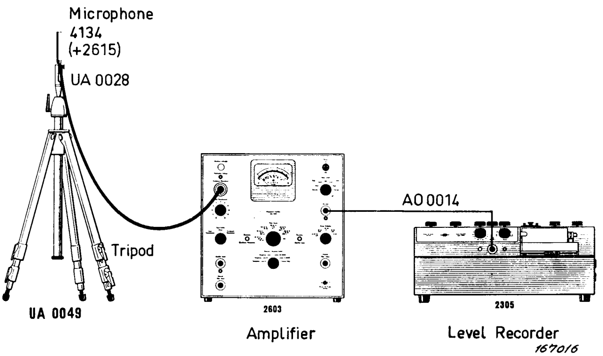


Fig. 4.6. Arrangement suitable for the graphic recording of noise over practically any length of time.

The recording device would then basically be a graphic level recorder or a magnetic tape recorder. In Fig. 4.6 an arrangement which is capable of recording the A, B or C weighted noise level over practically any period of time is shown. It consists of a Brüel & Kjær *1/2" Condenser Microphone Type 4134, a Microphone Amplifier Type 2603 and a Level Recorder Type 2305.* By choosing suitable paper drive and writing speeds on the Recorder a graphic recording of convenient length and with a convenient smoothing of undesirable rapid level fluctuations can be obtained, Fig. 4.7.

Should it be desired to carry out a statistical analysis of the variation in noise level with time, a method of analysis which has become of considerable importance in later years, this may be done automatically by connecting a *Statistical Distribution Analyzer Type 4420* directly onto the Level Recorder as indicated in Fig. 4.8. Some basic implications of statistical analysis technique are given in Appendix D, while section 4.4 of this chapter outlines the use of Type 4420 in a little more detail. Both the Level Recorder and the Statistical Distribution Analyzer are, however, very valuable tools also in noise monitoring systems.

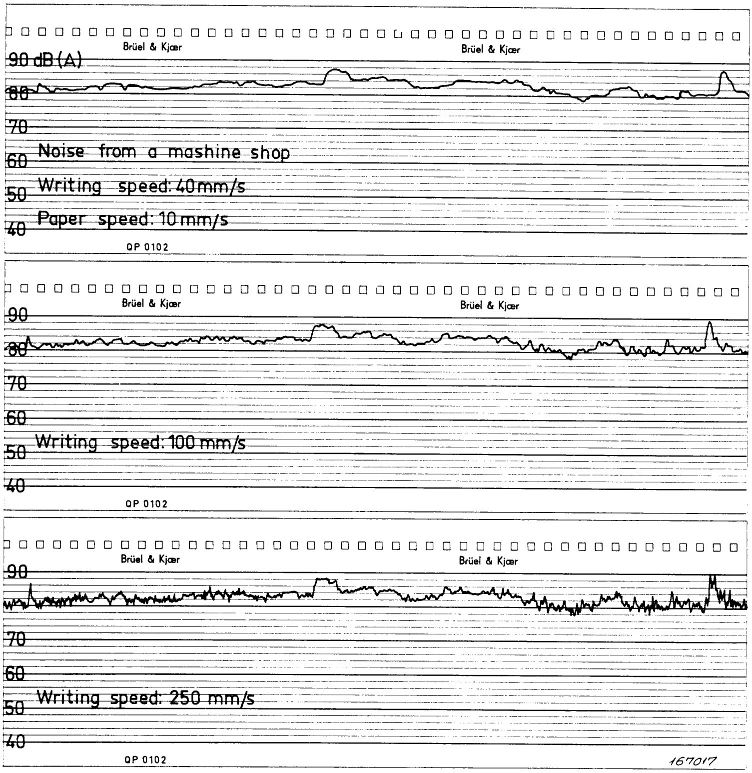


Fig. 4.7. Examples of the time recordings of noise in a workshop in terms of dB (A) and with various writing speeds of the recording pen.

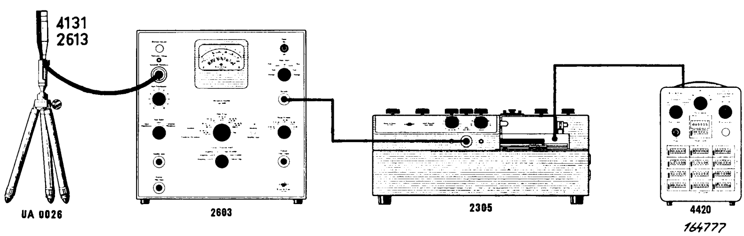


Fig. 4.8. Typical measuring arrangement used for automatic statistical analysis of for instance traffic noise.

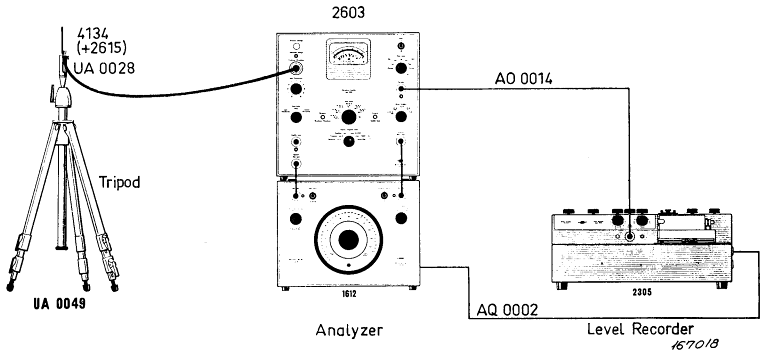


Fig. 4.9. Arrangement suitable for the automatic frequency analysis of noise, obtained by simply adding a Band Pass Filter Set Type 1612 to the set-up shown in Fig. 4.6.

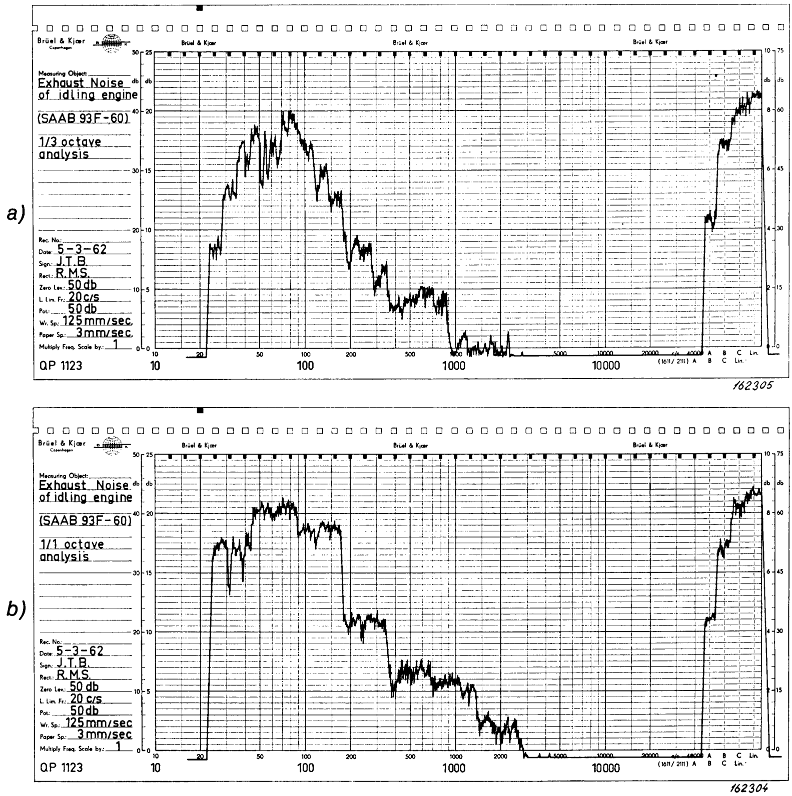


Fig. 4.10. Examples of automatically recorded spectrograms of the exhaust noise from the idling engine of an automobile.
a) 1/3 octave analysis
b) 1/1 octave analysis

As mentioned above the use of a Level Recorder Type 2305 allows the automatic recording of frequency analysis data. It is then necessary to add a *Band Pass Filter Set Type 1612* to the arrangement shown in Fig. 4.6. The resulting set-up is given in Fig. 4.9 and indicates that the switching between the various filters contained in Type 1612 is controlled from the paper drive system in the Level Recorder. In this way it is possible to use preprinted, frequency calibrated paper on the Recorder and to obtain frequency analysis data directly on the calibrated paper, see Fig. 4.10. As the filters in the Band Pass Filter Set can be switched for either 1/1 octave or 1/3 octave frequency analysis the figure shows examples of the result of both kinds of analysis.
When a thorough investigation of noise producing machinery is to be made, i.e. when frequency analysis data have to be collected at a number of measurement positions and under various operating conditions, the automatic analysis technique outlined above is of great help. If desired the combination of Microphone Amplifier Type 2603 and Band Pass Filter Set Type 1612 can be substituted by the *Audio Frequency Spectrometer Type 2112,* Fig. 4.11. The two arrangements shown in Figs. 4.9 and 4.11, respectively, are *exactly equivalent.*
A further method of frequency analysis of the noise is suggested in Fig. 4.12. The analyzer used in this case is the *Frequency Analyzer Type 2107.* While the previously described methods of analysis measure the noise in contiguous

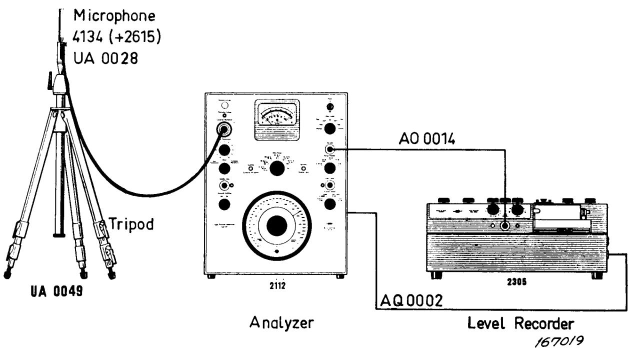


Fig. 4.11. Measuring arrangement employing the Audio Frequency Spectrometer Type 2112.

frequency bands, the Analyzer Type 2107 allows the analysis to be made by means of a continuously sweeping filter. Also, filter bandwidths as narrow as 6 % of the tuned in center frequency are available. It is therefore basically a *narrow band analyzer,* even though bandwidths up to (and slightly larger than) 1/3 octave may be selected.

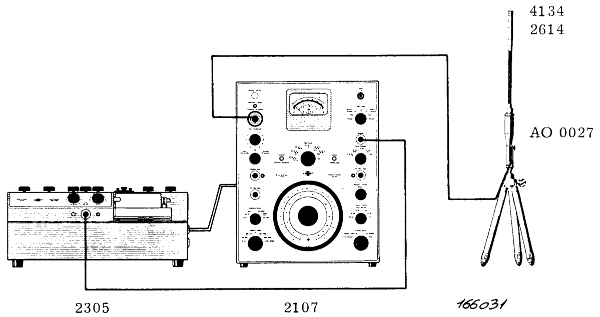
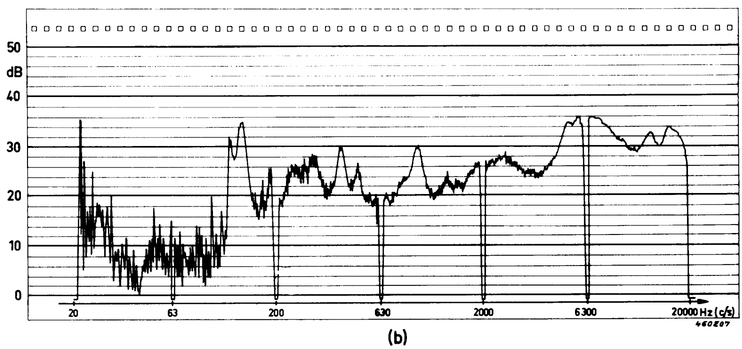


Fig. 4.12. Automatic narrow band frequency analysis arrangement utilizing the Frequency Analyzer Type 2107.

Fig. 4.13 shows the result of an analysis made by means of the Frequency Analyzer Type 2107 and automatically recorded on the Level Recorder Type 2305. In the example shown, use has not been made of frequency calibrated paper, the main reason here being a desire to "compress" the frequency scale. Preprinted, frequency calibrated recording paper is, however, also available for this case.

Up to now the frequency analysis equipment described has been of the type commonly used for noise investigation purposes. Two more specialized in-



(b)

Fig. 4.13. "Compressed" recording of the noise spectrum produced by an electric motor.

struments have, on the other hand, been specially developed by Brüel & Kjær, with a view to noise monitoring. These are the socalled *Noise Limit Indicators Type 2211, and 2212.*

Type 2211 has been designed to provide a high-speed accurate assessment of the quality of production line outputs as regards noise (and vibration) of the product. It measures the noise in several (up to 12) frequency bands simultaneously and compares the result with a preset "standard" for the particular article produced. Type 2212 differs slightly from Type 2211 in that the design in this case has been directed more towards the monitoring of traffic noise, and the "comparison" of this kind of noise against preset "standards". Typical examples of use of the Noise Limit Indicators are given in chapter 5, while Fig. 4.14 shows a photograph of the basic instrument.

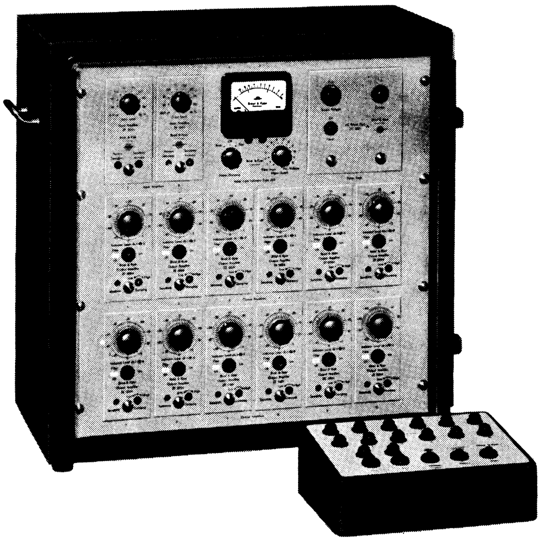


Fig. 4.14. Photograph of the Noise Limit Indicator Type 2211.

4.3. Selection of Microphone.

There are several factors to be considered in the selection of the most suitable microphone for a particular noise problem. Apart from environmental conditions such as temperature, humidity and wind there are problems of frequency range, directivity and dynamic range, to name some of the more important, purely technical aspects of the selection.

Generally speaking, *the condenser type microphone shows very good properties as regards temperature and long term stability, and has therefore been accepted as the most suitable measurement microphone.* Normally also humidity problems are of no great concern because of the heat developed by the cathode follower preamplifier on which the microphone cartridge is directly mechanically mounted. Problems with respect to measurements in wind are discussed later in this section and a variety of accessories are available for use on these occasions.

With regard to frequency range, directivity and dynamic range, however, there might not be any unique solution to the microphone problem, but certain compromises may have to be made. All these factors are interconnected and connected with the physical size of the microphone. *The smaller the physical dimensions of the microphone the wider is the frequency range and the lesser are the effects of directivity.*

On the other hand, *the sensitivity also becomes smaller as the dimensions decrease* so that only high intensity noise can be measured with the very small microphone (1/8"). A useful chart indicating the approximate dynamic ranges for the various microphones produced by Brüel & Kjær is given in Fig. 4.15.

The effective linear frequency range of a microphone is, to a certain extent, influenced by the sound reflection caused by the microphone itself and its mechanical mounting*). It thus also depends upon the angle between the

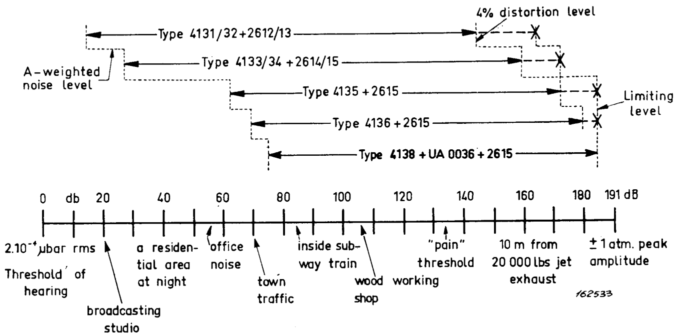


Fig. 4.15. Comparison of the dynamic ranges for the Brüel & Kjær condenser microphones.

direction of travel of the sound wave and the microphone diaphragm (Angle of incidence). Some typical frequency response characteristics for various Brüel & Kjær microphones are shown in Fig. 4.16, and the angle of sound incidence is marked on the curves. The curves marked, R, (random incidence response) refer to the response obtained when the microphone is placed in a diffuse sound field (the sound arriving with all angles of incidence, see also section 2.2 of chapter 2).

As will be clear from the above brief discussion and the table given in Fig. 4.17 some specific noise problems, where high intensity and/or very high frequency noise is involved, might need more or less specialized instrumentation for their solution. *In general, however, a compromise is made and either the microphone marked Type 4131 (with accessories) or the one marked Type 4134 is used.*

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*) See also chapter 2, section 2.2.

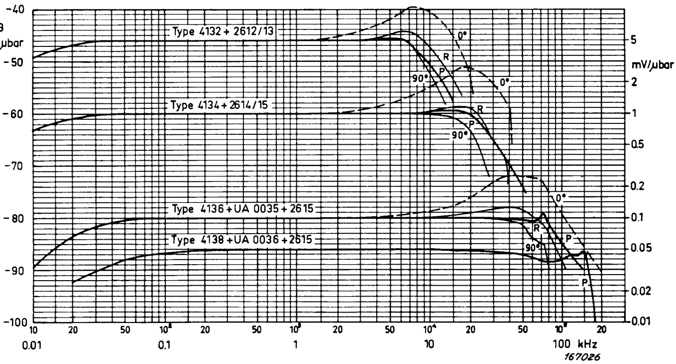

Fig. 4.16. Typical frequency response of different Brüel & Kjær condenser microphones (without accessories).
0° = free-field response at 0° (normal incidence).
90° = free-field response at 90° (grazing incidence).
R = random incidence response (diffuse field).
P = pressure response (towards higher frequencies the slope is about − 12 dB/octave).
NOTE: Valid with protecting grid for types 4131–34 (1" and 1/2") and without protecting grid for types 4135–36 (1/4") with exception of the dotted "R-curve" of 4135 which is with grid.

If *Type 4131* is chosen noise levels as low as 22 dB (A) may be measured, and when the noise source is placed in an *acoustically free field* and the microphone is pointed towards the source the frequency response of the microphone is linear up to some 18 kHz. This type of microphone is also normally supplied with the Precision Sound Level Meter Type 2203. On the other hand, in cases where measurements are to be made in more or less diffuse sound fields the frequency response of the microphone is not too excellent, see Fig. 4.16. However, by fitting it with a *Random Incidence*

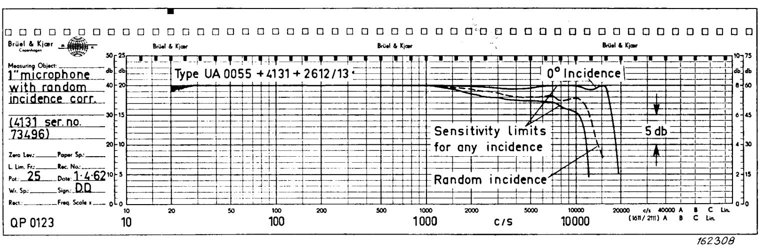

Fig. 4.18. Frequency response of the one inch condenser microphone Type 4131 equipped with the Random Incidence Corrector UA 0055.

Microphone Type	Main Application	Microphone Preamplifier	Optimum Free Field Response	Random Incidence Response	Pressure Response	Corr. factor with B&K read-out (typical)
4131, 1"	General SL measurements incl. low sound levels	2612 2613 2630 2203	20 Hz — 18 kHz (0° incidence)	20 Hz — 10 kHz (with UA 0055)	20 Hz — 2 kHz	
4132, 1"	Coupler measurements Audiometer calibration Sonic boom measurements Primary and secondary standard		20 Hz — 7 kHz (90° incidence)	20 Hz — 10 kHz	20 Hz — 7 kHz	0 dB (— 46 dB re 1 V/μbar)
4133, 1/2"	Free field gen. purpose Gen. SL measurements Loudspeaker — and microphone measurements etc.*)	2614 2615	20 Hz — 40 kHz (0° incidence)	20 Hz — 15 kHz (with UA 0052)	20 Hz — 5 kHz	+ 14 dB (— 60 dB re 1 V/μbar)
4134, 1/2"	Pressure gen. purpose Gen. SL measurements medium and high levels Coupler measurements Probe microphones		20 Hz — 20 kHz (90° incidence)	20 Hz — 25 kHz	20 Hz — 20 kHz	
4135, 1/4"	Free field SL measurements Model work	2614 2615	30 Hz — 120 kHz 0° incidence, without protection grid	30 Hz — 40 kHz with protection grid	30 Hz — 10 kHz	+ 28 dB (— 74 dB re 1 V/μbar)
4136, 1/4"	Random incidence SL measurements Coupler measurements Boundary layer Sharp pulses, click etc.	+adaptor UA 0035	30 Hz — 70 kHz 90° incidence, without protection grid	30 Hz — 70 kHz without protection grid	30 Hz — 70 kHz	+ 34 dB (— 80 dB re 1 V/μbar)
4138, 1/8"	Very high frequency and high level SL measurements Boundary layer — Very sharp pulses Model work Confined places Point source and point receiver	2614 2615 +adaptor UA 0036	30 Hz — 140 kHz	30 Hz — 140 kHz	30 Hz — 140 kHz	+ 40 dB (— 86 dB re 1 V/μbar)

Fig. 4.17. Chart indicating the main fields of application of the various Brüel & Kjær condenser microphones together with some pertinent considerations.

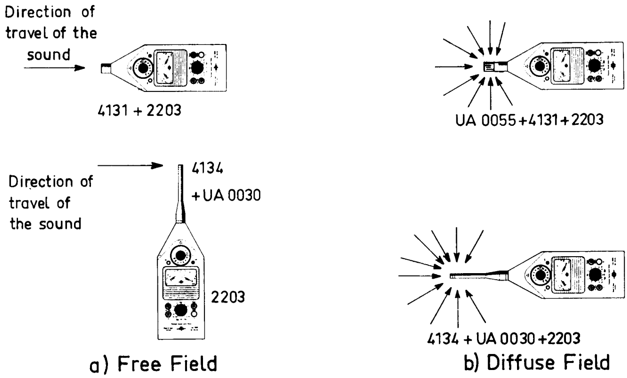

Fig. 4.19. Sketches showing how to use the Microphone Type 4131 and 4134 when the noise field is:
a) An acoustically free field.
b) An acoustically "diffuse" field.

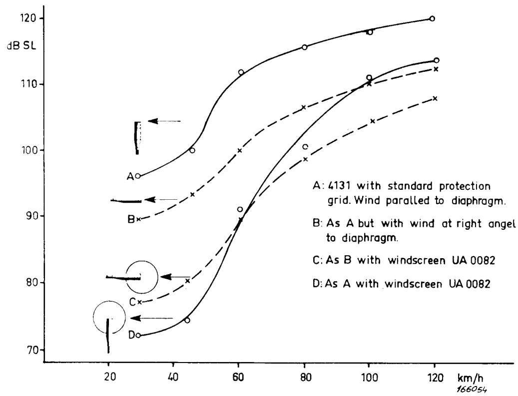

Fig. 4.20. Curves indicating wind noise as a function of wind speed (in the frequency range 20 Hz – 20 kHz) measured with and without application of the Windscreen UA 0082.

Corrector UA 0055 the response is considerably improved, Fig. 4.18. A great advantage gained by using a Microphone Type 4131 is that all Brüel & Kjær sound measuring equipment is then calibrated to *read the sound level (or S.P.L.) in dB re.* 2×10^{-5} *N/m*^{2} *(*2×10^{-4} *μbar) directly.*

If *Type 4134* is chosen the lowest noise level that can be measured will be of the order of 40 dB (A). The frequency response of this microphone is, on the other hand very good for noise measurements both in acoustically free fields and in diffuse fields. In contrast to Type 4131 the Microphone Type 4134

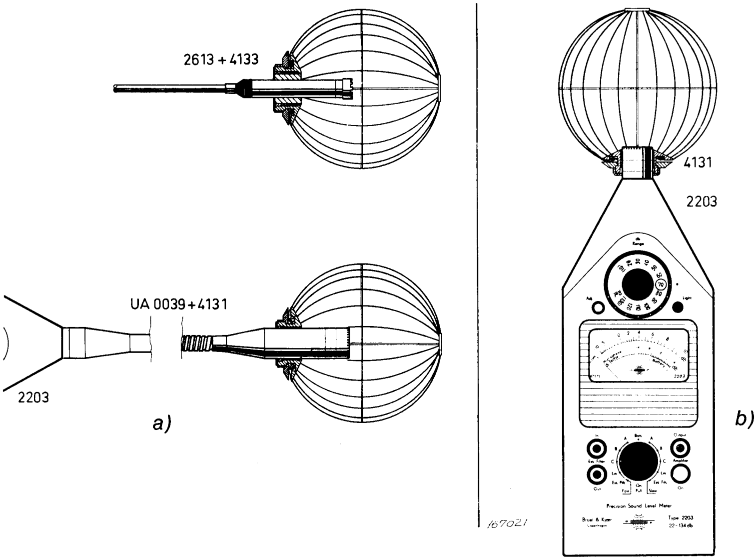

Fig. 4.21. Different methods of mounting the Windscreen Type UA 0082. The microphone should be mounted so that the diaphragm is close to the center of the screen (a) unless mechanical conditions restrict it (b).

should not, when measurements are made in *acoustically free fields,* be pointed towards the noise source. Actually, the *direction of travel of the sound wave should preferably be parallel to the microphone diaphragm,* i.e. the sound should impinge on the diaphragm at grazing incidence (90°). The frequency response will then be linear up to around 15 kHz, see Fig. 4.16. From Fig. 4.16 it can also be seen that the response to *randomly incident* sound (curve marked R) is practically *linear to around 25 kHz without the use of any "corrective" measures.* The sensitivity of the Microphone, however, does not allow a direct reading of sound level in dB re. 2×10^{-5} N/m^2 from the measuring amplifier or analyzers, but requires the addition of a "correction factor" of the order of 15 dB (Fig. 4.17).

In Fig. 4.19 sketches are shown demonstrating the use of the two microphones Type 4131 and Type 4134, respectively, both when measurements are made in acoustically free fields and in diffuse fields. As connected amplifier use is made of the Precision Sound Level Meter Type 2203. It should be noted that an Adaptor UA 0030 is necessary to mount the 1/2" Microphone Type 4134 onto the Sound Level Meter, which has originally been designed for use with 1" microphones (Type 4131).

When measurements are made out of doors it may often be necessary to "shield" the microphone from wind. The reason for this is that wind, when strong enough, causes a turbulent airstream to be developed around the microphone, which in turn causes the microphone diaphragm to move in a way similar to that produced by a high noise level. By applying a *Windscreen UA 0082* (or in very powerful uni-directional airstreams a Nose Cone), the undesired movement of the diaphragm will be reduced, Fig. 4.20. Sketches indicating the mounting of the Windscreen are shown in Fig. 4.21.

4.4. Selection of Analyzer and Read-out.

In section 4.2 some typical noise measuring arrangements were shown and the instrumentation necessary to perform a frequency analysis of the noise was briefly outlined. The frequency analysis equipment was here of two types: contiguous band analyzers (1/1 and 1/3 octave analyzers) and narrow band continuously sweeping analyzers. Both types of analyzers belong, however, to a group of analyzers normally called *constant percentage bandwidth analyzers* because the width of the analyzing filter, the filter bandwidth, is a constant percentage of the band center frequency independent of the absolute value of this frequency. A second group of frequency analyzers also exists where the filter bandwidth is a constant number of Hz, *not* proportional to the tuned in center frequency. These are called *constant bandwidth* analyzers. Normally the bandwidth of constant bandwidth analyzers is very narrow and allows the determination of a frequency spectrum in great detail. Such detailed analysis is important where the harmonic distortion in electrical or electro-acoustical equipment is to be investigated, or when analysis is made of the vibration response of randomly excited mechanical constructions con-

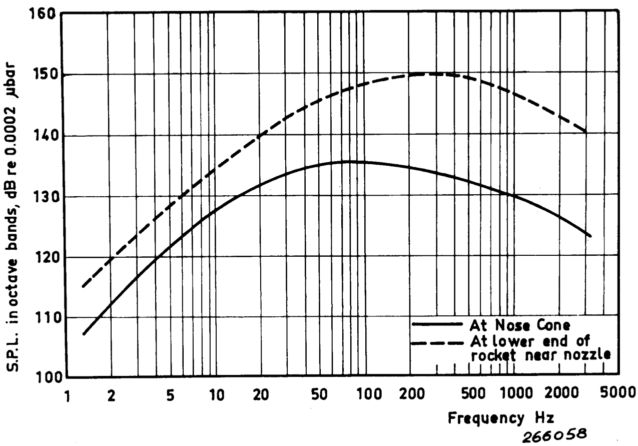

Fig. 4.22. Illustration of a noise spectrum which varies only slowly with frequency (noise from a jet aircraft).

taining a number of very lightly damped resonances. In the case of *acoustic noise measurements,* on the other hand, *too detailed* information of the noise spectrum is normally not desired and the previously mentioned *constant percentage type frequency analyzers are commonly preferred.* There are two basic reasons for this. Firstly, slight instabilities in noise producing machinery mostly produce a constant percentage type frequency deviation rather than of a constant absolute type, whereby measurement errors introduced by such instabilities are basically the same over the complete frequency range of measurement. Secondly, the ear responds to sound in much the same way as a constant percentage bandwidth analyzer having a bandwidth of about 1/3 octave (see also Chapter 3).

Following this trend in thought, a 1/3 octave frequency analyzer should be the most suitable analyzer for acoustic noise measurements. This is, however, not always true. Most noise control criteria are, for instance, based on 1/1 octave band data, and these data are normally much easier and less time consuming to obtain than 1/3 octave band data, when measurements are made

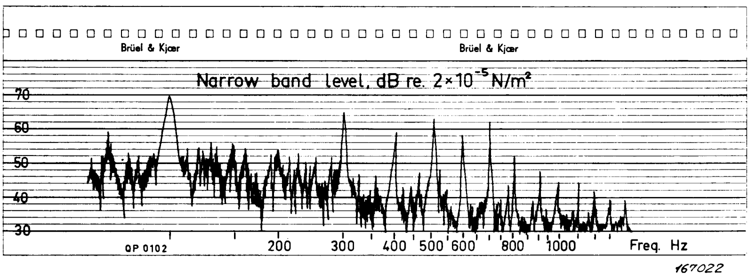

Fig. 4.23. A noise spectrum showing typical sharp peaks (noise from a large electric motor). ASEA.

in the field. On the other hand, when measurements are made of the noise produced by a specific machine, with the intent to investigate what changes can be made in the design of the machine to most effectively reduce the noise, even 1/3 octave bands are often too wide to obtain the required information. Also the kind of noise being investigated influences the choice of analyzer. If the noise is of a type producing continuous frequency spectra which varies only little in level with frequency, Fig. 4.22, 1/1 octave band analysis is completely adequate to describe the noise, while noise spectra containing more or less sharp peaks, Fig. 4.23, should preferably be described in terms of 1/3 octave or even narrower band data. For a determination of the loudness of the noise, however, 1/3 octave band data are generally sufficient due to their relation to the critical bandwidth of the ear (chapter 3).

Frequency Analyzer Type	Bandwidth	Type of Sweep	Remarks
2107 +1612	6 % – 29 % 1/3 and 1/1 Octave	Continuous Contiguous Bands	May be swept automatically
2112 (2603+1612)	1/3 and 1/1 Octave	Contiguous Bands	May be swept automatically
2203+1613	1/1 Octave	Contiguous Bands	Battery operated No automatic sweep
2211	1/3 or 1/1 Octave	Contiguous Bands	Simultaneous "read-out"

Fig. 4.24. Table of Brüel & Kjær frequency analysis equipment.

Before closing the discussion on the choice of frequency analyzer for acoustic noise measurement purposes it should be mentioned that in most cases the time required to perform a more detailed frequency analysis than one involving 1/1 octave bands normally is of such an order of magnitude that it requires the use of automatic recording. This is further discussed below in connection with the choice of read-out device. Finally, the table given in Fig. 4.24 indicates various types of frequency analyzers available from Brüel & Kjær.

Also the choice of read-out depends to a certain extent on the particular noise measurement problem at hand, and a number of questions have to be considered: What type of noise is involved? What time is available for measurement, what is the aim of the investigation, and what measurement accuracy is required? When the noise is of a more or less *"steady" type,* and the aim of the investigation is to obtain an estimate of the noise level, the read-out provided by the *instrument meter* of a precision sound level meter or an octave band analyzer, using its "Fast" or "Slow" characteristics*) may be quite satisfactory.

If, however, the noise is *transient or intermittent* (like for instance that produced by the fly-over of aircraft or by passing motor traffic) the use of *graphic level recording* or *statistical analysis* would be the appropriate kind of read-out. Also in cases of rapidly fluctuating noise levels the use of graphic level recording is normally preferred to a meter reading, due to the wide range of "averaging times" available on the recorder.

Finally, if a *careful frequency analysis* of the noise is required *graphic level recording* is desirable because the analysis can be carried out and recorded automatically on preprinted, frequency calibrated recording paper.

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*) See also section 4.2.

In connection with the above discussion on the choice of read-out it might be valuable to consider in a little more detail the concepts of averaging time, automatic recording of frequency analysis data and statistical analysis technique. Referring to chapter 2, section 2.1, the RMS value of a signal (noise) is given mathematically as:

$$A_{RMS} = \sqrt{\frac{1}{T} \int_0^T a^2 (t)\, dt.}$$

In this formula T is *the averaging time* i.e. the time used to physically determine the RMS value of the noise. Now, in the case of statistically varying signals such as noise the "correct" RMS value is only obtained if T is infinitely great. Because T cannot in practice be made infinitely great, and because the time of observation (reading of the meter) in practical noise measurements is normally considerably greater than the instrument averaging time, T, the observed RMS value of the noise fluctuates during measurements. By selecting a greater T in the instrument meter circuit the fluctuations can be brought to decrease.

Another factor which also influences the fluctuations in the observed RMS value is the measurement bandwidth. This is implicit in the formula given above, but it is very easy in practice to confirm that when the absolute measurement bandwidth decreases the fluctuations increase provided that the averaging time remains the same. A measure for the fluctuations in the RMS value of the noise is given by:

$$\varepsilon = \frac{1}{2\sqrt{BT}}$$

where B is the measurement bandwidth in Hz and T is the averaging time in seconds. To obtain a certain accuracy in a particular noise measurement it is therefore necessary to increase the averaging time when the absolute bandwidth of the measuring analyzer is decreased. This is one of the essential "laws" in the field of frequency analysis and is further discussed in a separate booklet*). It should be mentioned, however, that the use of a suitable averaging is very important in a number of noise measurement cases.

In graphic level recorders the averaging time is normally determined by the writing speed of the pen, the input range potentiometer and certain other factors. A chart indicating this relationship for the Brüel & Kjær Level Recorder Type 2305 is shown in Fig. 4.25, and the curve marked 50 (50) applies to the use of a 50 dB range potentiometer on the Recorder. This is the range potentiometer most commonly used in connection with noise measurements. When the Level Recorder Type 2305 is used in conjunction with the Audio Frequency Spectrometer Type 2112 for *frequency analysis* purposes (see Fig. 4.11) the averaging time, as given by Fig. 4.25, together

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*) **See also: "The Application of B & K Equipment to Frequency Analysis and Power Spectral Density Measurements".**

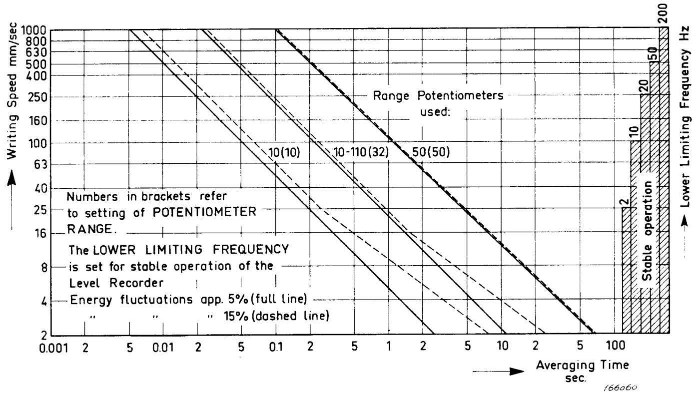


Fig. 4.25. Effective averaging time of the Level Recorder Type 2305 plotted against the setting of the WRITING SPEED control knob. The SETTINGS REFER TO THE LARGE FIGURES INDICATED AROUND THE CONTROL KNOB. The curves are given for standard resolution capabilities corresponding to the range potentiometer used and the setting of the knob marked POTENTIOMETER RANGE dB. Recommended settings of the control knob LOWER LIMITING FREQUENCY for stable operation of the Recorder are also shown.

with the absolute filter bandwidth determines the statistical error to be expected in the measurements, cfr. also formula stated above. Normally only the filters with the lowest center frequencies will be of great concern in this connection as these filters have the narrowest bandwidths.

Having selected a suitable averaging time the next problem that arises is the determination of the analyzer stepping (or scanning) rate. This is, when precalibrated paper is used on the Recorder, closely connected to the paper drive speed. Useful formulae, which also take the dynamic range of the measurements into consideration are given in Fig. 4.26.

Similar arguments are valid also when the Level Recorder is used in conjunction with the Frequency Analyzer Type 2107, and a set of formulae relating the Recorder writing speed, S, to the FREQUENCY ANALYSIS OCTAVE SELECTIVITY setting of the Analyzer is shown in Fig. 4.27.

Scan rate for 1/3 octave analysis:
Paper Speed $\leqq$ 0.05 $\times$ Writing Speed

Scan rate for 1/1 octave analysis:
Paper Speed $\leqq$ 0.15 $\times$ Writing Speed

Fig. 4.26. Formulae connecting the setting of the Level Recorder PAPER SPEED (small letters) with the writing speed of the pen (averaging time) when preprinted, frequency calibrated paper is used for recording of the output from the Audio Frequency Spectrometer Type 2112.

Table a.

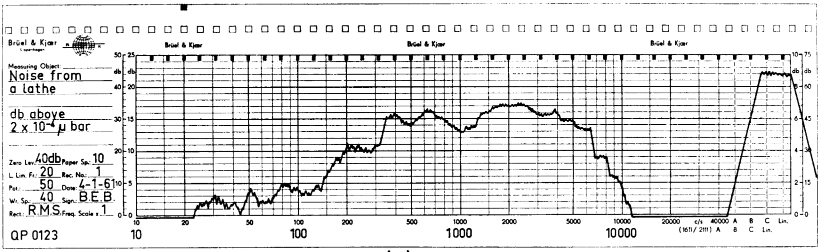
Setting of FREQ. ANAL. OCT. SELECT.	PAPER SPEED (Small letters) S (mm/sec)
"Max"	$S \leqq 0.10 \times$ Writing Speed
"40 dB"	$S \leqq 0.15 \times$ Writing Speed
"35 dB"	$S \leqq 0.20 \times$ Writing Speed
"30 dB"	$S \leqq 0.25 \times$ Writing Speed
"25 dB"	$S \leqq 0.30 \times$ Writing Speed
"20 dB"	$S \leqq 0.35 \times$ Writing Speed

Table b.

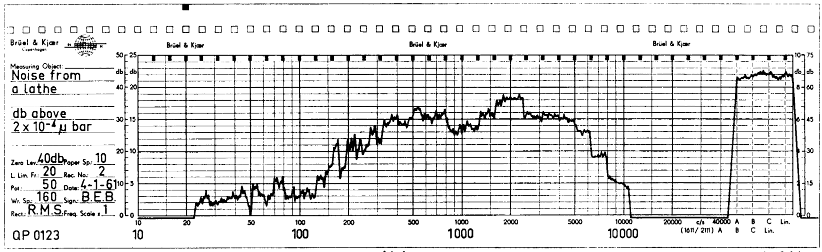
PAPER SPEED (S) (from Table a.)	10	3	1	0.3	0.1	0.03	0.01	0.003	0.001	0.0003
DRIVE SHAFT SPEED (RPM)	120	36	12	3.6	1.2	0.36	0.12	0.036	0.012	0.0036

Fig. 4.27. Similar to Fig. 4.26 but valid for use with the Frequency Analyzer Type 2107. It should be noted, however, that if frequency calibrated paper is not used, and the Analyzer drive is connected to the Level Recorder's "Drive Shaft II", the drive speed in RPM is found from Table b), independent of the actual paper drive speed.

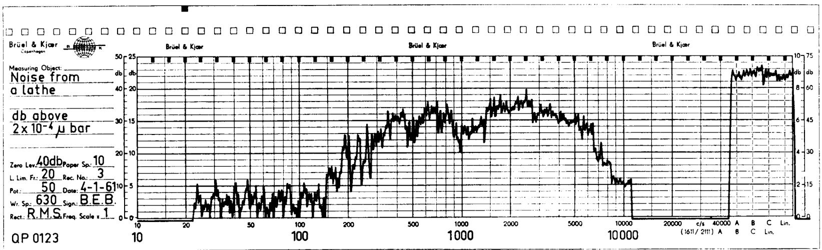
Before leaving the subjects of averaging time and frequency analysis it should be mentioned that for many purposes it would be reasonable to choose for the instrumentation *an averaging time which is of the same order as that of the human ear.* Just as a person can discern a rise and fall in sound levels, so can a record taken as a function of time, indicate similar fluctuations. Regarding the order of magnitude of the averaging time of the ear the reader is referred to chapter 3, section 3.5. Finally, the averaging time corresponding approximately to the "Fast" and "Slow" read-out characteristics of a sound level meter, and the corresponding setting of the Level Recorder Type 2305 are tabulated below.



(a) 161823



(b) 161824



(c) 161825

Fig. 4.28. 1/3 octave Spectrograms of the noise produced by a lathe recorded with three different averaging times:
a) Writing speed 40 mm/sec ($T \approx 3$ sec.)
b) Writing speed 160 mm/sec ($T \approx 0.65$ sec.)
c) Writing speed 630 mm/sec ($T \approx 0.16$ sec.).

S.L.M.	Averaging Time	2305 with 50 dB Pot. meter
"Fast"	0.27 sec.	400 (800) mm/sec.
"Slow"	1.05 sec.	100 (200) mm/sec.

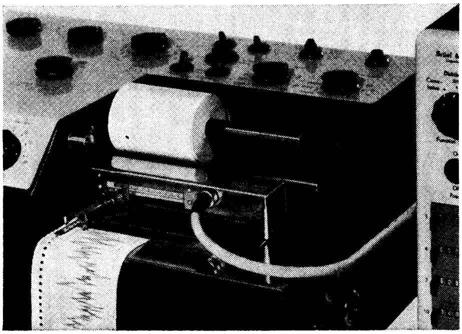


Fig. 4.29. Photograph showing how the contact set of the Statistical Distribution Analyzer Type 4220 is mounted onto the Level Recorder writing system.

Fig. 4.30. Photograph of the Statistical Distribution Analyzer with the level interval indicators. (The top indicator shows the total running time of the Analyzer).

Fig. 4.28 shows how the choice of averaging time affects the recording of a particular frequency spectrum.

Even if the graphic recording of noise measurements as a function of time is an excellent means of obtaining information on the time-dependency of the noise level many long time investigations may be more conveniently performed with the aid of an *automatic statistical distribution analyzer* such as the Brüel & Kjær Type 4420.

The Analyzer includes a set of twelve contacts, which is mounted on a Level Recorder Type 2305, see Fig. 4.29, and scanned by means of the Recorder's writing arm. In this way the recorded information is resolved into twelve level intervals ("class"-intervals) and the amount of time that the recording "stylus" spends within each interval is registered automatically on a set of indicators, Fig. 4.30. From the numbers registered on the indicators it is then possible to plot a so-called histogram of the noise, see Fig. 4.31. The great values

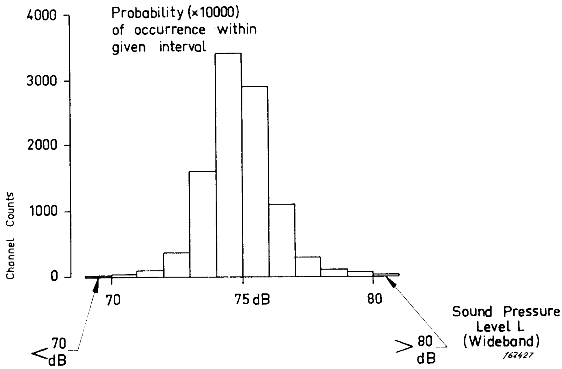


Fig. 4.31. Histogram of the noise level variations in a small machine shop measured over a period of 17 minutes.

of statistical analyses and the use of histograms, are that a reliable estimate of the mean value of a noise level is arrived at, a measure is obtained for the variability of the noise level around this mean, and it is possible to estimate what proportion of a certain period of time that a particular noise level is exceeded. These are all important factors in judging the seriousness of the exposure of people to a particular noise.

In the preceding discussion on noise measurement and analysis no mention has been made on detection and read-out devices suitable for measuring *impulsive noises,* i.e. the noise produced by an explosion, a sonic bang etc. The reason for this is that these kinds of noise cannot at present be easily measured and evaluated by means of metering instrumentation. Until a suitable, internationally accepted impulse sound level meter is available the best method of measuring impulse type noise may be to display the output from a microphone (with associated frequency linear amplifier) on the screen of a calibrated oscilloscope and photograph the oscillogram (and/or tape record the microphone output, see section 4.8) for later evaluation. Methods of evaluating such noises have been suggested by H. Niese, E. Port and others but are not as yet generally accepted. It is deemed, however, that the desired metering instrumentation for impulse sound measurements will be available in the not too distant future.

4.5. Calibration and Performance Checks.

Each instrument produced by Brüel & Kjær has been thoroughly checked and individually calibrated before it leaves the factory. All sound measuring amplifiers are calibrated in dB S.P.L. (Sound Pressure Level) re. 2×10^{-5} N/m² (2×10^{-4} μbar), as measured with a microphone giving an output of *5 millivolt*

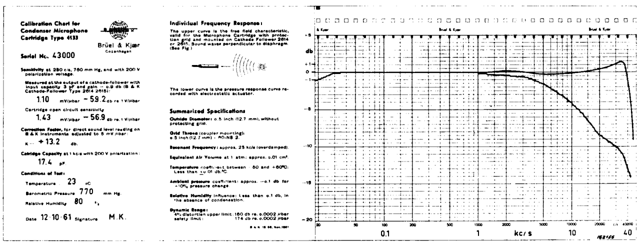


Fig. 4.32. Example of the calibration chart supplied with each Brüel & Kjær condenser microphone.

per microbar (5 mV/μbar). A special sensitivity adjustment arrangement allows, furthermore the adaption of microphones with sensitivities within the range 3.5 – 6 mV/μbar for direct reading of the S.P.L. in dB re. 2×10^{-5} N/m² (2×10^{-4} μbar).

The measurement transducers, in this case the microphones, are not only individually calibrated but they are also supplied with a full calibration chart, see Fig. 4.32.

In calibrating a "standard" noise measuring arrangement this can therefore be made directly from the figures given in the instrument data-sheets. Also, due to the excellent long-term stability of the B & K condenser microphone,

Fig. 4.33. Photograph of the Pistonphone Type 4220.

such a calibration would be of "lasting" value. If, however, cables are inserted between the microphone and the measuring amplifier, or other more "specialized" modifications are applied to the measuring set-up use should be made of the Brüel & Kjær *Pistonphone Type 4220* for calibration. The Pistonphone is a battery operated, easy-to-handle acoustic calibrator which, when used with a B & K condenser microphone produces a constant *sound pressure level of 124 dB* ±0.2 dB at 250 Hz at the microphone diaphragm. Using this sound pressure level as reference an accurate calibration of the equipment can be made. The use of a Pistonphone is also recommended for all precision sound measurements, and it allows an excellent check on the performance of the measuring instruments to be made whenever desired.
Although other, more elaborate calibration methods and equipment are available for laboratory calibration of microphones, the increased accuracy that can be obtained from such calibration methods is not generally justified for ordinary noise measurement purposes.
Fig. 4.33 shows a photograph of the Pistonphone Type 4220, while an example of its use is sketched in Fig. 4.34.

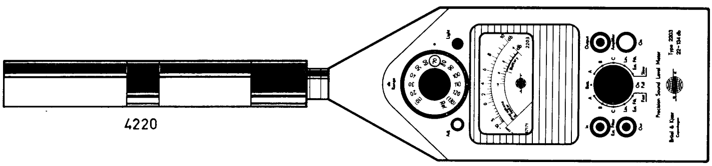


Fig. 4.34. Calibration of the Precision Sound Level Meter by means of the Pistonphone.

4.6. Effects of Reflections and Background Noise.
There are two main environmental effects that should be considered whenever noise measurements are carried out. These are the effects of sound reflection and of background noise.
As pointed out in chapter 2, section 2.2, any object, the physical dimensions of which are of the order of the wavelength of the sound or larger, will reflect the sound waves and thus cause a disturbance of the field. The amount of disturbance depends furthermore upon the sound reflecting properties of the object, its shape and the angle of the incident sound wave. *When the sound field is diffuse and/or the sound consists of many frequencies (wide-band noise) this presents no serious problems and the accuracy of the measurement results will depend mainly upon the accuracy of the instrumentation used.* However, if the sound being measured consists of free, plane or spherical, waves with one or two predominant frequencies there is a possibility of considerable undesired reflection and consequent measurement error. Measurements have shown that the maximum sound reflections from a human body will occur in the frequency range around 400 Hz. If the person operating the

noise measurement equipment stands close to the microphone a maximum uncertainty of around 6 dB may be obtained in this frequency range, somewhat dependent upon the sound absorbing properties of the operator's clothes. At frequencies above some 1,000 Hz reflections from the sound measuring amplifier may also upset the measured result, and *in critical*

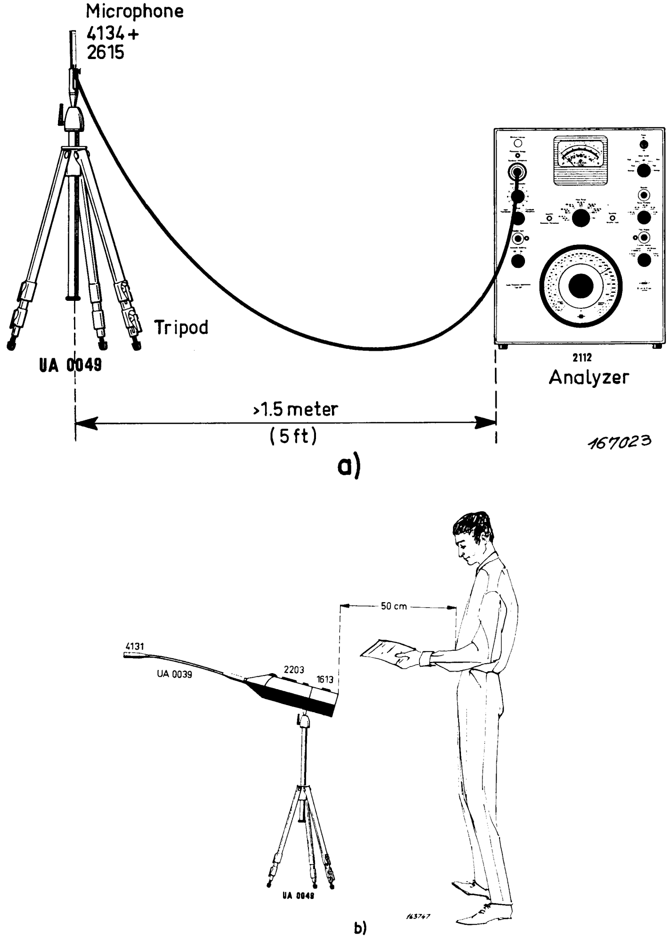


Fig. 4.35. Sketches showing how the measuring instruments should be operated to minimize undesired effects of reflection.
a) Example of mains operated equipment.
b) Use of the Precision Sound Level Meter Type 2203 (with Extension Connector UA 0039).

situations it is recommended to place the microphone some distance away from the measuring amplifier as well as from the operator, see Fig. 4.35. Fig. 4.35a) shows this for the case of mains operated measurement equipment while Fig. 4.35b) indicates how a small, portable sound level meter should be held to minimize reflections.
As mentioned above the presence of background noise at the place of measurement might affect the measured results. If, for instance, it is required to measure the noise produced by a particular piece of machinery in a factory the noise produced by other machinery might more or less "mask" that which is to be measured. In such cases either the machine being investigated has to be moved to a "quieter" place, or the other machinery, producing the background noise, has to be shut down. To be more able to judge when such measures have to be taken the chart shown in Fig. 4.36 should be consulted. If the noise level measured when the machine being investigated is shut off, i.e. the background noise level, is more than 10 dB lower than the noise level measured with the machine operating no correction of the measured result due to background noise is necessary. In cases where the difference between the "total" noise level and the background noise level is less than some 3 dB it is advisable to move the machine to a quieter place. For differences between 10 dB and 3 dB an approximate correction can be derived from the chart in Fig. 4.36. In many instances the influence of background noise upon the measurements may be reduced by choosing a narrower bandwidth for the

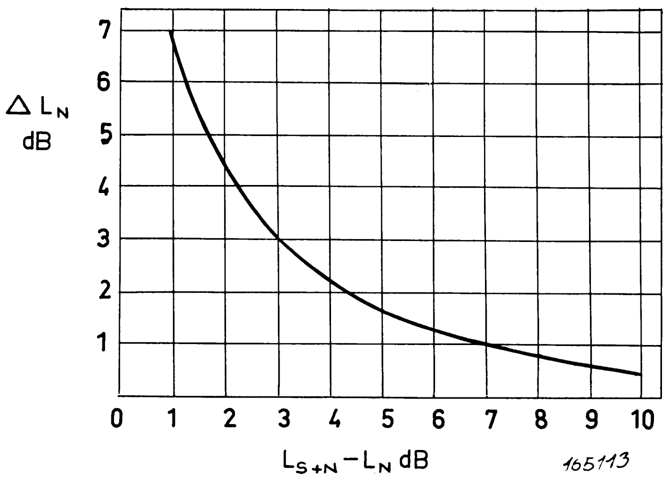


Fig. 4.36. Background noise correction chart.

frequency analysis. The conclusions drawn above with regard to corrective measures should also in this case, of course, be applied to each frequency band of interest in the analysis.

4.7. A General Measurement Scheme.

A careful study of the preceding sections of this chapter should enable the user of noise measurement equipment to perform thorough and meaningful noise measurements in most of the situations occurring in practice. It might be useful, however, to work out some sort of "measurement scheme" which, in more general terms, points out the main factors to be considered whenever noise measurements are to be made. The "scheme" outlined below may thus be taken as a "reminder" for the noise measurement engineer, and as a guide to the most important facts to be remembered and noted down.

1. *Determine by listening some main characteristics of the noise to be measured* (steady noise, transient noise, impulse noise, wide band noise, predominant tones etc.). Note down the most prominent characteristics observed in this way.
2. *Choose the most suitable instrumentation* (sound level meter, automatically recording frequency analyzer, oscilloscope, magnetic tape recorder). For further details, see sections 4.3, 4.4 and 4.8.
3. *Check instrument performance* (batteries, calibration data, microphone corrections etc.). See section 4.5.
4. *Make a sketch of the instrumentation system* with all type numbers and serial numbers included. (Section 4.2).
5. *Make a sketch of the measurement situation* (noise source position, microphone position(s) and orientation, position and approximate size of reflecting objects, room size etc.). See section 4.6.
6. *Measure the noise* and note down the noise level measured in each frequency band (overall S.P.L., dB (A), dB (B), dB (C), octave levels). Note down which characteristic, "Fast" or "Slow" that was used for the measurements, as well as an estimate of meter pointer fluctuations (± dB)*).
7. *Measure the background noise* in the same frequency bands as under Item 6 above and note down the results. (Section 4.6).

If measurements are made outdoors pertinent meteorological data should also be noted if they are considered important (wind, temperatures, humidity).

4.8. Signal Storage and Conversion.

In many cases of noise measurement it is convenient, and sometimes necessary to be able to record and store the original noise signal for later reproduction and analysis in the laboratory. Typical examples are the measurement and evaluation of impulsive noise like sonic bangs, transient or intermittent noise, and various kinds of semi-stationary noise.

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*) When measurement are made and recorded automatically on a graphic level recorder not only the type of analysis performed (time record, narrow band, 1/3 or 1/1 octave frequency analysis) has to be noted, but also the type of range potentiometer used on the recorder, the type of rectifier, the resolution, the writing speed (averaging time), paper speed and the zero level of the recording paper should be stated.

Normally the output signal from the measuring microphone is then fed to a magnetic tape recorder, either directly or via some amplifying device, see Fig. 4.37. When the noise is recorded on magnetic tape certain requirements have to be fulfilled by the tape recorder used. Firstly, it must be absolutely dependable so that there is no risk of "loosing" data because of improper functioning. Secondly it must have a flat frequency response, wide dynamic range and a minimum of wow and flutter. In some cases it is also important to operate the recorder from batteries and to have a variety of tape speeds available.
Many modern magnetic tape recorders fulfill most of these requirements, even though their basic recording principles may vary. In noise measurement,

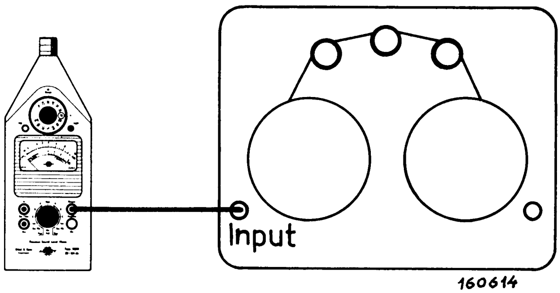

Fig. 4.37. Typical measuring arrangement used to record a transient noise onto magnetic tape for later analysis.

however, two types of recording have gained widespread usage, namely the direct recording (with high frequency bias) and the frequency modulation technique. When noise is to be recorded for later ordinary spectrum analysis of *single samples* the single track, *direct recording* technique is the simplest and most economical type of signal preservation. On the other hand if the stored data are to be analyzed with respect to time coincidence (impulse type measurements, cross power spectrum analysis, correlation analysis etc.), i.e. in cases where *phase preservation* is important and/or the signal contains necessary *DC information,* the multi-track *frequency modulation* technique is far superior to direct recording. Therefore when a tape recorder is chosen for a particular noise measurement all the above discussed factors should be duly considered.
During recording care should be taken not to overdrive the recorder amplifiers. For this purpose instrumentation tape recorders are often supplied with overload indicators which warn the operator when spurious overloadings occur. In cases where impulse noise is recorded it is advisable to set the recorder

gain control 10 to 30 dB lower than normal due to the very high crest-factors*) involved.

A problem which might also cause confusion on some occasions is the *calibration of the tape,* i.e. a determination of the absolute sound pressure level of the recorded noise. Here the use of the previously mentioned Brüel & Kjær *Pistonphone* Type 4220 is extremely helpful, in that it makes possible the recording of a reference signal with a very accurately known sound pressure level (see also section 4.5). Care need only be taken *either not to touch the gain controls of the instrumentation after the reference signal has been recorded, or to give exact information on changes in adjustment directly onto the tape.* If the tape recorder is supplied with an extra "voice" track (such as for instance the Brüel & Kjær Tape Recorder Type 7001) the necessary information may be recorded on this track. In this way it does not interfere with the measurements.

Even though the use of tape recording might save time "on the spot" because a thorough analysis of the noise can be postponed until the recording is back in the laboratory, it should be emphasized that *some kind of noise survey should also always take place "on the spot"* to ensure that the desired data have been recorded. Otherwise important factors might have been forgotten which would make a careful analysis of the tape in the laboratory completely useless.

The actual ultimate analysis of the recorded noise may take many forms and serve many purposes. It might, for instance, consist in the use of the signal for *psycho-acoustical experiments* and subjective comparison tests. In this connection multitrack recording and reproduction utilizing stereophonic principles are sometimes employed.

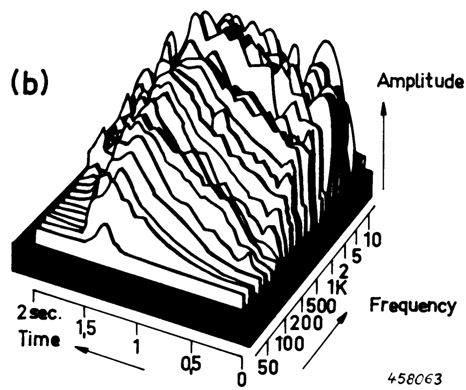

Fig. 4.38. Example of a three-dimensional analysis of a transient noise (a passing motor-cycle suddenly halting).

*) Crest factor = signal peak value/signal RMS-value, see also chapter 2, section 2.1

Or it may consist in a *frequency or time transformation* of the originally recorded signal by playing the tape back at a speed different from the one used during recording. This might be desirable to either bring a very low frequency signal up into the frequency range of commonly available frequency analyzers, or to bring a recorded "high" frequency signal down into the operating range of graphic pen recorders. An example of the latter is the transformation of a short impulse, say that produced by an explosion, down in frequency (lower tape speed) so that the exact shape of the impulse may be recorded graphically.

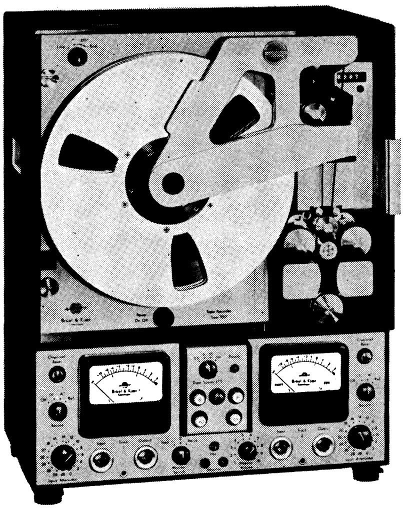

Fig. 4.39. Photograph of the Brüel & Kjær Tape Recorder Type 7001.

Finally, certain representative samples of the noise may be selected from the tape and formed into endless *tape loops* allowing very careful frequency analyses to be made. It is then possible to obtain a three-dimensional picture of for instance transient noise, see Fig. 4.38.
An instrumentation tape recorder which has been developed mainly for frequency transformation purposes is shown in Fig. 4.39. It is basically a *two-channel laboratory recorder* utilizing the frequency modulation technique. However, an extra voice channel has been included for marking and identification of special parts of the tape when desired. The voice channel is frequency limited and employs direct recording with high frequency bias.

4.9. Analog-to-Digital Transformation.

The Brüel & Kjær measuring instruments are basically of the analog type. However, the measured quantity may be transformed into digital form for

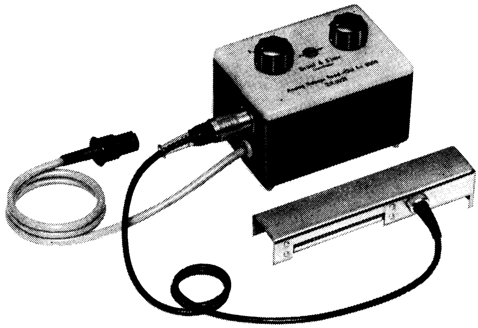

Fig. 4.40. The Analog Voltage Readout ZR 0021.

further data processing in several ways. One way of performing the necessary transformation is to substitute the electrical part of the Level Recorder directly by a digital voltmeter, or other types of analog-to-digital converters. A second method, which at the same time acts as a log converter (linear to logarithmic transformation), is to supply the Level Recorder with the Analog Voltage Readout ZR 0021, see Fig. 4.40, before the analog-to-digital conversion takes place. This small accessory instrument (ZR 0021) produces a DC voltage output which is proportional to the measured signal (RMS) level in dB by connecting a special linear potentiometer to the writing system of the Recorder. The potentiometer has 600 windings and gives a voltage resolution which is about 2.8 times that of the silver lamellae of the Recorder range potentiometer. It is possible to obtain the analog voltage output and use the Level Recorder for writing curves at the same time.

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5. Examples of Noise Measurement Practice.

5.1. Measurement of Noise Emitted by Machines. Sound Power Estimations.

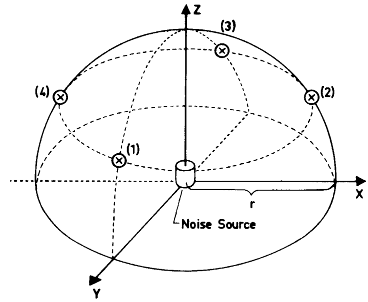
Because there are a great many noise sources and noise "environments" to which a person is daily exposed, and because the measurement techniques necessary to control these noises might vary considerably, it is the intention in this Chapter to exemplify some typical noise measurement techniques in common usage. To do so it may often be useful to distinguish between measurements on noise sources individually and measurements "in noisy environments", i.e. environments where the noise might be produced by several noise sources.

There are, of course, many cases where a clear distinction is difficult to make which will become evident from later sections. In this section, however, measurements are described which can be distinctly classified as measurements on individual noise sources, in that they are commonly made to characterize the noise produced by permanently installed machines.

The noise level produced by a specific machine at a certain place is, in general, not only dependent upon the sound radiating characteristics of the machine itself but also upon the type of mounting used as well as upon the environment in which the machine is placed (sound wave reflections). It has therefore been generally recommended to carry out the measurements with the machine mounted under acoustically well defined conditions as outlined for instance by the I.S.O. (Recommendation R.495). From such measurements it is also possible to estimate the acoustic power radiated from the machine, a quantity which is often very useful cfr. section 2.2 p. 13.

There are basically three different acoustical environments which may be used, the acoustically free field, the diffuse field and, under special circumstances the semi-reverberant field. The acoustically *free field* is, as defined in Section 2.2, a field without any sound reflecting obstacles. When operated under these circumstances the machine will radiate free progressive sound waves. Free field conditions are, however, not always possible to obtain in practice especially when the machine on which measurements are being made is relatively large. To obtain nearly ideal free field conditions special sound absorbing rooms, socalled anechoic chambers, have to be constructed, and in general the construction of such rooms requires large investments.

A practical approximation to the acoustically free field, which also approximates actual operating conditions for the noise source under test, is to mount a)

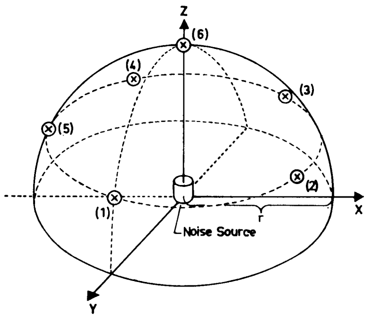


Micr. Pos.	X	Y	Z
(1)	0	0.82r	0.58r
(2)	0.82r	0	0.58r
(3)	0	-0.82r	0.58r
(4)	-0.82r	0	0.58r

r= Radius of Hemisphere

⊗ = Microphone Positions

b)



Micr. Pos.	X	Y	Z
(1)	0	0.89r	0.45r
(2)	0.85r	0.28r	0.45r
(3)	0.53r	-0.72r	0.45r
(4)	-0.53r	-0.72r	0.45r
(5)	-0.83r	0.28r	0.45r
(6)	0	0	r

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Fig. 5.1. Examples of the distribution of measuring points over a hemisphere surrounding the source of noise.
a) 4 measuring points.
b) 6 measuring points.

it on a smooth, hard reflecting plane above which no disturbing sound reflecting obstacles are present. Such conditions may be obtained for instance outdoors. The measurements are carried out by determining the sound pressure level at various points surrounding the machine, see Fig. 5.1. The points are selected so as to lie on a hypothetical hemisphere around the source, the radius of the hemisphere being large enough to ensure the existence of "far" field*) conditions.

To check that "far" field conditions really do exist at the measurement stations use can be made of the inverse-distance law, i.e. by doubling the distance to the source the sound pressure level should decrease by 6 dB. (This distance should actually be measured from the acoustic center of the source for the frequency band in question. For general purposes, however, it may be sufficiently accurate to measure the distance from the surface of the source.)

*) For definition of the acoustic "far" field, see section 2.2, p. 13.

Far field conditions exist roughly at distances of more than one wavelength away from the source or at 2 to 3 times the largest linear dimensions of the noise producing item–which ever is the greatest. In the most usual case a measurement distance of twice the linear dimensions of the machine will suffice.

From the free field measurements over a hemisphere as described above it is possible to estimate the sound power radiated from the noise source as well as its *directivity index.*

The *sound power* can be calculated from the formula:

$$10 \log_{10}\left(\frac{P}{P_o}\right) = 20 \log_{10} \left(\frac{p_m}{p_o}\right) + 10 \log_{10} \left(\frac{2 \pi r^2}{S_o}\right)$$

where:

P is the estimated sound power of the machine in W.

P_o is the general sound power reference level, $P_o = 10^{-12}$ W.

p_m is the mean sound pressure being measured.

p_o is the general sound pressure reference level, $p_o = 2 \times 10^{-5}$ N/m²
(2 × 10^{-4} μbar)

$2 \pi r^2$ is the surface of the test hemisphere of radius r.

S_o is a reference surface, $S_o = 1$ m².

According to the I.S.O. recommendation the quantity p_m^2 is the mean value in space of the squares of the RMS sound pressures recorded at the measurement stations. When the measuring points are chosen so that all the measurement stations are associated with equal areas on the hypothetical hemisphere, see Fig. 5.1, and there are n measurement points then:

$$p_m^2 = \frac{1}{n} \sum_n p_i^2$$

An alternative formula, which might be easier to use in practice is:

$$\frac{p_m}{p_o} = \sqrt{\frac{1}{n} \sum_n \left(\frac{p_i}{p_o}\right)^2}$$

where

$$\sum_n \left(\frac{p_i}{p_o}\right)^2 = \left(\frac{p_1}{p_o}\right)^2 + \left(\frac{p_2}{p_o}\right)^2 + \left(\frac{p_3}{p_o}\right)^2 + \cdots \left(\frac{p_n}{p_o}\right)^2$$

p_1; p_2; p_3 - - - p_n are the sound pressures measured at the various measurement stations.

When the mean sound pressure is determined as described above it is possible to also determine a *directivity index, DI.* This may be of considerable interest in practice as most noise sources do not radiate the sound equally in all directions, Fig. 5.2. The *directivity index* in the i'th direction can be calculated from the following formula:

$$DI = 20 \log_{10}\left(\frac{p_i}{p_o}\right) - 20 \log_{10}\left(\frac{p_m}{p_o}\right) + 3 \text{ dB.}$$

It should be mentioned that to effectively characterize a noise source both its sound power level and its directivity should be determined in 1/1 or 1/3 octave bands.

Also the measurements should be made with the machine operating under rated conditions (normal operating conditions) and it should preferably be mounted either on vibration isolators, which ensure no undesired transmission of vibrations to connected structures that might amplify the sound radiation, or under conditions similar to those recommended by the manufacturer for normal installation.
All the sound pressure levels measured should be corrected for the influence of background noise (section 4.6) before they are applied to the formulae given above.

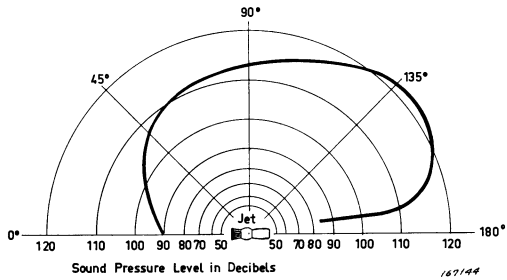


Fig. 5.2. Radiation pattern of a noise source with pronounced directivity.

The second type of well-defined acoustical environment is, as mentioned earlier the *diffuse field.* Such a field may be realized in a large, highly reverberant enclosure. In an ideally diffuse field the average sound energy density is uniform everywhere in the room (section 2.2, p. 14), and it is clear that in this case *it is not possible to determine* the directivity of the noise source.
On the other hand, the diffuseness of the field allows a relatively easy estimation of the sound power because the sound energy density in the room is directly related to the difference between the sound energy emitted by the machine and that absorbed by the room boundaries. A measure of the absorption at the boundaries is obtained by determining the room reverberation time T. When the volume of the room and its reverberation time are known the sound power level can be found from the formula:

$$10 \log_{10} \frac{P}{P_o} = 20 \log_{10} \frac{p_m}{p_o} - 10 \log_{10} \frac{T}{T_o} + 10 \log_{10} \frac{V}{V_o} - 14 \text{ dB.}$$

Here T_o is a "reference" reverberation time, $T_o = 1$ second, V is the volume of the room, $V_o = 1\ m^3$ ("reference" volume) and the factor 14 dB includes the constants relating the reverberation time to the sound absorption.
p_m is again the mean sound pressure, which in an ideally diffuse field can be obtained from a single measurement. However, in practice it is wise to take a number of measurements (n) at various measuring points in the field and average the results as described earlier.

The required minimum volume V of the room depends both on the geometric size of the noise source and on the wavelengths of the lowest frequency band being considered in the measurements. When 1/3 octave band measurements are used a simple formula relating the minimum volume of the room to the wavelength, λ_o, of the center frequency of the *lowest* 1/3 octave has been suggested:

$$V \geqq 9\,\lambda_o^3$$

With regard to the shape of the room ratios of height to width to length of $2:3:5$ or $1:\sqrt[3]{2}:\sqrt[3]{4}$ are often used. To further increase the diffuseness of the sound field the room may be constructed so that no two walls are parallel, see for instance Fig. 2.8, and use may be made of sound reflecting obstacles and/or rotating vanes. The reverberation time, T, of the room should be as great as possible ($T > 1.5$ sec.), and will be greater the harder and less absorbing the surface of the room is.

In carrying out the measurements it is good practice to place the noise source near one of the corners in the room, and to keep both the noise source and the microphone positions *at least* $\lambda_o/4$ away from all the room walls. Measurements should not be taken in the *immediate* vicinity of the noise source as its "near" field effects might here outrule the diffuseness of the reverberant field. Even though the acoustically free field and the diffuse field are the most well defined acoustic environments, and thus very well suited for measurements on noise sources, they are, for economical reasons, very rarely found in industrial establishments.

Therefore the third kind of acoustical environment mentioned at the beginning of this section, the *semi-reverberant field,* may be the most common environment. It is, from a measurement point of view, inferior to both the free field and the diffuse field, but because of its practical usefulness a brief discussion of the method of measurement to be used under semi-reverberant conditions should be included here.

The only requirement to the room in which such measurements are to be made is that it should be large enough to allow the microphone to be situated in the far field of the noise source. The main factor in the measurements is that a *noise source of known sound power,* and preferably with radiation and frequency characteristics similar to those produced by the machine to be tested, is available. What is actually accomplished by the measurements is thus a comparison between the sound power produced by the known noise source and that produced by the machine being investigated. If a source of known sound power is available which produces a sufficiently uniform power spectrum this may also be used as reference source.

Measurements are taken at a number of measurement positions, preferably situated over a hypothetical hemisphere with the machine as its center in the same manner as discussed earlier for free field measurements. The machine is then substituted by the reference source and the measurements repeated at the same measurement stations.

From the sound power level of the reference source and the mean sound pressure levels determined from the measurements the sound power level of the machine under test can be calculated:

$$10 \log_{10} \frac{P}{P_o} = 10 \log_{10} \frac{P_r}{P_o} + 20 \log_{10} \frac{p_m}{p_o} - 20 \log_{10} \frac{p_{m_r}}{p_o}$$

In the above formula the same notation has been used as in earlier formulae given in this section. However, P_r is the sound power of the reference source, and p_{m_r} is the mean sound pressure produced by the reference source at the surface of the hypothetical hemisphere.

Of course, only limited information on the directivity index of the machine can be obtained from measurements under these conditions.

It might be worth mentioning that if a suitable reference sound source is not available, a prototype of the machine to be tested may be taken to a well equipped acoustical laboratory where its sound power and directivity index can be established under more ideal conditions. This prototype can then later be used as a reference source.

If the machine cannot be moved it might be possible to find an acoustically equivalent location for the reference source. In such cases, however, it may be more advantageous to choose measurement positions in the reverberant field in the room (see also Fig. 2.9, p. 15) than on an hypothetical hemisphere surrounding the test object.

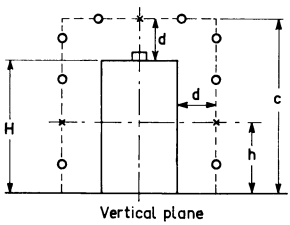
When comparison measurements are made it might not be necessary to perform a complete frequency analysis of the sound pressure level at each measurement station, and use may then be made of a portable precision sound level meter (section 4.2) switched either for linear operation or with the A-weighting network inserted.

The use of A-weighting may be preferable from a practical point of view because disturbing low frequency sounds are then automatically attenuated. (Care should be taken, however, that the main part of the sound radiation from the machine under test is not also heavily attenuated).

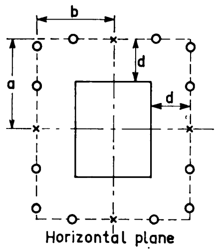
With regard to background noise the same considerations as described earlier should be applied.

Finally a method which might allow useful comparison measurements to be made in a standardized manner should be mentioned. This method is based on *near-field sound pressure level measurements* and makes use of a socalled "prescribed surface".

The "prescribed surface" should be as simple as possible and its area should be easy to calculate. It should conform approximately to the external casing of the machine being tested and should be marked out around the machine at a well defined average distance (to be specified in the test report or test code). The number and disposition of the measuring stations depend upon the irregularity of the acoustic field and on the size of the machine. An example of the disposition of measuring points on a "prescribed surface" is shown in Fig. 5.3.



l (Metres)	d (Metres)
$\geq 0{\cdot}25$	1
$< 0{\cdot}25$	$4l \leq d \leq 1$ $d > 0{\cdot}25$



l = Maximum linear dimension of machine
$h = \frac{H}{2}$ but not less than 0·25 Metre
x = Key measuring points
o = Other measuring points marked off at intervals of 1m. from key points

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Fig. 5.3. Disposition of measuring points on a "prescribed surface".

When the sound pressure at the various measurement stations have been determined a mean sound pressure, p_m, can be calculated as described earlier. Furthermore, if the area of the "prescribed surface" is set equal to the surface-area of an "equivalent" hemisphere the radius of this hemisphere can be found from

$$r = \sqrt{\frac{S}{2\pi}}$$

where S is the area of the "prescribed surface".
From the mean sound pressure, p_m, and the radius of the "equivalent" hemisphere, r, it is recommended to calculate the sound pressure level at a *reference distance*, d, from the machine according to the following formula:

$$20 \log_{10} \frac{p_d}{p_o} = 20 \log_{10} \frac{p_m}{p_o} - 20 \log_{10} \frac{d}{r}$$

The reference distance, d, should preferably be chosen equal to 1, 3 or 10 m, depending upon the size of the machine.

As the method of near-field sound pressure level measurements is, basically, intended for comparison purposes use may be made of A-weighting instead of octave (or 1/3 octave) band measurements.

Also in this case, however, proper correction for background noise must be made before determining p_m, and sound reflections from walls or near-by objects should have no significant influence on the measurements.

Before finishing this discussion on the measurement of noise emitted by machines it should be mentioned that in some cases the sound pressure level at a certain distance, d, may be a more meaningful quantity to specify than the sound power. This is especially true when the machine being tested produces an impulsive type noise which can be measured by some sort of impulse sound level meter and when the purpose of the measurement is to estimate the sound level of the noise at the position of the operator of the machine.

Also, as different types of machinery produce different types of noise, a number of specific test codes have already been prepared, see Chapter 6. It is likely that this kind of standardization will continue on an international basis and it is highly recommended when specific measurements are made, to follow already developed standard test codes whenever possible. In the test report reference should then be made to the test code used. The test report should, furthermore, contain the following general information:

Description of the machine and of its conditions of installation and operation.

Dimensional description of the test environment and location of the machine.*)

Meteorological conditions, if appropriate, e.g. ambient temperature, relative humidity and barometric pressure.

Description of measuring apparatus used:

1. When a sound level meter is used, the grade employed and the weighting network used should be stated.
2. When a frequency analyser is used, the bandwidth and centre frequencies should be stated.

Position of measuring points.

Results of sound pressure level measurements.

Background noise levels.

Sound pressure level values corrected for background noise if necessary.

When required, the calculated octave band sound power levels.

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*) When the test environment consists of a reverberant or semireverberant room the reverberation time of the room should also be stated.

When required the sound pressure level at the reference radius or reference surface corrected as for free-field conditions.

In the case of measurements in an anechoic environment, when required, the directivity index, DI.

Note. Values of the directivity index at intervals of 30° are generally sufficient.

In the cases where use have been made of a reference sound source the noise characteristics of the source.

Additional information to be given for near-field sound pressure level measurements.

Description of the prescribed surface and equivalent hemisphere.

Results of sound pressure level measurements, either average or individual, as specified in the test code.

Effects, if any, of environment.

Extrapolation of the results to the reference radius specified in the test code.

As mentioned in section 4.7 it is also of considerable value to determine, by listening, some of the main characteristics of the noise produced by the machine and note these characteristics down in the report (steady noise, transient noise, impulse noise, wide band noise, predominant tones etc.). In cases where standardized test codes exist such characteristics may already be accounted for in the code. Nevertheless, their restatement in the report may be of considerable value when the noise is being judged with respect to its psychological effects.

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5.2. Noise Measurements in Machine Shops and Offices. General Noise Control.

Representative examples of "noisy interior environments" are machine shops and typists offices (or rooms containing other business machines). The acoustic noise present in these types of room is normally composed of the noise emitted from several machines more or less simultaneously and the measurement problem here often consists of determining an average noise level. This average noise level is then compared with some accepted noise criterion for the specific type of room in question (see section 3.8) and on the basis of this comparison decisions may be made as to necessary changes in the environment.

The decision to make noise measurements in offices and machines shops is nearly always triggered by complaints about the noise. Because such complaints are sometimes more related to the annoying effect of the noise than to the noise *level* as such (except in cases where the noise level is high enough to cause hearing damage) no unique solution to the problem can be outlined. In many cases the psychological effect produced by the fact that the

noise is being measured and "something" done about it is as effective as the noise reduction actually obtained by the treatment finally decided upon. When complaints have been made about noise, however, it is always wise to take measurements, and thereby obtain an objective measure of the seriousness of the complaints.
The first measurements to be made might consist in measuring the average noise level in the room with a portable sound level meter (e.g. B & K Type 2203) in terms of dB (A). A reasonably accurate average level can be obtained by taking an arithmetic average of the dB (A) values measured at approximately equally spaced points in the room, see Fig. 5.4.*)

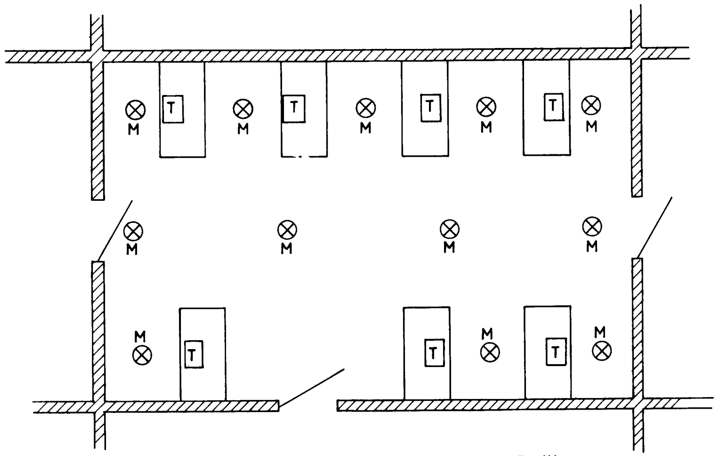

Fig. 5.4. Example of the distribution of measurement positions used determine the average noise level in a typical typing pool.

If the result of these measurements is found unacceptable, or questionable, a more thorough investigation in terms of octave or 1/3-octave noise spectrum analysis should be performed. It is then necessary to determine the average sound pressure level in the room within each octave (1/3 octave) frequency band separately and the use of an automatic recording technique as described in section 4.4 is highly recommended. In this way also written "evidence" is produced.

*) Actually the arithmetic average of the measured dB (A) values represents some sort of geometric average value. It has been shown, however, that if the spread in dB (A) values is less than 10 dB the difference between the arithmetic average of the dB (A) values and the actual arithmetic average of the weighted sound pressure is less than —1.5 dB.

Typical examples of cases where the *annoying* effect of the noise is a predominant factor may be found in larger typing pools. The typist does generally not complain about the noise produced by her own typewriter and for which she is prepared, but she may complain about the "overall" noise level produced by the other machines, especially if the room is somewhat reverberant. In such cases an acoustic treatment of the room resulting in only slightly lower "overall" noise level but significant changes in reverberation effects might produce the desired result.
On the other hand, examples of cases where the noise *level* effect is predominant are found in factory machine shops. After a first noise survey in terms of dB (A) at various measuring points it might be wise to select one or more of the measurement stations, which are considered to be representative, and then perform a more thorough analysis of the noise at these positions. Such thorough analyses normally consist in determining the frequency spectrum of the noise, as well as the statistical distribution of the overall noise level over a certain period of time, see also section 4.4, especially **Fig. 4.31**.
If it is felt, by comparing the measured results with various noise control criteria, that steps should be taken towards reduction of the noise a variety of considerations have to be made. As the subject is very involved and includes details on sound radiation, sound propagation, sound insulation and sound absorption as well as various aspects of mechanical vibrations in solid structures it is not possible to give here more than some basic practical hints.

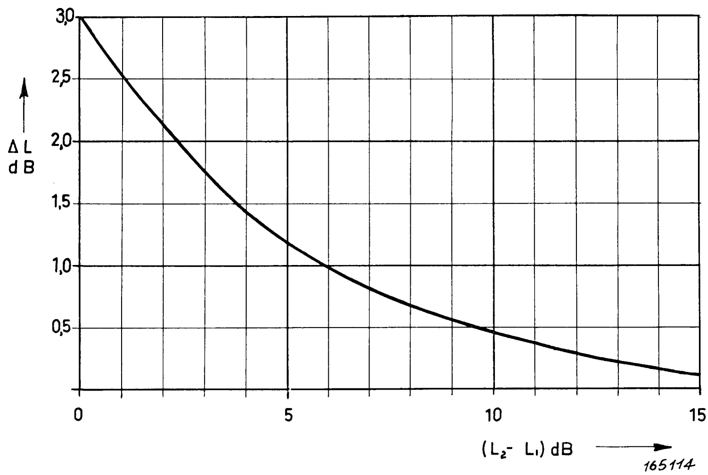

Fig. 5.5. Noise level addition chart. To use the chart the level difference (in dB) between the two noise levels, L_1 and L_2 to be combined is calculated (X-axis). From the chart a dB-value (ΔL) is then found which should be added to the highest of the levels, L_1 or L_2, to give the combined noise level.

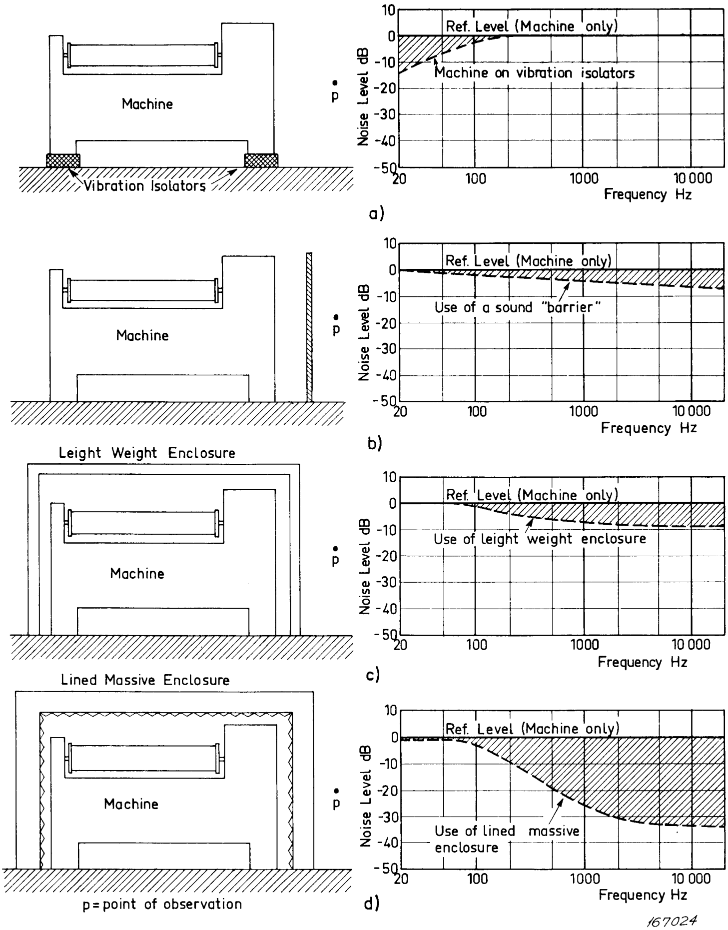

Fig. 5.6. Examples of various methods of noise source isolation:
a) Use of vibration isolators.
b) Use of a sound "barrier".
c) Use of a light-weight acoustic enclosure.
d) Use of a heavy massive enclosure lined with sound absorbing material.

For further details the reader is referred to the bibliography given at the end of this section.

The first problem to tackle when it is found that the noise level at a particular place is too high, is to locate the source(s) of the noise. If there is likely to be more than one source the contribution from the various sources should be determined. By measuring the noise level produced by each source separately

and adding the levels two by two according to the curve shown in Fig. 5.5 the total noise level can be calculated and a good idea obtained of the effects of the individual sources. (The result of the calculation should, of course, correspond to the noise level measured with all sources on!)
The next problem would then be to determine which source(s) should be considered the most serious one(s) and to study whether this source could be removed or quietened. To be able to quieten a noise source it is normally necessary to investigate closer the noise producing mechanism (vibrations) as well as the radiation characteristics of the source, and in many cases it is found that changes in the design may be necessary. If such changes are too complicated or too expensive to make it might be more convenient to work on the path of the noise from the source to the observer. When the observer is in the direct radiation field from the source, as is normally the case with a person operating a noisy machine, then either the operator should be supplied with some sort of ear defenders or an enclosure might have to be built around the machine. It should, however, be noted that if the noise is of a low frequency nature and the noise source is mounted directly on the floor (or wall) without the use of any vibration isolation mounts, the floor (or wall) may act as a sounding board. The main noise radiation will in such cases take place from the attached structures rather than from the vibration producing source itself and considerable noise reduction can be obtained simply by supporting the "source" on vibration isolators.
Fig. 5.6 gives an example on the effectiveness to be expected from different kinds of noise source isolation. It also indicates within which frequency ranges the methods suggested are most effective and a very efficient noise reduction may be obtained by applying two (or more) methods simultaneously, see Fig. 5.7.

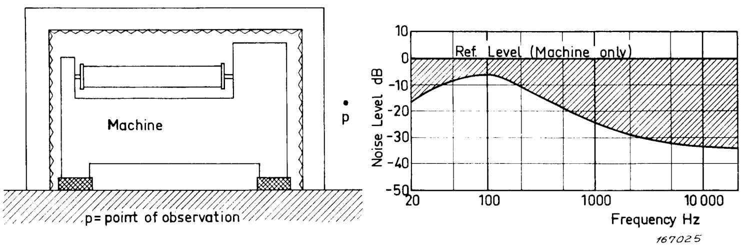

Fig. 5.7. Noise source isolation employing both the method a) and d) suggested in Fig. 5.6.

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5.3. Traffic Noise Control.

Social surveys in towns have shown that noise is one of the most undesirable by-products of the mechanized operations that characterize modern society. Also, these surveys showed that road traffic noise was one of the primary sources of noise annoyance and an active "fight" against this noise is being carried out in a number of countries.

One way of reducing traffic noise in towns and residential areas is to reduce the number of noisy vehicles passing through these areas. This may be done by rerouting heavy traffic and/or allowing traffic to pass through certain streets and roads in one direction only. Another method is to reduce the time during which the vehicles produce maximum noise, i.e. smoothing the flow of traffic by preventing unnecessary starts, stops and accelerations.

A third method consists in reducing the maximum noise that particular vehicles are capable of producing. The use of either (or all three) of these noise control methods do, however, require legislative means to be prepared by local or governmental authorities. In the cases of the first two methods careful noise surveys and statistical analyses of noise levels and occurrences must be carried out before decisions are made. The last method, on the other hand, is left more or less to technical considerations being made by the vehicle manufacturers.

In order to illustrate the use of statistical measurement techniques in conjunction with traffic noise problems some measurements were made by B & K in one of the main streets in Copenhagen in October 1963. The measuring arrangement used is shown in Fig. 5.8 and the microphone was placed about 1.2 m above the pavement.

Two different sampling times were utilized, 100 min. and 15 min. and one set of data was measured from 2.30 p.m. to 4.10 p.m. (100 min.). Seven sets of data were measured with a 15 min. sampling time from 2.15 p.m. to 4.15 p.m. and typical histograms are shown in Figs. 5.9 and 5.10. The dynamic range of the Level Recorder used to obtain the curve shown in Fig. 5.9 was 50 dB while the potentiometer range for the curve given in Fig. 5.10 was 25 dB. The Microphone Amplifier was switched to "linear".

The noise level of 85–87.5 dB of the curves in Fig. 5.10 takes place between 31 % and 37 % of the sampling time, while the noise level of 85–90 dB of the

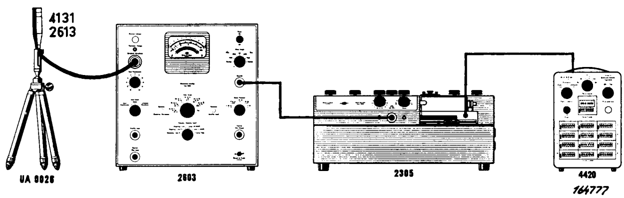


Fig. 5.8. Typical measuring arrangement used for statistical distribution analysis of traffic noise.

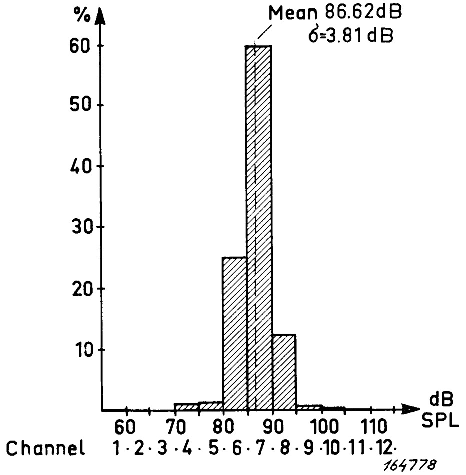


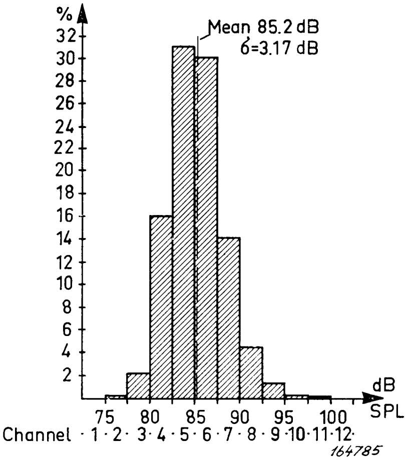
Fig. 5.9. Histogram of traffic noise measured on a busy street in Copenhagen during the hours 2.30 p.m. to 4.10 p.m.

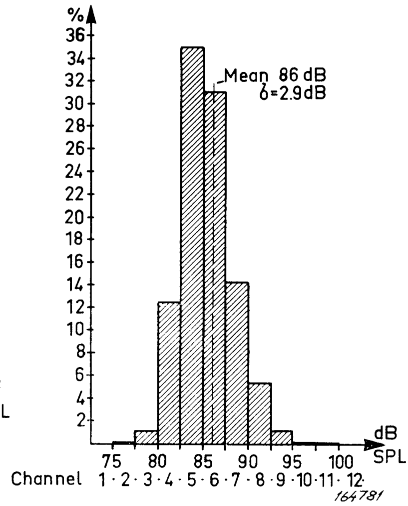
curve in Fig. 5.9 takes place 60 % of the sampling time. This looks a little confusing but the interval ranges and sampling time in the two cases are different. In Fig. 5.9 a channel unit is equal to 5 dB while in Fig. 5.10 it is only 2.5 dB, and the sampling times are, as stated above, 100 min. and 15 min. respectively. If the sampling time is increased, when measurements on traffic noise are made, one may find that the standard deviation is increasing. This can be explained by the relative large noise level variations during a day.

Another application of a Statistical Distribution Analyzer which may be of value in traffic investigations is as follows. If the phenomena being investigated follow no particular time sequence, it is possible to synchronize the triggering pulses with the events. This condition is obtained, if the period selector on the Statistical Distribution Analyzer Type 4420 is switched to the "Ext." position, and the synchronizing signal is connected to the "Ext. Gen." pin of the remote-control socket at the rear of the instrument.

The measuring set-up shown in Fig. 5.11 will give the statistical distribution of noise level with respect to the events (for example number of cars). The synchronizing signal should, however, be such that the "Ext. Gen." pin of the Statistical Distribution Analyzer is either shorted to ground or given a negative-going pulse, whereby the total register and the counter for which contact is made will register one digit.

Regarding the third method of traffic noise control, i.e. the reduction of the maximum noise produced by individual vehicles, certain restrictions have been laid down in many countries. Such restrictions generally demand the





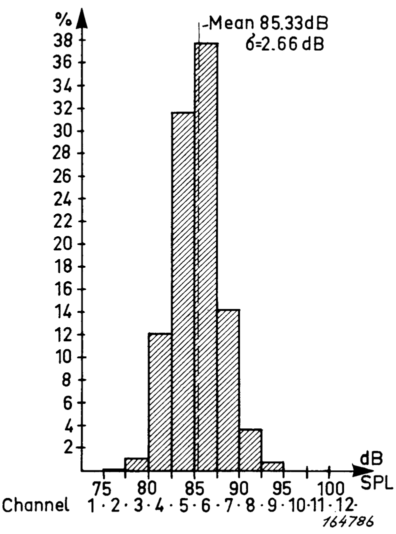


Fig. 5.10. Histograms of traffic noise obtained from 2.15 p.m. to 4.15 p.m. The sampling time for each curve is 15 min.

noise produced by a vehicle to be below specified limits when measured in a prescribed manner (a typical such limit is 85 dB (A)).

Three measurement methods have been internationally accepted and have been published in the form of an I.S.O.-Recommendation (R. 362). One of these is, however, given preference because it is related to normal driving conditions, and this method is sometimes termed the *moving vehicle test.* The second method is a stationary vehicle test, and when this test is used the

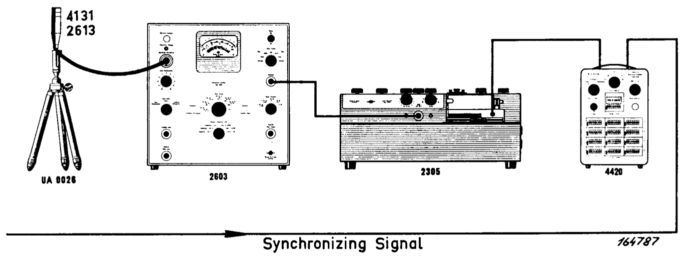


Fig. 5.11. Measuring arrangement for statistical distribution analysis of noise level with respect to events.

relationship between the result obtained and that of the moving vehicle test should be established for typical examples of the vehicle model concerned. The third method concerns measurements with the vehicle in motion under conditions which are different from the ISO reference test. In the following some details of the reference moving vehicle test will be outlined.

From a number of carefully controlled psycho-acoustic experiments it has been found that relatively good correlation exists between subjective assessment of motor vehicle noise and sound level meter readings obtained with the A-weighting network inserted. Even though deviations from this correlation in some cases (especially in the case of motorcycles) become very significant the international recommendation is based on the use of dB (A) as the measuring unit.

A suitable acoustical environment for the measurements would consist of an open space of some 50 m radius, of which the central 20 m, for example would consist of concrete, asphalt or equivalent material. Acoustical focussing effects and sites between parallel walls should be avoided. It is also important that wind and wind noise do not affect the measurements and the background noise level should be at least 10 dB below that produced by the test vehicle. Fig. 5.12 shows a sketch of a typical test site. The vehicle should follow the path C–C, and the microphones should be located 1.2 m above the ground level. When the front of the vehicle reaches the position indicated in the figure by the line A–A the throttle should be fully opened and held there until the rear of the vehicle reaches the line marked B–B. *At least two measurements should be made on each side of the vehicle as it passes the measuring positions.*

The vehicle should be driven in second gear (or third gear if it has more than 4 gears) at a speed corresponding to 3/4 of the maximum engine speed, or at 50 km/h, whichever is the lowest.

The measurement report should, apart from the sound level meter readings, also include details on the state of loading of the vehicle as well as the basis of horse power rating.
From the three methods of traffic noise control discussed above, i.e. rerouting of the traffic in towns and residential areas, smoothing of the traffic flow, and reducing the maximum noise emitted from vehicles the latter is, in the long run, the only really effective method. Local rerouting and smoothing of traffic might be helpful over certain, limited periods of time, but as both the number of vehicles and the local population densities are assumed to increase more or less continuously in the future *the reduction of the noise produced by the vehicles themselves must be seriously considered by the authorities as well as by the vehicle manufacturers.* Not only intake and exhaust noises are important in this connection but also the noise produced by the mechanical functioning of for instance large diesel engines should be further investigated and reduced.

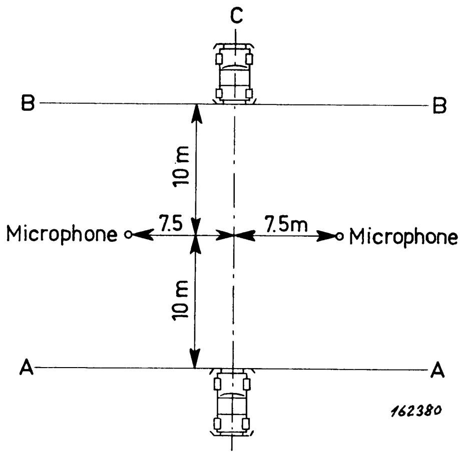


Fig. 5.12. Typical test site used for the moving vehicle test recommended by I.S.O.

The problem of reducing the noise emitted from motor vehicles is, however, in some cases not only a technical problem. Especially with regard to motorcycles and sports cars some people (especially young motor enthusiasts) seem to demand that their vehicle produces a certain amount of "roaring". This might put the sports car and motorcycle manufacturer into an economical dilemma when effective noise control regulations are laid down, and it seems that some psychological and educational efforts are necessary to change the situation into one which will be acceptable in societies of the future.

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5.4. Aircraft Noise Measurement and Control.

The problem of aircraft noise in the vicinity of airports has increased rapidly all over the world during the past decades and, as expressed by Prof. E. J. Richards in his paper "The Constraining Order of Airport Noise": "It does not require a very large crystal ball to envisage the growth of aviation during the next fifteen years." It is therefore very important when designing new aircraft, when recommending their take-off and landing procedures ,and when planning new airports to seriously consider the noise problems involved.

As the character of the noise produced by various types of flight vehicles, such as piston engined aircraft, jet aircraft, helicopters and vertical take-off and landing vehicles, varies considerably, it has been very difficult to find an objective measure for the noise which correlates reasonably well with an average subjective impression.

In 1959, however, a method of assessing noise nuisance from *piston engined aircraft* as well as from *jet aircraft* was suggested by K. D. Kryter, and the term PNdB (perceived noise level) was introduced. This method along with various restrictions and extensions, has now been internationally recommended in the I.S.O. Recommendation No. 507.

One of the great advantages of the existence of an internationally accepted method of aircraft noise measurement and evaluation is that well defined measures of accepted noise levels may be laid down. Even though the exact value of these measures might vary from airport to airport and from country to country they can, nevertheless, be clearly understood by everyone concerned. As an example of such measures it may be mentioned that there is a tendency at present to accept values of 110–112 PNdB during daytime and about 100 PNdB during the night as maximum tolerable noise levels in built-up areas near airfields. These values are, however, high and every technical effort possible should be made to reduce them.

The I.S.O. Recommendation No. 507 does *only* apply to the noise produced by piston engined and jet aircraft and it is specifically stated that the Recommendation does *not* apply directly to the noise produced by helicopters or vertical take-off flight vehicles. The noise produced by these vehicles is being intensively investigated at present (1967).

In describing the aircraft noise around an airport various methods may be employed. One method consists in actually measuring and analyzing the noise at a large number of different points around the airfield over a period of several days (or weeks, or months). This is a very time-consuming method and may, in a somewhat modified version, be more applicable for monitoring purposes. A more direct method is to determine the noise characteristics received on ground from a certain type of aircraft operating under various conditions, and then, from the measured data, estimate different sets of noise "contours"*) which the aircraft will produce around a particular airport. When such noise contours are estimated for all types of aircraft operating from the airport in question a relatively reliable estimate of the total noise nuisance produced in near-by areas may be made. The estimated noise levels can, of course, be conveniently checked by a few direct measurements.

To produce the desired estimates of noise contours a certain number of measurements have to be made of the noise from the aircraft. In carrying out these measurements the measuring microphone should be located on an essentially flat terrain, 1.2 m above ground level. The ground should preferably exhibit low sound absorption characteristics ("reflecting" surface), and no obstruction which might influence the sound field from the aircraft should be present within the cone shown in Fig. 5.13.

As shown in the figure the measurements can be made by means of a Precision Sound Level Meter (B & K Type 2203) switched for operation "Lin. 20–20ooo Hz" and recorded on a high quality magnetic tape recorder (f. inst. B & K Type 7001). The arrangement should be acoustically calibrated by means of a Pistonphone as described in section 4.5, and if necessary the microphone should be supplied with a Windscreen (UA 0082, Fig. 4.21).

Tape recordings are then made for a number of aircraft operating conditions (full power, climb power, reduced climb power, etc.) and the vertical distance from the microphone to the aircraft as this passes over the microphone must be determined exactly. Furthermore, it is desirable to repeat the measurements for several different flight altitudes, and to check that background noise does not influence the measurements (see also section 4.6).

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*) By a noise "contour" is here meant a contour of equal maximum perceived noise level describing the noise field on ground.

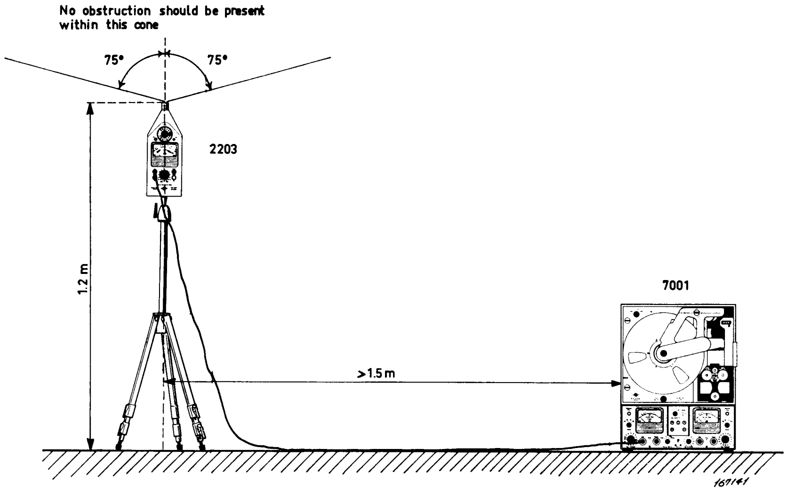

Fig. 5.13. Measuring arrangement used to record the noise from aircraft fly-over.

Analyses of the recorded data can be made in the laboratory by means of an arrangement as shown in Fig. 5.14. The frequency analysis should be made in terms of octave bands and the *maximum sound pressure level in each octave* noted. (A frequency analysis of each measurement according to the above mentioned measurement conditions must, of course, be made.)
From the maximum sound pressure levels in each octave band it is now possible to estimate a maximum perceived noise level from the chart shown in Fig. 5.15 and the formula:

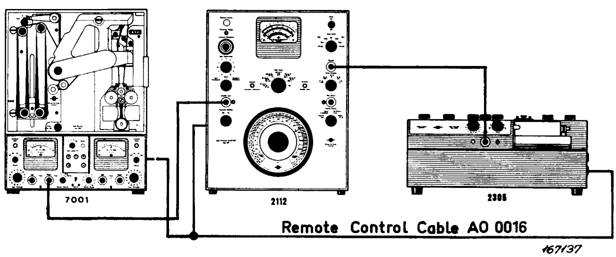

Fig. 5.14. Arrangement used for laboratory analysis of data recorded on magnetic tape.

$$N_{tot} = N_{max} + 0.3\,(\Sigma N - N_{max})$$

Actually, the calculation procedure to be used is analogous to the one suggested by Stevens for the calculation of loudness (see Appendix C, p. A 11) with the exception that Stevens' loudness index curves are substituted by the Noys curves given in Fig. 5.15. N_{tot} (Noys) is converted to PNdB by the scale shown to the right in Fig. 5.15.

In this way a maximum PNdB-value can be assigned to each measurement condition and a curve indicating the maximum perceived noise level as a function of aircraft altitude, can be constructed for each specified operating condition of the aircraft. An example of such a curve is shown in Fig. 5.16. (It might be mentioned at this point that a curve of the kind shown in Fig. 5.16

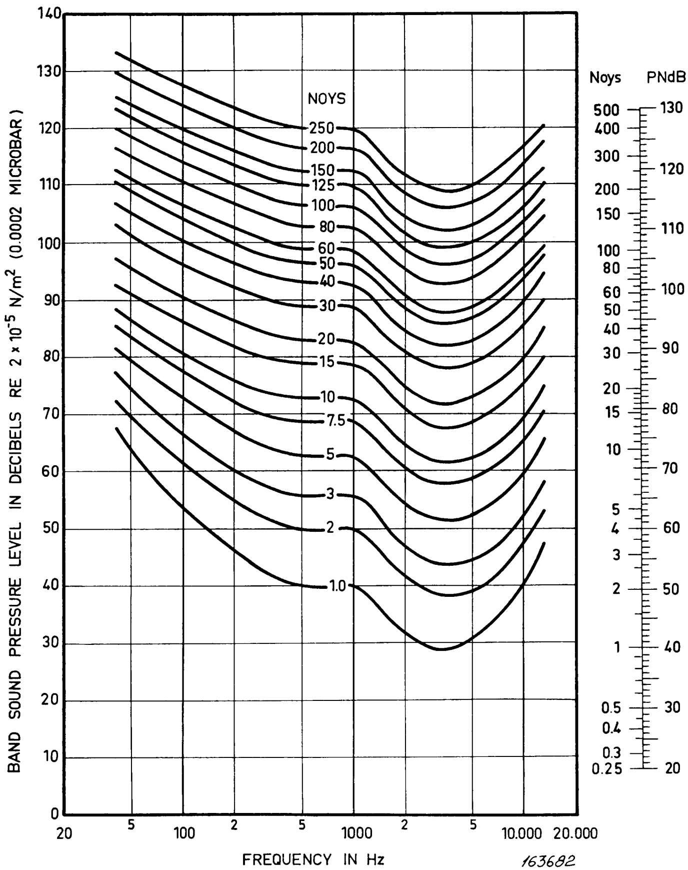

Fig. 5.15. Equal "noisiness" contours.

may also be estimated from only a few measurement points taking the inverse distance law and the attenuation characteristics of the air as a function of distance and frequency into account).

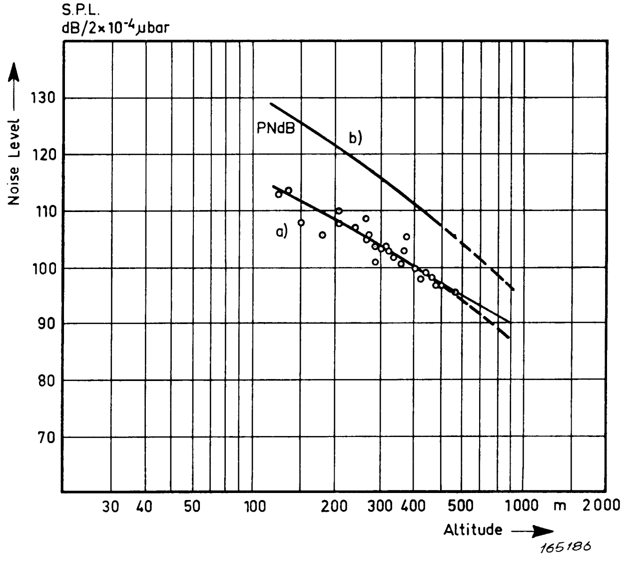

Fig. 5.16. Acoustic noise produced by Caravelle Stage III during take off. (Engine setting: 7350 r.p.m. Climb Power). The noise is measured as a function of the shortest distance from the measuring point to the aircraft.
a) The overall maximum sound pressure level during fly-over.
b) PN dB values obtained under the same conditions as a). (F. Ingerslev and E. Smed).

When curves of the kind shown in Fig. 5.16 and the flight path of the aircraft are known the maximum perceived noise level on ground can be easily estimated and "mapped", assuming that the noise field produced by the aircraft is rotationally symmetrical. If the flight path of the aircraft is not straight and the assumption of a rotationally symmetric noise field is violated proper corrections should be made to the estimates.

To allow estimates of the above type to be made, as well as other theoretical predictions, the measured acoustical data should be accompanied by the following additional information.

Atmospheric conditions:

Air temperature in degrees Celcius Relative humidity in per cent	measured at the same point near ground level in the neighbourhood of the observation point.

Atmospheric pressure at sea level (1 mb = 100 N/m^2 = 9.87 $\times$ 10^{-4} atm)	in millibars or in newtons per square meter or in normal atmospheres.
Wind speed at the microphone in metres per second (1 kn = 0.5144 m/s)	or in knots, and direction.

Aircraft conditions:

Type and model of aircraft and engine
Aircraft gross mass (total mass in kilogrammes or in pounds)
(1 lb = 0.4536 kg)
Aircraft configuration (flap and landing gear positions)
Airspeed in metres per second (or knots)
Aircraft height in metres (or feet)
(1 ft = 0.3048 m)
Power setting (rev/min, engine pressure ratio or other characteristic specified by the manufacturer).

There are two basic noise contour sets for aircraft in flight which might be of special importance: The noise contour set for *take-off operation,* and the noise contour set for *landing operation.*

In the case of *take-off operation* the following operating conditions should be known:

a) maximum aircraft gross weight (maximum total mass).
b) maximum power.
c) meteorological conditions equivalent to the International Civil Aviation Organization (I C A O) Standard Atmosphere with zero head wind.
d) climb speed of V_2*) + 10 knots (1 knot = 0.5144 m/s).

When these conditions are known, as well as the relevant set of take-off profiles specified for the type of aircraft in question (see for instance Fig. 5.17), the aircraft flight path during take-off may be estimated and used in the procedure for noise estimations described above.

Similarly, in the case of *landing operation* it is important to know:

a) the use of instrument landing procedures with a 3° glide slope,
b) maximum engine power, consistent with normal aircraft configuration, to maintain a uniform rate of descent consistent with a) above.

To illustrate the final result of aircraft noise estimations made according to the described procedures Fig. 5.18 shows a "map" of the noise produced by a Caravelle III during take-off from Oslo Airport.

It is also possible to construct a set of noise contours for aircraft operating on ground. As this will normally have to be done with the aircraft operating in a stationary position the near-by contours will simply be a directional

*) V_2 is the initial climb-out safety speed, as defined by I C A O (I C A O Annex B, Aeroplane Performance P A M C).

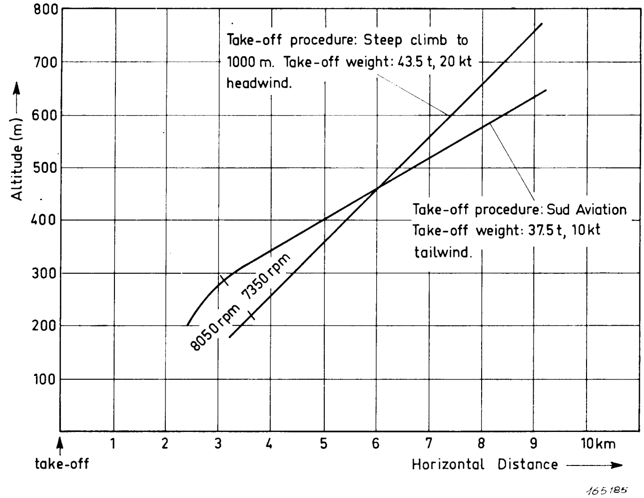

Fig. 5.17. Take off profiles for two different take off procedures at standard temperature (Caravelle Se 210).

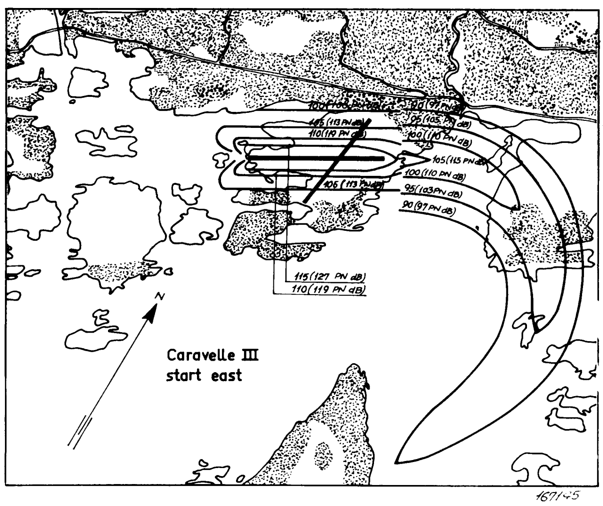

Fig. 5.18. Example of a noise contour "map" describing the noise disturbance produced by a Caravelle III during take-off.

characteristic of the noise produced by the aircraft. The noise contours at more distant points, however, will be greatly affected by buildings, wind, ground attenuation and temperature.

Although the noise level (or rather the "noisiness" level) in PNdB is at present regarded as a relevant measure of aircraft noise as perceived on ground, other factors such as the frequency of occurrence of noisy flights, periods over which the noise exceeds, say 80 PNdB etc. also influence the nuisance caused by the noise. To try and take some of the known factors, besides the perceived noise level, into account in estimating noise nuisance effects various measures have been suggested such as the socalled Noise and Number Index (N.N.I.), the Index of Community Nuisance (I.C.N.) and others.

In the I.S.O. Recommendation No. 507 these factors have been considered in a measure defined as the *Noise exposure index*, $\overline{Q}$:*)

$$\overline{Q} = k \times \log \frac{1}{T} \sum_i N_i \times T_i \times 10^{L_i/k}$$

Where L_i = maximum perceived noise level ($PNdB_{max}$) of an aircraft operation.

T_i = duration in seconds during which the recorded signal when passed through weighting network A (IEC Rec. 179) remains within 10 dB of the highest level.

N = number of operations in a specified time interval (e.g. day-time, night-time etc.)

T = specified time interval.

K = 10 (recommended for planning purposes).

Actually, measures of noise nuisance in terms of $\overline{Q}$, N.N.I., I.C.N. etc. are based on a number of social surveys and their greatest value at present might be the possibility they offer for comparison purposes. Even though a "critical" range of N.N.I. values of 50 to 60 N.N.I. has been suggested as a maximum tolerable "nuisance" during day-time much more work needs to be done before any real "nuisance scale" can be established.

When an effective control of the noise produced by aircraft is desired it is not enough to estimate the noise from various aircraft and determine a noise exposure index. The actually produced noise must also be measured and monitored at various selected positions around the airport. Such monitoring systems are presently in use at many airports and the need for aircraft noise monitoring is likely to increase greatly in the future. Because the procedure used to determine the perceived noise level in PNdB requires a certain amount of calculation it is not too well suited for monitoring purposes and some other measure is therefore normally used. It has been recognized that it is possible to obtain an approximate value of the maximum perceived noise level by using a precision sound level meter with weighting network A inserted, i.e. by measuring the maximum dB (A) value with a certain correction factor. This

*) Subject to revision.

method is thus often used in monitoring systems, at least as a "first measure".*) If the noise is simultaneously recorded on a magnetic tape recorder (unweighted) it is possible later to play back the tape and analyze the critical part of the recording more thoroughly in terms of PNdB.

A measuring system of this kind has been installed at Oslo Airport, Fig. 5.19, and its principle of operation is briefly: When the signal from one of the microphones exceeds a preset limit in dB (A), a number of relays are activated at the control measurement station starting a magnetic tape recorder and indicating visually that certain noise limits have been exceeded by lighting a number of red indicator lamps. The lamps are located on special control panels both at the measurement station and in the airport control tower. To allow the time of exceedance to be determined the exact time is recorded on a second track of the the magnetic tape.

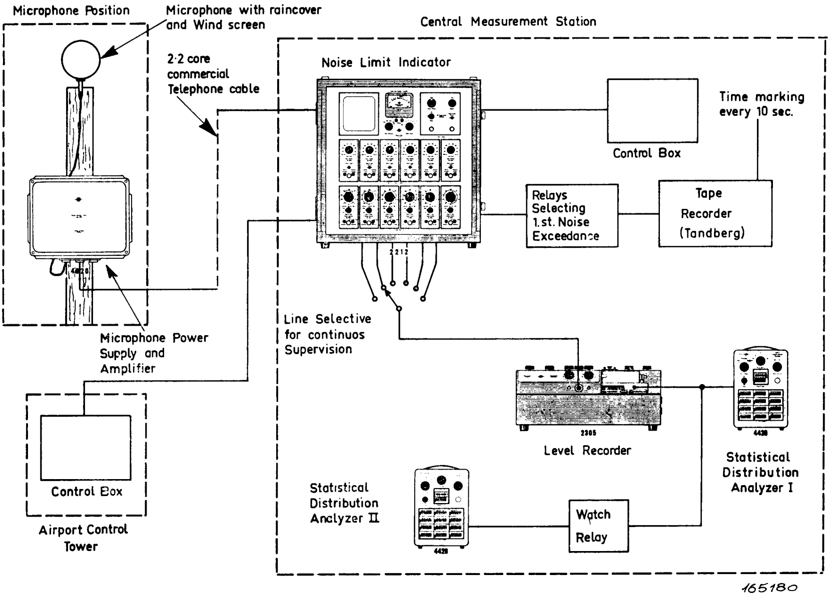

Fig. 5.19. Block diagram of the noise measuring and monitoring system used at Oslo Airport. (G. Arnesen).

A separate recording system which utilizes a graphic level recorder and two Statistical Distribution Analyzers is used for continuous recording of the noise level at a preselected microphone position. The Statistical Distribution Analyzers also allow statistical analysis of the time duration of various noise levels to be made.

*) Recently the use of a special N-weighting network, thus measuring aircraft noise in terms of dB (N), is becoming generally accepted.

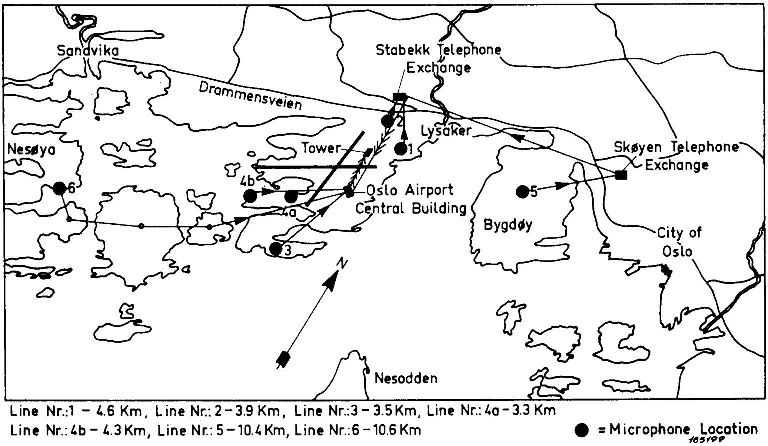

Fig. 5.20. Map of Oslo Airport and the surrounding area showing microphone and cable locations. (G. Arnesen).

One of the great problems in the setting up of a proper aircraft noise measuring and monitoring system is the transmission of the noise signal from the microphone position to the central measurement station. In the above described system this problem has been solved by using local telephone lines, see Fig. 5.20. However, the frequency and dynamic range limitations of normal telephone lines often impose severe restrictions upon the transmitted signal and other means like special F.M. of P.M. radio transmission links might have to be considered. It should be mentioned in this connection that it is

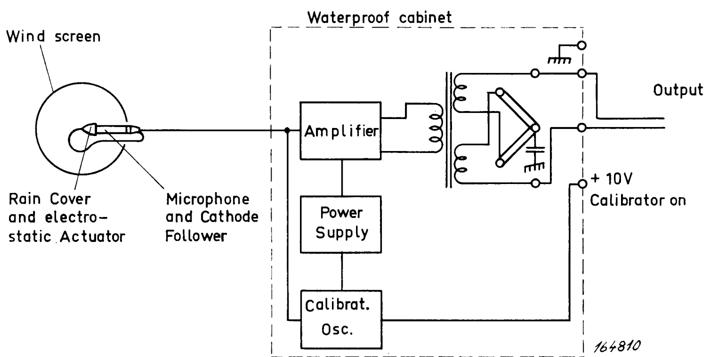

Fig. 5.21. Block diagram showing the principle of the Outdoor Microphone System (Brüel & Kjær Type 4920).

deemed *essential to keep the dynamic range of the combined measurement system in excess of 40 dB over the frequency range 45 Hz to 11200 Hz.* Furthermore, the microphones used should be shielded from rain, snow, wind and other weather conditions and means should be installed for checking and calibration purposes. A microphone system which fulfils these requirements is shown in Fig. 5.21 and Fig. 5.22 shows an example of its installation in the field. As can be seen from the figure the microphone is here mounted on top of a telegraph pole. This kind of mounting is advantageous with respect to background noise and at the same time it ensures the least possible influence on the measured result by nearby obstructions.
The Statistical Distribution Analyzers shown in Fig. 5.19 resolve the recorded information into twelve class intervals and present a numerical display of the data as discussed in section 4.4 and Appendix D.

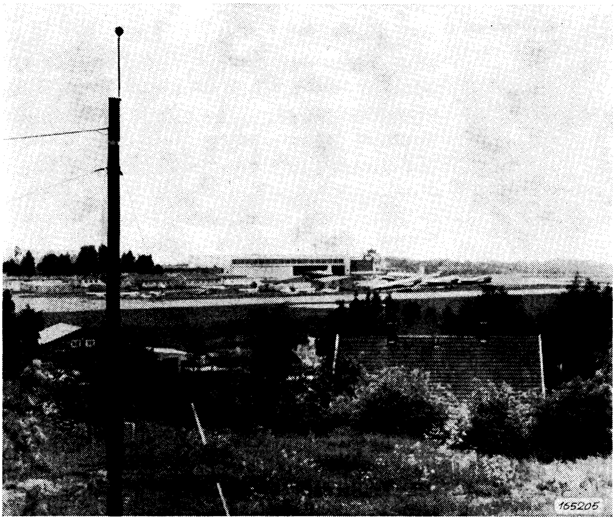

Fig. 5.22. Example of mounting of the Outdoor Microphone System Type 4920. (G. Arnesen).

To be able to distinguish between day and night noise one of the Analyzers is set to operate continuously day and night, while the other only operates at night. The continuous operation can go on for about 11 days and nights before the main counter has reached its maximum number of counts (1.000.000 counts 1 count/sec.). It is thus only necessary to reset the counters and check the arrangement every 11 days. If desired this period can be prolonged by the use of a different count rate. Count rates as slow as 1 count per 10 seconds are available on the Analyzers, and the actual count rate used should be set according to the expected rate of change in the noise level.

By switching the statistical distribution analysis arrangement to operate on the various microphones, a means is obtained for investigating how the noise exposure varies with time in various places, and also to check to what extent various noise reduction regulations function over certain periods of time. It therefore forms a very valuable tool for the evaluation of proposed noise reduction regulations.

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5.5. Product Noise Analysis and Control.

The quality of modern office and household equipment is actually judged differently by different people. Some might judge the quality according to the look of the equipment. Others study the technical specification sheets. Still other people look for rigidity, compactness ease of handling, ease of storage, etc. However, in later years where the general noise level in an office and an ordinary household has been increased manyfold due to all the various machines and appliances considered necessary, one of the "qualities" that is nearly always looked for, is the *noiselessness* of the specific item. It has therefore become necessary for manufacturers of such equipment to minimize and control the noise emitted by their products.

To minimize the radiated noise the various possible noise producing and amplifying mechanisms contained in a specific product must be identified and quietened, a task which is by no means easy. Because most modern machinery is a complicated combination of forcing motions and complex structural configurations the characteristics of the radiated sound may be widely different from the characteristics of the actual noise (or rather vibration) producing mechanisms. To thoroughly analyse the problems it is normally necessary to employ a combination of sound and vibration measurements and each specific case might require its own particular technique. There are, however, some general principles upon which most of the investigations can be based:

> The radiated noise must be frequency analyzed to determine which frequency ranges are the most predominant ones.
>
> The noise radiation characteristics of the product should be determined to find those parts of the structural configuration which are the most "efficient" radiators of noise.
>
> The mechanical vibration of these parts should be measured and frequency analyzed.

From this point on, vibration measurement techniques should be used to trace down the real source of the noise. It should furthermore be pointed out that not only the actual forcing motions might be considered as real noise sources. Very often a structural resonance (or several structural resonances) amplify an originally insignificant vibration so that it becomes a major noise source. Also, it is sometimes easier to dampen a resonance than to change the forcing motion characteristics of a particular machine.

When the major noise sources have been located the question of how much is gained by reducing the noise from each particular source arises. Here, of course, the sensitivity characteristics of the ear (Fig. 3.3) plays an important role in that, in general, noises which contain frequencies in the middle and high frequency range need to be dampened more than very low frequency noises. To go into details on the various methods which might be employed in the actual quietening of noise sources is deemed to be outside the scope of this booklet. It should, on the other hand, be mentioned that the effective contributions of each separate noise source to the overall radiated noise must be seriously considered and "ranked". An example of such a ranking is shown in Fig. 5.23, for the case of a piston engine. Apart from purely technical

considerations a ranking system also allows economical aspects of effective noise reduction to be taken into account.
After having reduced the radiated noise to acceptable levels, methods should be devised to check that these levels are not exceeded by production line units, which means that some sort of production control with regard to noise should be incorporated in the manufacturing and check-out processes. One way of achieving this is to install a small acoustic test chamber and the associated instrumentation in the check-out area, or directly in conjunction with the production line. A major problem in the inclusion of an acoustic test in a production area arises from the relatively high background noise level

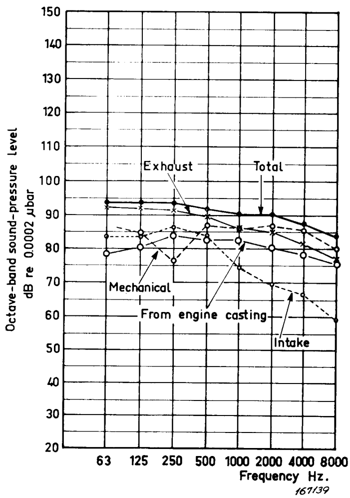

Fig. 5.23. Total noise from a combustion engine and contributions of various engine components.

existing in these areas, and in many cases a test measuring directly the mechanical vibrations at a specific point on the construction is preferable. The microphone should then be substituted by a vibration pick-up. In a few cases the background noise may be eliminated, from a measuring point of view, by means of electrical filters, but in general the construction of a relatively expensive test chamber is necessary. As such test chambers must normally be "tailormade" for each particular production facility it is adviceable to consult an acoustical expert for their construction. One general requirement should, however, be mentioned:
The room must have a "shell" of heavy material to attenuate the disturbing sound from outside. This "shell" can be built as a brick wall, single or double,

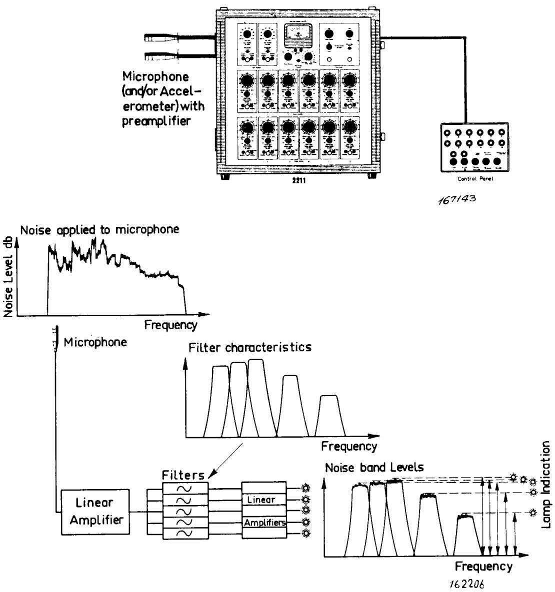

Fig. 5.24. Typical measurement instrumentation used to check the noise and/or vibration of series produced items.
a) Measuring arrangement.
b) Principle of operation.

or a wooden wall with sand filling, the thickness depending upon the desired sound attenuation. Also, a thorough investigation must be made of the sound field produced in the room by the test object, and the positioning of the unit being tested as well as that of the microphone picking up the noise is normally rather critical. On the other hand direct acoustic noise testing has the advantage, over mechanical vibration measurements, that it is the actually radiated noise that is being measured and it does not involve any mechanical contact between the test object and the measuring equipment.*)

A typical measurement instrumentation to be used in conjunction with noise control on a production line is shown in Fig. 5.24 and consists of a microphone (or vibration pick-up) connected to a Noise Limit Indicator Type

*) At low frequencies the test chamber becomes very large, and so do the thickness and mass of the walls required to obtain sufficient sound insulation. It might therefore sometimes be advantageous to combine mechanical vibration and acoustic noise measurements in that mechanical vibration measurements are used at low frequencies and noise measurements in a fairly lightweight and inexpensive chamber at higher frequencies. A reasonable "dividing point" could be a frequency between 400 and 800 Hz.

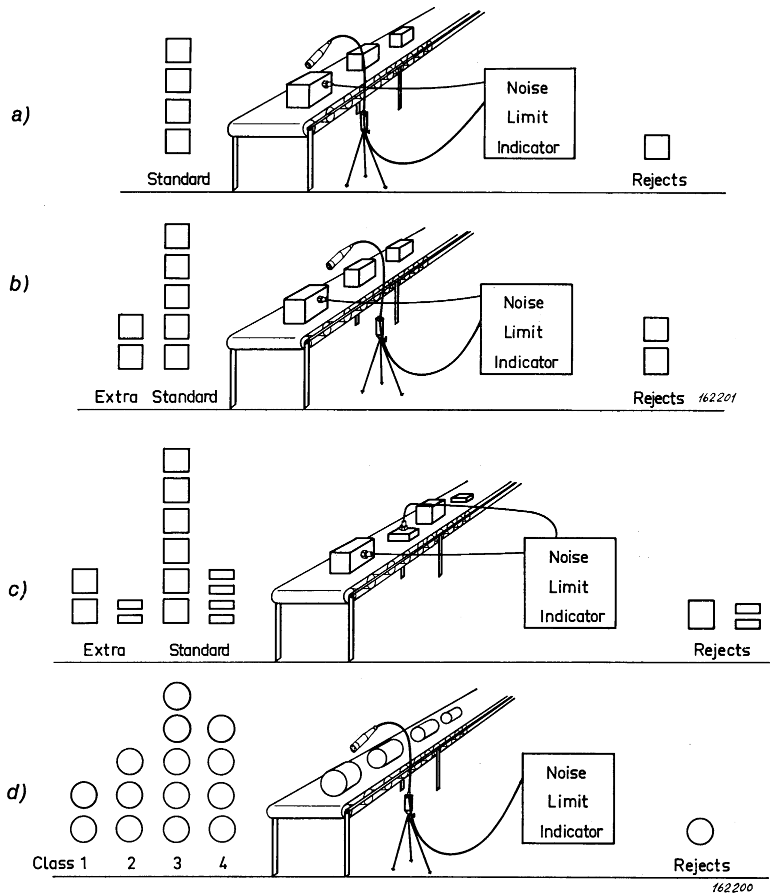

Fig. 5.25. Different measuring possibilities with the Noise Limit Indicator.

a) Simple testing dividing the objects from a production line into "rejects" and "standards" with respect to noise and vibration.

b) Same as a), but additionally dividing the approved objects into two classes, "standard" and "extra".

c) If only one check of the noise or vibration of a unit is required the two inputs of the instrument may be used to serve two production lines or two kinds of products on a line e.g. two types of motors, each with its own noise frequencies and limits.

d) When investigating the noise or vibration level of a series of units, the instrument may be used to divide the units into 3, 4 or 5 classes as regards noise or vibration.

2211. As mentioned in section 4.2 (p. 44) the Noise Limit Indicator measures the noise and/or vibration in several frequency bands simultaneously and compares the result with a preset "standard". The bandwidth can be chosen to be 1/1 octave or 1/3 octave, whichever is required, and the frequency bands and the levels set as the maximum for each of the bands should be chosen as a result of careful laboratory investigations as explained earlier in this section. It may also be adviceable to keep a check on the overall noise level produced by the test object by means of wideband or weighted measurements, a check which can be easily performed by the Noise Limit Indicator, utilizing one of its 12 channels.

The Noise Limit Indicator can be used for a wide range of testing since a number of measurements can be carried out simultaneously, for instance:

1. Simple "go–no go" testing for noise or vibration or both simultaneously (Fig. 5.25a).
2. Testing of units as in 1. but additionally dividing the "go" objects into two classes: "Standard" and "Extra (Fig. 5.25b).
3. Dividing units into three classes, "extra", "standard" and "rejects" with respect to noise only checking two types of units. Alternatively tests on one type of unit from two directional points (Fig. 5.25c).
4. Dividing units into three classes as above with respect to vibration only checking on two types of units, or on one type of unit at two positions.
5. Dividing one type of unit into 3, 4 or 5 classes with respect to noise or vibration (only one microphone or accelerometer is needed) (Fig. 5.25d).

Several other combinations are also possible and might be derived from the specific requirements to the test considered.

An interesting feature of a noise (and/or vibration) check of the type suggested above is the possibility it opens to quickly obtain an indication of which part of the tested specimen that might be faulty or not up to standards: As each frequency band being checked can normally be referred back to some specific noise producing and/or radiating mechanism, a too high noise level in one of the bands often indicates an irregularity in the mechanism producing that particular noise.

Finally it may be stated that quality tests by means of noise or vibration analysis seems to be advantageous for practically all kinds of mechanical equipment containing moving and especially rotating parts.

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6. Standards and Recommendations.

On the following pages standards and recommendations related to acoustic noise measurements have been listed. It has been hoped to produce a survey of the various national standards available in the different countries of the world. Although contacts have been made with acoustic groups in most countries it is practically impossible to guaranty the completeness of such a survey. The author therefore regrets any unintentional ommission and would appreciate any supplementary information pertinent to this list.
In order to facilitate the use of the list the various standards have been grouped according to subjects:

A. General.
B. Noise Rating Recommendations.
C. Noise Measuring Equipment.
D. Measurement of Noise emittet by Machines.
E. Measurement of Noise Transmission Loss in Buildings.
F. Measurement of Vehicle and Traffic Noise.

Finally the author wishes to express his gratitude to all those persons involved in compiling the list.

A. General

Country	Identification of Standard	Contents of Standard	Issuing Institution
Austria	**ÖAL-Richtlinie Nr. 3**	Schalltechnische Grundlagen für die Beurteilung von Lärmbelästigungen.	Österreichischen Arbeitsring für Lärmbekämpfung, Regierungsgebäude, 1012 Wien.
Belgium	**NBN576.02-1961 25 F**	Niveaux Physiques et subjectif d'un son ou d'un bruit et échelle de sonie.	Institut Belge de Normalisation. 29 av. de la Brabançonne. Bruxelles 4.
	NBN576.03-1961 55 F	Les lignes isosoniques normales pour sons pour écoutes en champ libre et le seuil d'audition binauriculaire en champ libre.	
C.S.S.R.	**ČSN 01 1304**	Quantities, units and symbols of acoustics.	Office for Standards and Measurements. Praha 1 - Nové Město, Václavské Náměstí 19
	ČSN 01 1607	Loudness and loudness level of sound.	
	ČSN 368820	Objective methods for noise measurements.	

Country	Identification of Standard	Contents of Standard	Issuing Institution
France	S 30-003	Lignes Isosoniques Normales pour Sons Purs Ecoutes en Champ Libre et Seuil d'Audition Binauriculaire en Champ Libre.	L'Association Française de Normalisation. 19, rue du 4-Septembre. Paris - 2e.
	S 30-004	Expression des Caractéristiques Physiques et des Caractéristiques Psycho-Physiologiques d'un Son ou d'un Bruit.	
	S 30-005	Méthode de Calcul du Niveau d'Isosonie.	
Germany (D.B.R.)	DIN 1318	Lautstärke, Begriffsbestimmungen.	Beuth-Vertrieb GmbH. Berlin W15 und Köln.
	DIN 45630	Grundlagen der Schallbewertung.	
	DIN 45631	Berechnung des Lautstärke-Pegels aus dem Geräusch-Spektrum.	
	VDL 2058	Beurteilung und Abwehr von Arbeitslärm.	
Great Britain	B.S. 2497: 1954	The normal threshold of hearing for pure tones by earphone listening.	British Standards Institution. 2 Park Street, London W. 1.
	B.S. 3045: 1958	The relation between the sone scale of loudness and phone scale of loudness level.	
	B.S. 3383: 1961	Normal equal loudness contours for pure tones and normal threshold of hearing under free-field listening conditions.	
	B.S. 3593: 1963	Recommendation on preferred frequencies for acoustical measurements.	
Hungary	M. Sz. 3391-51 M. Sz. 3391-60	Akustische Grundbegriffe und Formeln.	Magyar Szabványügyi Hivatal. Budapest IX, Üllöi út. 25.
	M. Sz. 3392-54	Akustische Messungen.	
Switzerland	—	»Lärmbekämpfung in der Schweiz«.	Eidgenössische Drucksachen und Materialzentrale. Bern 3.
U.S.A.	S1. 2-1962	Method for physical measurement of sound.	United States of America Standards Institute. 10 East 40th Street, New York, N.Y. 10016.
	S1. 6-1960	Preferred frequencies for acoustical measurements.	
	S3. 4	Procedure for the Computation of the loudness of noise.	

Country	Identification of Standard	Contents of Standard	Issuing Institution
International (I.S.O.)	**R. 131**	Expression of the physical and subjective magnitudes of sound or noise.	International Organization for Standardization. 1, Rue de Varembé. Geneva. Switzerland.
	R. 226	Normal equal loudness contours for pure tones and normal threshold of hearing under free-field listening conditions.	
	R. 266	Preferred frequencies for acoustical measurements.	
	R. 357	Expression of the power and intensity levels of sound or noise.	
	R. 454	Relation between the loudness of narrow bands of noise in diffuse-field and in a frontally incident free-field.	
	R. 532	Procedure for calculating Loudness Level.	

B. Noise Rating Recommendations

Country	Identification of Standard	Contents of Standard	Issuing Institution
Austria	**Bundesgesetzblatt 288**	Kraftfahrverordnung 1955.	Staatsdruckerei, Wien.
	Bundesgesetzblatt 103	Seenverkehrsordnung 1961.	
C.S.S.R.	**ČSN 730531**	Protection against noise transmission in buildings.	Office for Standards and Measurements. Praha 1 - Nové Město, Václavské Náměstí 19
Great Britain	**B.S. 4142: 1967**	Method of rating industrial noise affecting mixed residential and industrial areas.	British Standards Institution. 2 Park Street, London W. 1.
Hungary	**SZOT 6/1965 (IV)**	Verordnungen des Landesrates der Gewerkschaften.	Magyar Szabványügyi Hivatal. Budapest IX, Üllöi út. 25.
South Africa	**SABS 083-1962**	Code of practice for the rating of noise for hearing conservation.	South African Bureau of Standards. 55 Visagie Street, Pretoria.
Switzerland	—	»Lärmkämpfung in der Schweiz«.	Eidgenössische Drucksachen und Materialzentrale. Bern 3.
U.S.A.	**S3. 1-1960**	Criteria for background noise in audiometer rooms.	United States of America Standards Institute. 10 East 40th Street, New York, N.Y. 10016.

C. Noise Measuring Equipment

Country	Identification of Standard	Contents of Standard	Issuing Institution
Australia	**AS Z37-1967**	Sound Level Meters Type 1 - General Purpose.	Standards Association of Australia. Science House. 157 Gloucester Street. Sydney.
	AS Z38-1967	Sound Level Meters Type 2 - Precision.	
Belgium	**NBN576. 80-1962 60 F**	Sonomètre de précision.	Institut Belge de Normalisation. 29 av. de la Brabançonne. Bruxelles 4.
C.S.S.R.	**ČSN 356870**	Sound level meter and band pass filter.	Office for Standards and Measurements. Praha 1 - Nové Město, Václavské Náměstí 19
France	**S 30-002**	Fréquences Normales pour les Mesures Acoustique.	L'Association Française de Normalisation. 19, rue du 4-Septembre. Paris - 2e.
	S 31-005	Sonomètres d'Usage Courant.	
Germany (D.B.R.)	**DIN 5045**	Meßgerät für DIN-Lautstärken Richtlinien.	Beuth-Vertrieb GmbH. Berlin W15 und Köln.
	DIN 45633	Präzisionsschallpegelmesser Anforderungen.	
Germany (D.D.R.)	**TGL 200-7755**	Geräte zur Messung des Schalldruckpegels.	Amt für Standardisierung. Mohrenstrasse 37a. Berlin W. 8.
Great Britain	**B.S. 3489: 1962**	Sound level meters. (industrial grade).	British Standards Institution. 2 Park Street, London W. 1.
	B.S. 3539: 1962	Sound level meters for the measurement of noise emitted by motor vehicles.	
U.S.A.	**S1. 4-1961**	Specification for general purpose sound level meters.	United States of America Standards Institute. 10 East 40th Street, New York, N.Y. 10016.
	Z24. 10-1953	Specification for an Octaveband filter set for analysis of noise and other sounds.	
	S1. 11-1966	Octave, half-octave and one-third octave filter sets.	
International (I.E.C.) (I.S.O.)	**IEC-123**	Recommendation for sound level meters.	International Organization for Standardization. 1, Rue de Varembé. Geneva. Switzerland.
	IEC-179	Specification for precision sound level meters.	

D. Measurements of Noise Emitted by Machines

Country	Identification of Standard	Contents of Standard	Issuing Institution
Austria	**ÖAL-Richtlinie Nr. 1**	Messung des Geräusches von Maschinen.	Österreichischen Arbeitsring für Lärmbekämpfung. Regierungsgebäude, 1012 Wien.
Belgium	**NBN 263-1951**	Conditions acoustiques de travail d'installations de chauffage, ventilation, etc.	Institut Belge de Normalisation. 29 av. de la Brabançonne Bruxelles 4.
C.S.S.R.	**ČSN 123062**	Measurement of noise and vibration from ventilators.	Office for Standards and Measurements. Praha 1 - Nové Město, Václavské Náměstí 19
	ČSN 178055	Measurement of noise emitted by computers.	
	ČSN 350000	Measurement of noise emitted by electrical machines.	
France	**S 30-006**	Règles Générales pour la Rédaction des Codes d'Essais Relatifs a la Mesure du Bruit Émis par les Machines.	L'Association Française de Normalisation. 19, rue du 4-Septembre. Paris - 2e.
	S 31-006	Code d'Essais pour la Mesure du Bruit Émis par les Machines Électriques Tournantes.	
Germany (D.B.R.)	**DIN 9756**	Lautstärkemessung an Rechenmaschinen.	Beuth-Vertrieb GmbH. Berlin W15 und Köln.
	DIN 42540	Geräuschstärke von Transformatoren; Bewerteter Schalldruckpegel (Schallpegel).	
	DIN 45632	Geräuschmessung an elektrischen Maschinen, Richtlinien.	
Germany (D.D.R.)	**TGL 39-440**	Prüfvorschriften für Fahrzeuggetriebe.	Amt für Standardisierung. Mohrenstrasse 37a. Berlin W. 8.
	TGL 39-703	Prüfvorschriften, Auspuffgeräuschdämpfer, Verbrennungsmotoren.	
	TGL 39-767	Verbrennungsmotoren, Geräuschmessungen, Meßverfahren.	
	TGL 50-29034	Geräuschmessungen an rotierenden elektrischen Maschinen, Richtlinien.	
	TGL 153-6011	Wälzlager, Laufgeräusch, Meßverfahren (Entwurf).	
	TGL 153-6012	Wälzlager, (Radial-) Rillenkugellager, Laufgeräusch, zulässige Werte (Entwurf).	
	TGL 200-4504	Elektrische Hausgeräte, Geräuschmessungen, Meß- und Prüfverfahren.	
International (I.S.O.)	**R. 495**	General Requirements for the Preparation of Test Codes for Measuring the Noise Emitted by Machines.	International Organization for Standardization. 1, Rue de Varembé. Geneva, Switzerland.

E. Measurements of Noise Transmission Loss in Buildings

Country	Identification of Standard	Contents of Standard	Issuing Institution
Austria	ÖNORM B8115	»Hochbau, Schallschutz und Hörsamkeit«.	Österreichischen Normenausschuss. Bauernmarkt 13, 1010 Wien.
Belgium	NBN576. 06-1963 20 F	Mesure «in situ» de l'isolement acoustique aux sons aériens.	Institut Belge de Normalisation. 29 av. de la Brabançonne. Bruxelles 4.
C.S.S.R.	ČSN 358840	Measurement of sound insulating properties of building structures.	Office for Standards and Measurements. Praha 1 - Nové Město, Václavské Náměstí 19
France	S 31-002	Mesure, en Laboratoire et sur Place, de la Transmission des Sons Aériens et des Bruits de Chocs dans les Constructions.	L'Association Française de Normalisation. 19, rue du 4-Septembre. Paris - 2ᵉ.
Germany (D.D.R.)	TGL 10687	Bauphysikalische Schutzmaßnahmen, Schallschutz.	Amt für Standardisierung. Mohrenstrasse 37a. Berlin W. 8.
Great Britain	B.S. 2750: 1956	Recommendation for field and laboratory measurement of airborne and impact sound transmission in buildings.	British Standards Institution. 2 Park Street, London W. 1.
Hungary	M.E.-83-65	Technische Vorschriften des Ministeriums für Bauwesen.	Magyar Szabványügyi Hivatal. Budapest IX, Üllöi út. 25.
Netherlands	NEN 1070	Sound insulation measurement in dwellings.	Nederlands Normalisatie-Instituut. Polakweg 5, Ryjswyjk (ZH)
Sweden	SIS 025251	Bestämning af ljudisolering. (Measurements of sound insulation).	Sveriges Standardiseringskommission. Stockholm.
U.S.A.	Z24. 19-1957	Laboratory Measurement of Airborne sound transmission loss of building floors and walls.	United States of America Standards Institute. 10 East 40th Street, New York, N.Y. 10016.
International (I.S.O.)	R. 140	Field and laboratory measurements of airborne and impact sound transmission.	International Organization for Standardization. 1, Rue de Varembé. Geneva. Switzerland.

F. Measurement of Vehicle and Traffic Noise

Country	Identification of Standard	Contents of Standard	Issuing Institution
Austria	**ÖAL-Richtlinien Nr. 2**	Messung des Geräusches von Kraftfahrzeugen.	Österreichischen Arbeitsring für Lärmbekämpfung. Regierungsgebäude, 1012 Wien.
Belgium	**NBN576. 30-1962 35 F**	Methode de mesure du niveau des bruits émis par les véhicles.	Institut Belge de Normalisation. 29 av. de la Brabançonne. Bruxelles 4.
C.S.S.R.	**ČSN 090862**	Noise of Diesel engines. Method of measurement.	Office for Standards and Measurements. Praha 1 - Nové Město, Václavské Náměstí 19
	ČSN 300512	Measurement of noise emitted by road motor vehicles.	
	ČSN 300513	Measurement of internal noise emitted by road motor vehicles.	
France	**S 31-007**	Mesure du Bruit Product par les Véhicules Automobiles.	L'Association Française de Normalisation. 19, rue du 4-Septembre. Paris - 2e.
Great Britain	**B.S. 3425: 1961**	Measurement of noise emitted by motor vehicles.	British Standards Institution. 2 Park Street, London W. 1.
India	**IS: 3028-1965**	Method of measurement of noise emitted by motor vehicles.	Indian Standards Institution. Manak Bhavan, 9 Bahadur Shah Zafar Marg, New Dehli 1.
New Zealand	**NZSS 1726**	Measurement of noise emitted by motor vehicles.	
South Africa	**SABS 097-1965**	Code of practice for the measurement and limitation of noise emitted by motor vehicles.	South African Bureau of Standards. 55 Visagie Street, Pretoria.
Switzerland	—	»Lärmbekämpfung in der Schweiz«.	Eidgenössische Drucksachen und Materialzentrale. Bern 3.
International (I.S.O.)	**R. 362**	Methods of measurement of noise emitted by vehicles.	International Organization for Standardization. 1, Rue de Varembé. Geneva. Switzerland.
	R. 507	Procedure for describing noise. around an airport.	

Appendix A

On the Measurement of Statistically Fluctuating Signals.

A stationary sinusoidal signal is completely described by means of three quantities, the maximum amplitude, the frequency and the phase.

However, a great number of processes occurring in nature give rise to signals which are quasi stationary but neither sinusoidal nor periodic. Typical examples are rocket engine noise, noise from certain types of machines (for example from typewriters), crowd noise, music played by an orchestra, electrical resistor noise, tube and transistor noise, and signals derived from aerodynamic turbulence, traffic counters etc. Since the amplitude values of these types of signals are not periodic, it has been found convenient to introduce the concept of *amplitude density* instead of amplitude.

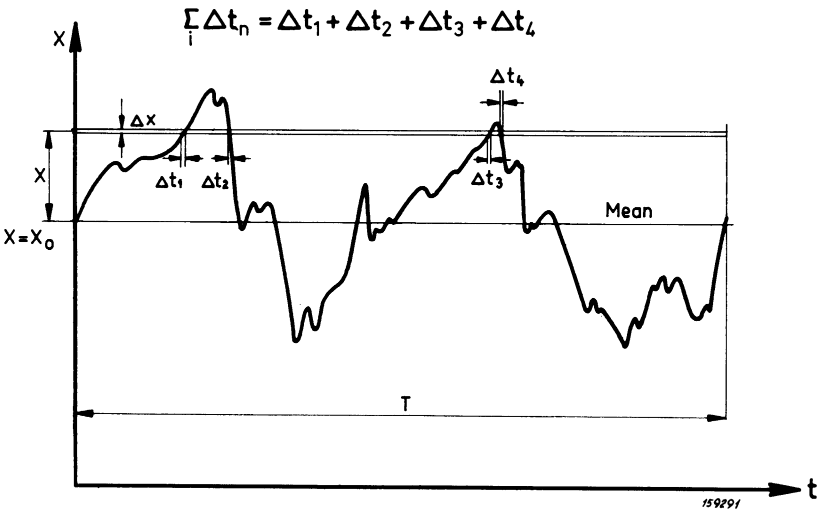


Fig. A1. Time record of a random process.

To give a meaning to the word density it is obviously necessary to divide the amplitude scale into small divisions Δx and define a measure for instantaneous amplitude values to be found within Δx. The latter can be done by measuring the length of time that the signal being investigated spends between x and $x + \Delta x$ relative to the total length of time over which the phenomenon is being studied (see also Fig. A1).

$$\text{Amplitude probability: } P(x;\, x+\Delta x) = \frac{\sum_i \Delta t_n}{T} \qquad \text{(a)}$$

$$\text{The amplitude density is thus: } p(x) = \lim_{\Delta x \to 0} \frac{P(x;\, x+\Delta x)}{\Delta x} \qquad \text{(b)}$$

By varying the value of x from $-\infty$ to $+\infty$ and plotting p(x) as a function of x the amplitude density curve for the signal in question is found.
The shape of this curve can vary considerably, the most well known amplitude density curve being that obtained from a normal (Gaussian) random process. This process is an analytical (continuous) process, and the normalized*) amplitude density curve is given by:

$$p(x) = \frac{1}{\sigma\sqrt{2\pi}} \; e^{-\frac{(x - x_o)^2}{2\sigma^2}}$$

σ = standard deviation (RMS value)
x_o = mean value (see also Fig. A1)
The above formula can be derived in several ways, both by solving the differential equations used in theoretical physics to describe certain (diffusion) processes and from a purely statistical point of view when an infinite number of independent events are combined.
From the Gaussian curve a number of interesting characteristics can be deduced:

1. The two parameters σ and x_o characterize this curve in a manner similar to the way the constants a and b characterize the straight line $f(x) = ax + b$.
2. If $x_o = 0$ the curve is centered around zero as a mean, see Fig. A2.
3. The average absolute deviation from the mean is:

$$x\big|_{\text{average}}\big| = \int_{-\infty}^{+\infty} |x| \, p(x)\, dx$$

4. The Standard deviation (RMS deviation) from the mean is:

$$\sigma = \sqrt{\int_{-\infty}^{+\infty} x^2 \, p(x)\, dx}$$

The expression given under 3 and 4 are for the type of signal description used here, equivalent to those also used to characterize the amplitude of *periodic* signals. The equivalence of the expression given under 3 and 4 for periodic and random signals will be clear from the following:
If the phenomenon is studied over a certain period of time, T, then the probability of finding instantaneous amplitude values between x and $x + \Delta x$ is according to (a) and (b) (see also Fig. A1):

$$P(x; x + \Delta x) = \int_{x}^{x+\Delta x} p(x)\, dx = \frac{\sum_i \Delta t_n}{T} = \frac{\Delta t}{T}$$

where p(x) is the amplitude density, and $\Delta t = \sum_i \Delta t_n$

---

*) Normalized: $\int_{-\infty}^{+\infty} p(x)\, dx = 1$ where p(x) is the amplitude density.

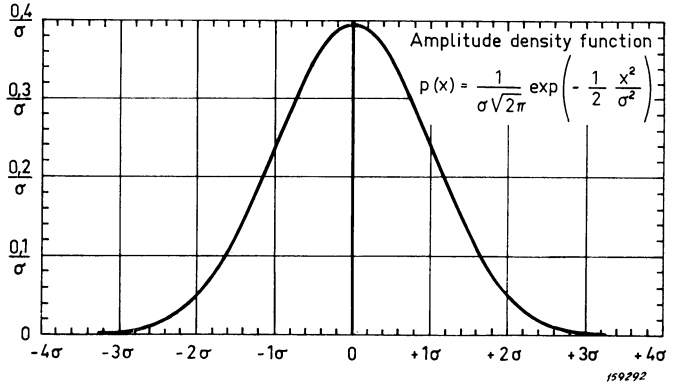


Fig. A2. The normalized Gaussian amplitude density curve.

The arithmetic average deviation is given by:

$$x|_{average}| = \int_{-\infty}^{+\infty} |x|\, p(x)\, dx = \lim_{\Delta x \to 0} \sum_{-\infty}^{+\infty} x\, P(x; x + \Delta x) =$$

$$= \lim_{\Delta t \to 0} \sum_{0}^{T} |x| \frac{\Delta t}{T} = \frac{1}{T} \int_{0}^{T} |x|\, dt = (A|_{average}|)$$

which is the well-known expression for the arithmetic average value of a periodic signal.

Similarly the expression for the standard deviation can be shown to be equivalent to

$$\sigma = \sqrt{\frac{1}{T} \int_{0}^{T} x^2\, dt} = (A_{RMS})$$

Appendix B

Decibel and Ratio Conversions.

The following table has been prepared in order to facilitate the conversion from *dB* to *sound pressure ratios* and vice versa. However, with a slight modification it may also be used for dB to sound intensity (power) conversion and vice versa.

dB	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9
0	1.000	1.012	1.023	1.035	1.047	1.059	1.072	1.084	1.096	1.109
1	1.122	1.135	1.148	1.161	1.175	1.189	1.202	1.216	1.230	1.245
2	1.259	1.274	1.288	1.303	1.318	1.334	1.349	1.365	1.380	1.396
3	1.413	1.429	1.445	1.462	1.479	1.496	1.514	1.531	1.549	1.567
4	1.585	1.603	1.622	1.641	1.660	1.679	1.698	1.718	1.738	1.758
5	1.778	1.799	1.820	1.841	1.862	1.884	1.905	1.928	1.950	1.972
6	1.995	2.018	2.042	2.065	2.089	2.113	2.138	2.163	2.188	2.213
7	2.239	2.265	2.291	2.317	2.344	2.371	2.399	2.427	2.455	2.483
8	2.512	2.541	2.570	2.600	2.630	2.661	2.692	2.723	2.754	2.786
9	2.818	2.851	2.884	2.917	2.951	2.985	3.020	3.055	3.090	3.126
10	3.162	3.199	3.236	3.273	3.311	3.350	3.388	3.428	3.467	3.508
11	3.548	3.589	3.631	3.673	3.715	3.758	3.802	3.846	3.890	3.936
12	3.981	4.027	4.074	4.121	4.169	4.217	4.266	4.315	4.365	4.416
13	4.467	4.519	4.571	4.624	4.677	4.732	4.786	4.842	4.898	4.955
14	5.012	5.070	5.129	5.188	5.248	5.309	5.370	5.433	5.495	5.559
15	5.623	5.689	5.754	5.821	5.888	5.957	6.026	6.095	6.166	6.237
16	6.310	6.383	6.457	6.531	6.607	6.683	6.761	6.839	6.918	6.998
17	7.079	7.161	7.244	7.328	7.413	7.499	7.586	7.674	7.762	7.852
18	7.943	8.035	8.128	8.222	8.318	8.414	8.511	8.610	8.710	8.810
19	8.913	9.016	9.120	9.226	9.333	9.441	9.550	9.661	9.772	9.886

As 0 dB corresponds to a sound *pressure* ratio of 1 and 20 dB to a sound *pressure* ratio of 10 practically all ratio to dB conversions (and vice versa) are possible by means of the table.

Sound Pressure Calculations:

1) *dB-to-ratio conversion:*
   Subtract a whole number of $n \times 20$ from the dB value to be converted which gives a positive remainder between 0 and 20. Look up the ratio in the table corresponding to the remainder. The value sought is then $10^n \times$ value from the table.
   Numerical Example:
   If the sound pressure level is 74 dB re. 0.0002 μbar what is then the actual sound pressure (in μbar)?
   Answer: 74 dB = $(3 \times 20 + 14)$ dB.
   14 dB corresponds to a pressure ratio of 5.012 (according to table). Thus when $20 \log \frac{p}{p_o} = 74$ dB, then:
   $$p = 10^3 \times 5.012\, p_o = 10^3 \times 5.012 \times 0.0002 \approx \mathbf{1}\ \mu\mathbf{bar}.$$

2) *Ratio-to-dB conversion:*
   Divide the pressure ratio to be converted by 10^n so that a number, A, is obtained which lies between 1 and 10 (i.e. ratio $= A \times 10^n$). Look up the number in the table which is as close to A as possible. Add the dB-value

(from the table) corresponding to this number to n $\times$ 20. The result **is the** desired sound *pressure* level in dB.

Numerical Example:

If the sound pressure is found to be 3.56 μbar what is then the sound pressure level in dB re. 0.0002 μbar?

Answer: $\frac{p}{p_o} = \frac{3.56}{0.0002} = 17800 = 1.78 \times 10^4$

From the table it is found that a pressure ratio of 1.78 corresponds to approximately 5 dB, thus:

Sound Pressure Level = 5 + 4 $\times$ 20 = **85 dB re. 0.0002 μbar.**

Sound Intensity (Power) Calculations.

1) *dB-to-ratio conversion:*

Multiply the dB-value to be converted by 2 and proceed as under "Sound Pressure Calculations" above.

Note: The reference level is in this case normally (10^{-16} W/m^2) which corresponds to the intensity of a free progressive sound wave in atmospheric air with a sound pressure of 0.0002 μbar (2×10^{-5} N/m^2).

Numerical Example:

If the sound intensity level is 83 dB re. 10^{-16} W/cm^2 what is then the actual sound intensity level in W/cm^2?

Answer: 83 dB $\times$ 2 = 166 = (8 $\times$ 20 + 6).

From the table it is found that 6 dB corresponds to a ratio of 1.955.

Thus, the sound intensity level is:

P = $2 \times 10^8 \times 10^{-16}$ = **2×10^{-8} W/cm^2.**

2) *Ratio-to-dB Conversion:*

Proceed as under "Sound Pressure Calculations" above and divide the result by 2.

Numerical Example:

If the sound intensity is found to be 5×10^{-7} W/cm^2 what is then the sound intensity level in dB re. 10^{-16} W/cm^2?

Answer: $\frac{p}{p_o} = \frac{5 \times 10^{-7}}{10^{-16}} = 5 \times 10^9$

From the table it is found that a ratio of 5 corresponds to approximately 14 dB, thus:

Sound Intensity Level = $\frac{14 + 9 \times 20}{2}$ = **97 dB re. 10^{-16} W/cm^2.**

Appendix C

Loudness Determination According to Zwicker and Stevens.

When the "subjectively felt" loudness or loudness level is to be estimated from objectively measured sound pressure level data these data must be available in the form of a sound spectrum. Such a spectrum is normally measured by means of frequency analyzers having a bandwidth of 1/3 octave or 1/1 octave. If the measured spectrum is available in terms of 1/3 octave data use can be made of an estimation method suggested by *E. Zwicker.* This is based on the set of graphs shown in Figs. C1–C10 and contains three steps.

Step 1 consists in selecting the appropriate graph and plotting the measured 1/3 octave data onto the graph. The correct graph is selected by considering whether the sound field being explored is of the *free-field type* (frontal sound) or of the *diffuse field type,* and then choosing the corresponding *chart which includes the highest third-octave band level measured.* For 1/3 octave bands higher than 280 Hz (band center frequency 315 Hz) the band levels can be directly plotted on the chart. However, due to the fact that the critical bands in hearing have bandwidths which below 280 Hz are wider than 1/3 octave the third octave band levels are in this frequency range combined according to the power law illustrated in Fig. 4.40 of the text, and exemplified below:

$$L_{90\div180} = 10\log\left(\text{antilog}\,\frac{L_{100}}{10} + \text{antilog}\,\frac{L_{125}}{10} + \text{antilog}\,\frac{L_{160}}{10}\right)$$

Step 2 consists in connecting the band level – "lines" (see Fig. C13) and averaging the area enclosed by the "stepped" figure.

The connections between the band levels are made as illustrated in Fig. C13a): When the level in the next higher band is higher a vertical line is drawn between the two levels, while when the level in the next higher band is lower the connection between the two band levels is made by means of a downward sloping curve interpolated between the dashed curves on the graph.

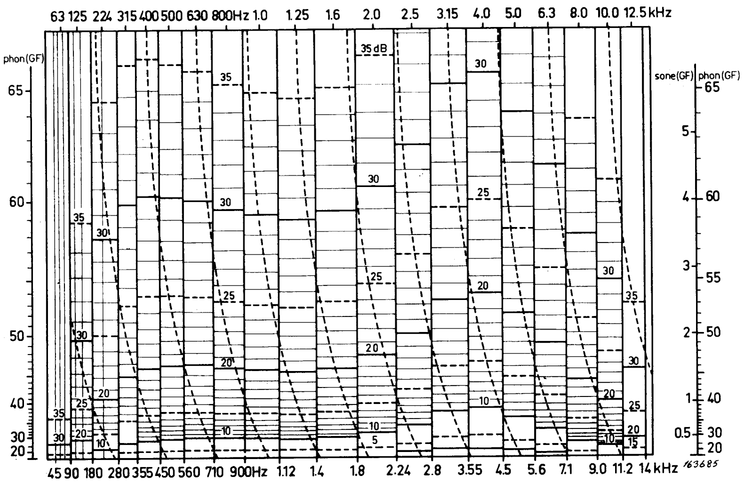


Fig. C1. Frontal sound (10–35 dB).

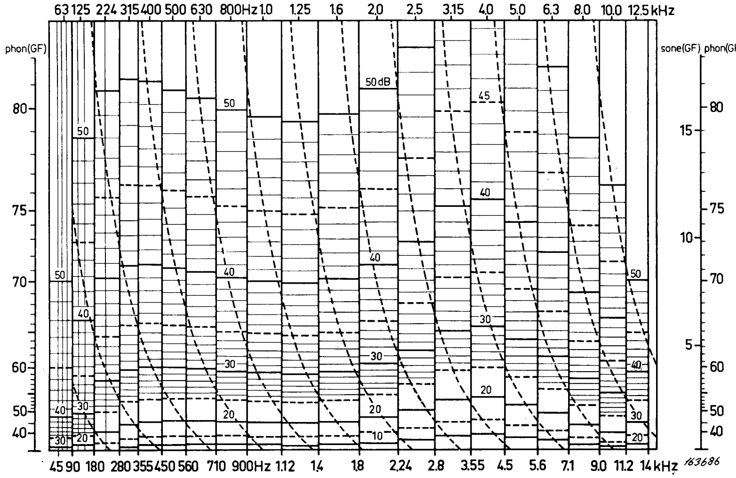


Fig. C2. Frontal sound (20–50 dB).

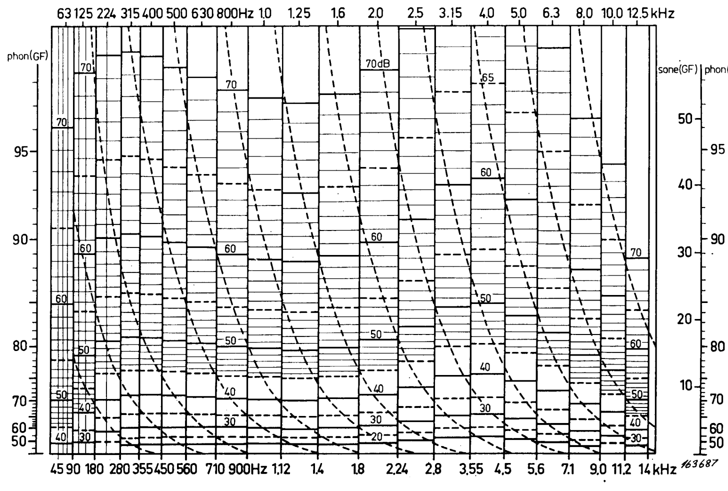


Fig. C3. Frontal sound (40–70 dB).

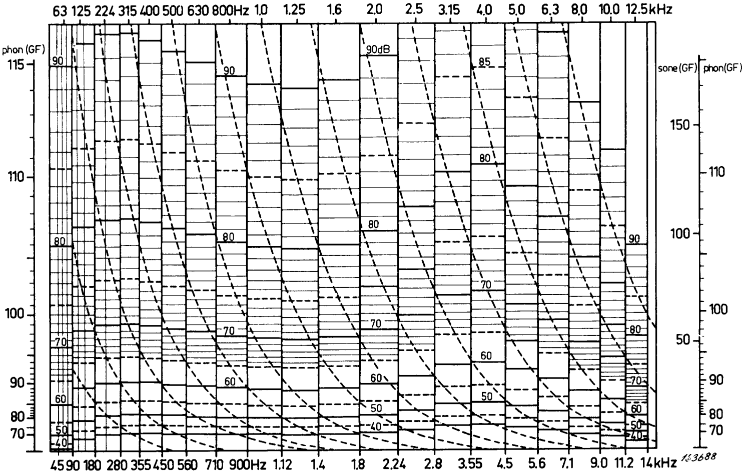


Fig. C4. Frontal sound (60–90 dB).

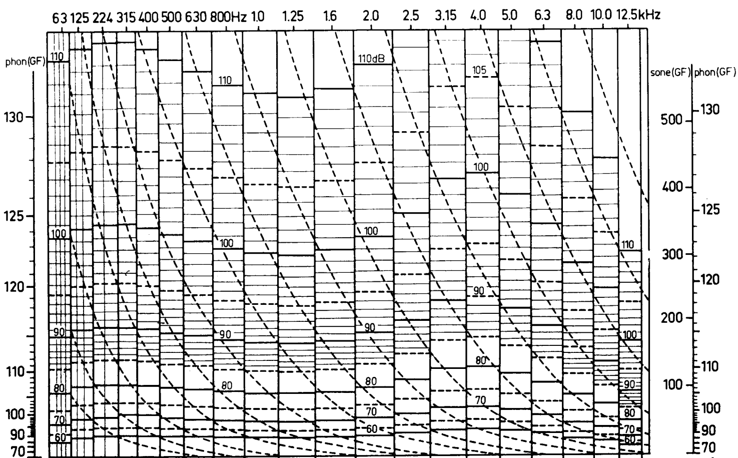


Fig. C5. Frontal sound (80–110 dB).

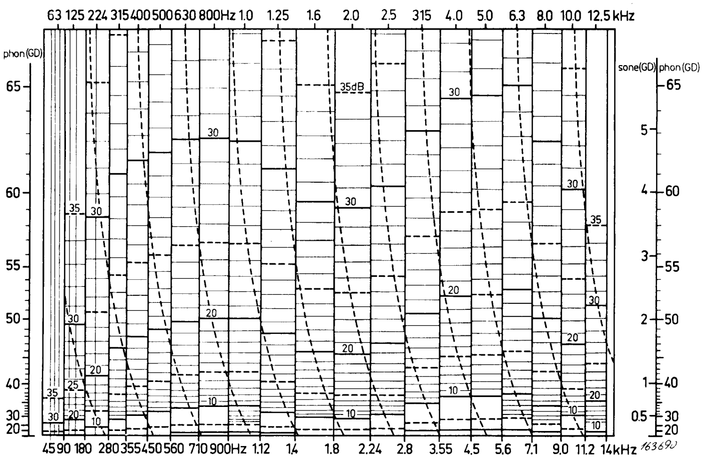


Fig. C6. Diffuse field (10–35 dB).

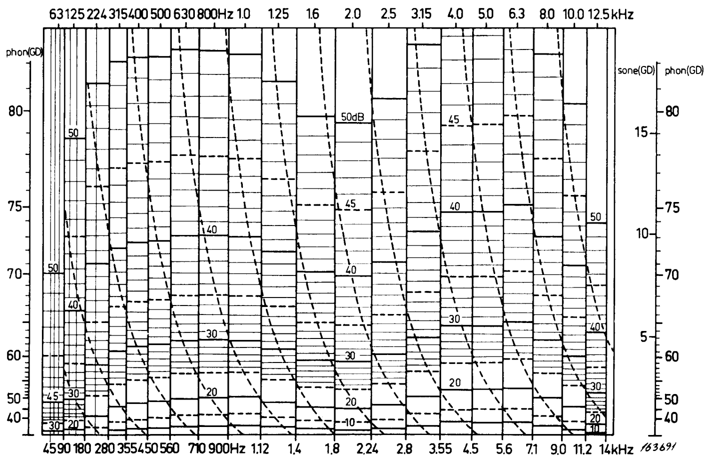


Fig. C7. Diffuse field (20–50 dB).

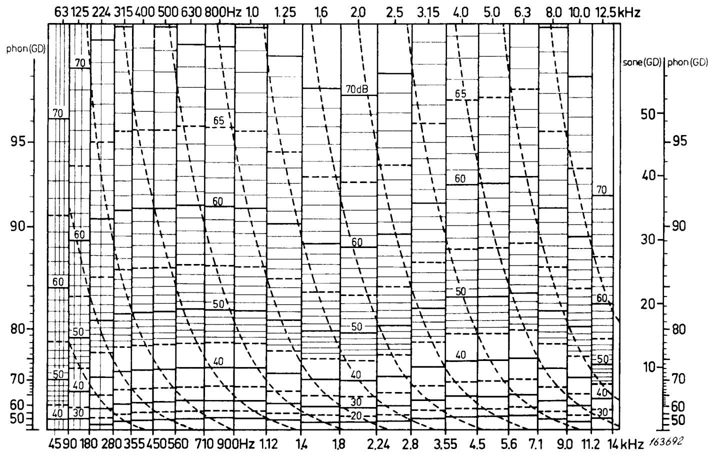


Fig. C8. Diffuse field (40–70 dB).

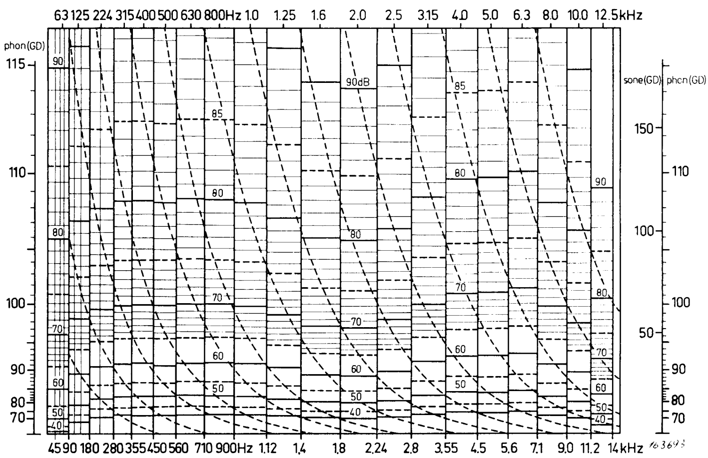


Fig. C9. Diffuse field (60–90 dB).

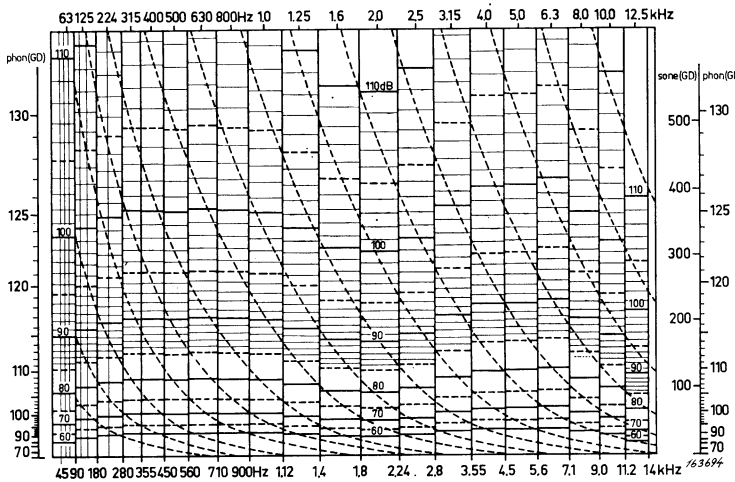


Fig. C10. Diffuse field (80–110 dB).

The averaging is made by converting the area inside the stepped figure into a rectangle with the same base, i.e. the width of the graph (Fig. C13b).

Step 3 consists in reading the resulting total loudness value (in sones (GF) or sones (GD)), or the resulting total loudness level value (in phons (GF) or phons (GD)), from the scales shown to the right in the figures C1–C10. The value is equal to the height of the rectangle.

If the measured spectrum is available in terms of 1/1 octave data the loudness (or loudness level) can be estimated by means of a method originally suggested by *S. S. Stevens* (1/1-octave data may, of course, also be constructed from more detailed analyses).

Here each octave band sound pressure level is converted into a *loudness index* by means of the curves shown in Fig. C11. In the figure the frequency axis is "calibrated" in terms of band center frequencies. The various loudness indices found in this way for the sound spectrum at hand are summed by means of the formula:

$$S_t = S_m + 0.3\,(\Sigma S - S_m)$$

where S_m is the greatest of the loudness indices and ΣS is the sum of the loudness indices of all the bands. S_t is the total loudness in sones (OD). By applying the nomographic scales to the right in Fig. C11 the total loudness value can be converted into a total loudness level value in phons (OD).

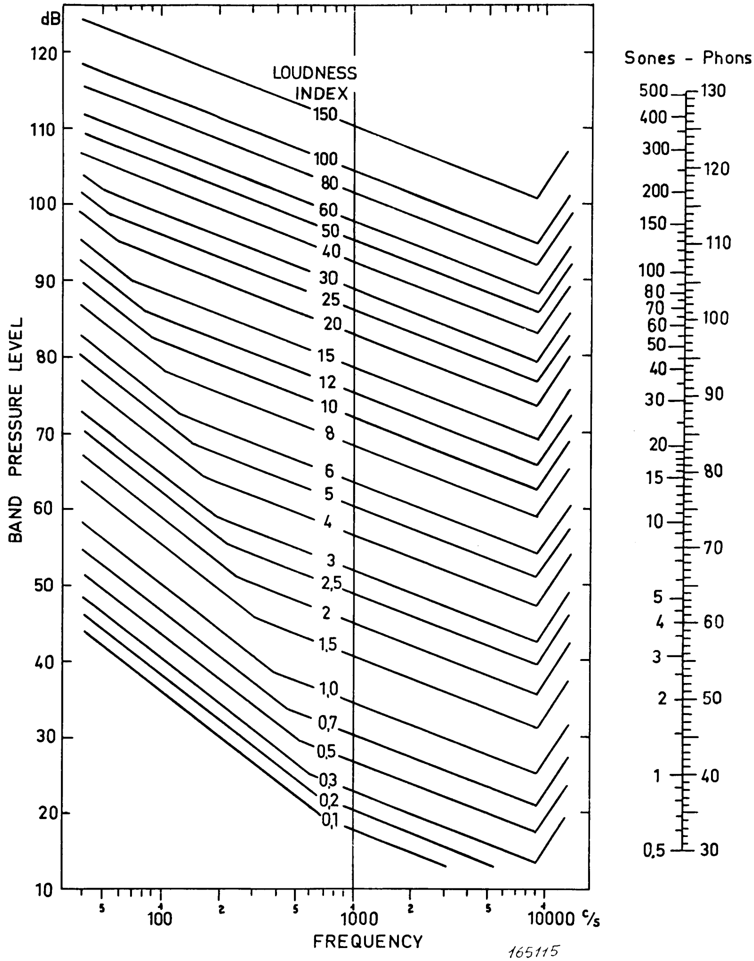
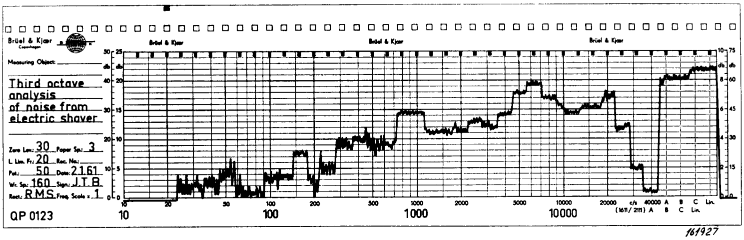
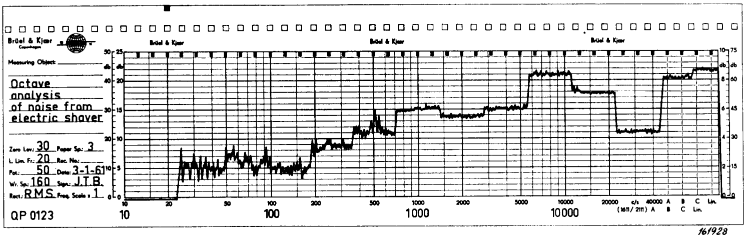


Fig. C11. Contours of equal loudness index.

In the use of the two above mentioned methods of loudness calculation it should be noted that the method due to Zwicker can be used even when the sound spectrum is very irregular and the sound contains pronounced pure tones. The method due to Stevens, on the other hand, can only be used when



a)



b)

Fig. C12. Analyses of the noise from an electric shaver:
a) 1/3 octave analysis.
b) 1/1 octave analysis.

the sound spectrum is relatively smooth and the sound contains *no* pure tone. Also, the method is only applicable to diffuse sound fields.

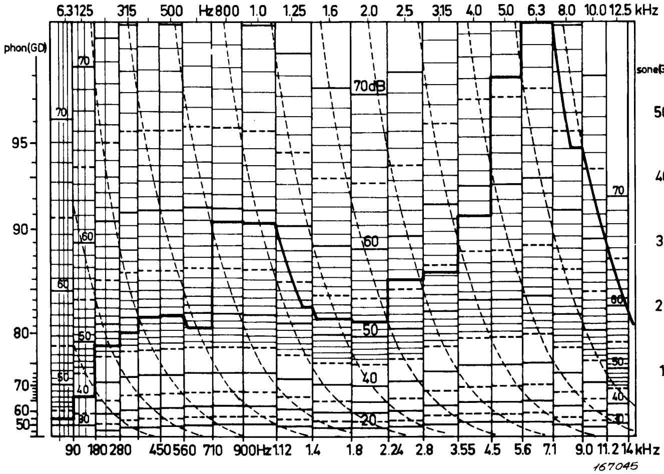
To demonstrate the use of the two methods consider the sound spectra shown in Fig. C12. The two spectra have been obtained from measurements on the sound produced by an electric shaver; the sound field was very nearly diffuse. Fig. C13a shows how the 1/3 octave data have been transferred onto the

Table 1.
Measurements on Electric Shaver.

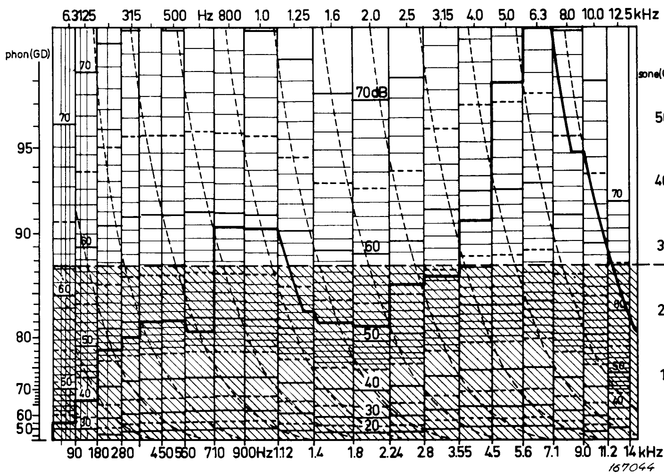
Band center frequency Hz	31.5	63	125	250	500	1000	2000	4000	8000
Band pressure level (dB)	40	42	40	47	54	60	58	60	72
Loudness index	0	0.16	0.37	1.44	2.84	4.8	5.2	7.0	17.5

$$S_t = S_m + F(\Sigma S - S_m) = 17.5 + 0.3 \times 21.8 = 24 \text{ sones}$$

24 sones → 86 phons



a)



b)

Fig. C13. Calculation of loudness and loudness level according to Zwicker's method.

a) The 1/3 octave data from Fig. C12 have here been transferred onto one of Zwicker's diagrams.

b) "Averaging" of the stepped curve, showing how the equivalent "rectangle" is obtained. The crossing of the dashed horizontal line (top of "rectangle") with the scales to the right indicate the total loudness and loudness level.

appropriate Zwicker graph while Fig. C13b illustrates how the stepped curve in a) is transformed into an equivalent rectangle. From the height of the rectangle the total loudness value is found to be approximately 28 sones (GD). The corresponding loudness level value is 87.5 phons (GD).
In table 1 the conversion of the 1/1 octave band pressure levels to loudness indices can be seen together with the calculation of the overall loudness according to Stevens methods.

Appendix D

Statistical Analysis Technique.

Although it may be fortunate for the sufferer that the sounds which must be measured in the field are seldom constant, this fickleness does create measurement problems. As can be seen from Fig. D1, which is a continuous record of the total sound pressure *level* on a busy street in Copenhagen, it is quite meaningless to quote a sound level as measured with a sound level meter at a single instant in time. The sound level varies with time over at least 15 dB, and the only proper description of the events seems to be statistical. Because the technique outlined below has very much in common with the theory described in Appendix A, and to avoid confusion, the term *level* should be specified a little closer. The term refers to some descriptive value of a rapidly varying quantity, usually RMS, though other values are some times used, e.g. peak or absolute average. In Appendix A it was shown how the RMS value (or level) of such a rapidly varying and statistically fluctuating signal could be determined by applying statistical technique to the *instantaneous* amplitude values of the signal. In the following similar statistical methods are applied, not to the instantaneous value of the signal itself, but to its *RMS value* which, due to the statistical nature of the signal and the finite

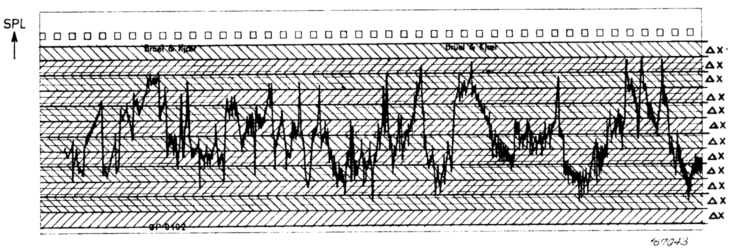


Fig. D1. Reproduction of a graphic level recording with indication of the "class" intervals introduced by the Statistical Distribution Analyzer Type 4420.

time of observation (averaging time T in Appendix A), will also vary statistically. An excellent instrument for the determination of noise *level* fluctuations is the Statistical Distribution Analyzer Type 4420. It should be operated in conjunction with a Level Recorder Type 2305 and resolves the Recorder chart width into twelve "class" intervals of width Δx, see Fig. D1. That part of the total measuring time which the Level Recorder pen spends within a particular "class" interval is registered on an electro-mechanical counter, and each "class" interval has its own counter.

The total measurement time is indicated by a separate counter. By dividing the number of counts registered on each "class" interval counter by the number of counts registered on the "total time" counter a histogram as shown in Fig. D2 (and Fig. 4.31 of the text) can be plotted which then is a measure of the statistical distribution of the sound level with time.

As mentioned in Appendix A a Gaussian random variable is completely specified by its mean value and standard deviation. When the quantity measured is an outcome of many independently varying phenomena, such as for instance the noise level in a busy street the mean value and the standard deviation still give a good description of this quantity.

Mathematically the mean value M, and standard deviation, σ, are expressed as

$$M = \sum_{x=0}^{\infty} x \; p(x) \qquad \text{(a)}$$

and

$$\sigma = \sqrt{\sum_{x=0}^{\infty} x^2 \; p(x)} \qquad \text{(b)}$$

and it is possible from a histogram in the form of Fig. D2, quite easily, to calculate the mean value and the standard deviation in terms of "class" intervals (or "channels units"):

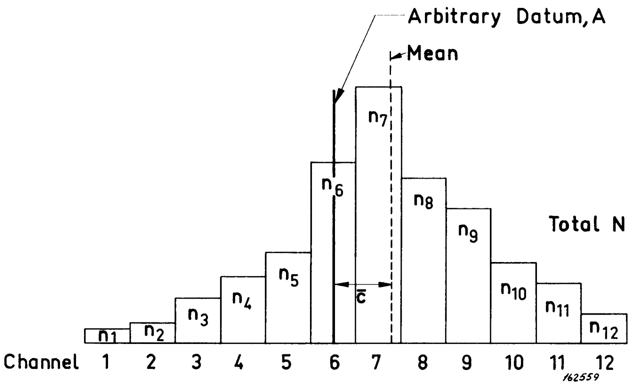


Fig. D2. Example of a level distribution histogram with nomenclature for the formulae (c) and (d).

Suppose that the total count is N, and those in the channels 1, 2, 3 .... 12 are n_1, n_2, n_3, ... n_{12}, respectively (Fig. D2). If the *mean* is likely to be somewhere near the centre of the recorder scale, it is convenient to choose the mid-point of interval 6 as an arbitrary datum, A. The mean lies above A by an amount $\bar{c}$ channel units. The mean gives, in effect, the axis of the centre of gravity of a flat plate cut out to exactly the same shape as the histogram.

$$\bar{c} = \frac{1}{N}\,[(n_7 - n_5) + 2\,(n_8 - n_4) + 3\,(n_9 - n_3) + 4\,(n_{10} - n_2) + 5\,(n_{11} - n_1) + 6\,n_{12}] \quad \text{(c)}$$

The standard deviation, σ, is analogous to the centroidal radius of gyration of the above mentioned plate. To simplify calculation, the following formula takes A as a datum once again, and assumes (as is justified) that N is a large number:

$$\sigma^2 = \frac{1}{N}\,[(n_7 + n_5) + 4\,(n_8 + n_4) + 9\,(n_9 + n_3) + 16\,(n_{10} + n_2) + 25\,(n_{11} + n_1) + 36\,n_{12}] - \bar{c}^2 \quad \text{(d)}$$

Hence the standard deviation, in channel units.

So far statistical data have been described in terms of probability density (amplitude density, Appendix A) and histograms. There are, however, other methods of description. One such method is the use of a *cumulative probability plot.* This can be regarded as a summation over many Δx widths ("class" intervals) in the way described below:

If, for instance, the Level Recorder pen is situated at a position x it might be that 60 % of the time the level is less than x which is the same thing as saying that 40 % of the time it is more than x. The sum of all the probabilities for the class intervals above this x is therefore 0.4 and the probability of the reading being less than x is $1 - 0.4 = 0.6$. A graph showing this idea looks like a descending flight of steps, Fig. D3, which if more and more narrower class intervals were used, would become a smooth curve. In the case of data from the Statistical Distribution Analyzer Type 4420 there are, as discussed above, 12 steps, allowing an adequate approximation to the smooth curve. When switched to "Cumulative" the Distribution Analyzer will allow the plotting of a cumulative probability plot as exemplified in Fig. D3.

As the same amount of information is contained in the two kinds of presentation (Figs. D2 and D3) it is actually left to the operator to choose which type of plot he would prefer. It should be mentioned, however, that data such as the mean value and the standard deviation can be obtained more directly from the histogram Fig. D2.

Note: The calculations shown have all been based on "channel units", and when it is desired to perform calculations in realistic units (e.g. level units) care should be taken when the Level Recorder is fitted with a *logarithmic* range potentiometer. Very often it is only desired to determine which level occurred most frequently (mean) and a standard deviation in dB. The mean

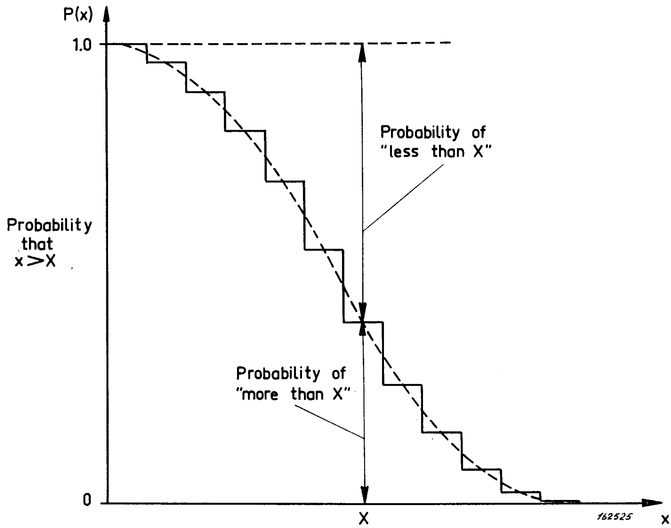


Fig. D3. Cumulative probability plot for a varying signal level showing the summation of probability for all elements of width Δx above each particular value of x. A smooth curve (dotted) would result from using an analyzer of infinite resolution. The steps indicate the approximations that are possible by using the Statistical Distribution Analyzer Type 4420.

value calculated according to the described principles will then be a *geometric* mean and the standard deviation will be some sort of measure of the logarithmic spread in levels. If a true arithmetic mean value and true standard deviation have to be determined the logarithmic channel units must be converted into *linear* scales, and the calculation can no longer be performed according to the formulae (c) and (d). It is then necessary to consult the original formulae (a) and (b).

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