power level is convenient to use in the English system and that 10^{-13} watt is the reference power.

Sound Intensity Level (L_I) is ten times the logarithm to the base ten of the ratio of the sound intensity I to the reference intensity of 10^{-16} watt per sq cm (or its equivalent of 1 picowatt per sq m). Thus

$$L_I = 10 \log_{10} \frac{I}{10^{-16}} \text{ dbi} \tag{6}$$

where

I = watts per square centimeter

or

$$L_I = 10 \log_{10} \frac{I}{10^{-12}} \text{ dbi} \tag{7}$$

where

I = watts per square meter.

The unit is the *dbi*. Either formula gives the same result.

Sound Pressure Level L_p is twenty times the logarithm to the base 10 of the ratio of the sound pressure p to the reference sound pressure of 0.0002 microbar, i.e.,

$$L_p = 20 \log_{10} \frac{p}{0.0002} \text{ dbc} \tag{8}$$

where

p = sound pressure, microbars (dynes per square centimeter).

The unit is the *dbc*, where *c* stands for the C scale or flat scale on the sound level meter.

Loudness N is the intensive subjective attribute of an auditory sensation, in terms of which sounds may be ordered on a scale extending from soft to loud. The unit is the sone. The number of sones is directly proportional to the loudness. By definition, a 1000 cps pure tone with a sound pressure level of 40 dbc has a loudness of 1.0 sone.

Loudness Level (L_N) of a sound is numerically equal to the sound pressure level L_p of a simple tone of frequency 1000 cps that is judged by the listeners to be equivalent in loudness. The unit is the phon. In this text, for a 1000 cps tone, L_N in phons is assumed to be related to N in sones by the formula

$$L_N = 33 \log_{10} N + 40 \text{ phons} \tag{9}$$

This approximation is assumed valid[3] for $N > 1$.

Sound Level at a point in a sound field is the reading in decibels of a sound level meter constructed and operated in accordance with the latest edition of *American Standard Sound Level Meters for the Measurement of Noise and Other Sounds*.[4] The reading is taken with the proper weighting network switched into the circuit. The unit is dba, if the reading is taken on the A scale; dbb if taken on the B scale, and dbc if taken on the C or flat scale. The use of these scales is discussed later.

Attenuation is ten times the logarithm to the base 10 of the ratio of the sound intensities at any two points along any continuous acoustic path in the direction away from the source. The unit is the decibel. For a signal confined to a channel or duct, the intensity values are averaged over the cross-section.

Transmission Loss TL is ten times the logarithm to the base 10 of the sound energy incident on an obstruction in an acoustic path to the sound energy that is transmitted through the obstruction. The unit is the decibel.

Noise Reduction NR is the difference in decibels of the sound pressure levels at two points along an acoustic path in the direction away from the source; alternatively, it is the difference in decibels of the sound pressure levels existing at a single point before and after the addition of acoustic treatment to the path.

APPARATUS FOR MEASURING SOUND

The measurement of sound or noise is usually accomplished by means of (*a*) a sound level meter SLM consisting of a microphone, an amplifier, a variable attenuator, weighting networks, and an indicating meter which reads directly in decibels, and (*b*) an octave band analyzer OBA which is a set of filters for determining the sound pressure level of the sound being measured in each of eight octave-frequency bands. The approved sound level meter and octave band analyzer should comply with the specifications in the latest version of the *American Standard Sound Level Meters for Measurement of Noise and Other Sounds*, Z24.3-1944, and *American Standard Specifications for an Octave-Band Filter Set for the Analysis of Noise and Other Sounds*, Z24.10-1953, published by the American Standards Association.

The SLM is designed to indicate either the sound pressure level L_p or the sound level (if weighting networks are used) above the standard reference level of 0.0002 microbar. The SLM itself has three weighting networks, which are approximations to the equal *loudness contours* for pure tone sounds of three discrete loudness levels. The equal loudness contours give the L_p of a 1000 cps pure tone that sounds equally as loud to the average listener as the tone whose loudness level is desired.[2]

Unfortunately, standard sound level meters do not give an indication of the loudness of more complex noises. To serve as a basis for determining the loudness of more complex noises, measurements of complex sounds are taken on the flat scale (C scale) of the SLM using the OBA to determine the distribution of the sound pressure level as a function of frequency. Computations of loudness and loudness level are made from these data.

Allowable deviations in response and acceptable tolerances recognized in the standard for the sound level meter are: ±0.5 db at 80 cps to 630 cps; +2.0, −2.5 db at 25 cps; ±2.5 db at 2000 cps; ±6.0 db at 8000 cps. Calibration of the SLM and OBA should preferably be made before, during, and after each use by a calibrated loudspeaker.[2] In turn, the loudspeaker should be calibrated at the factory at frequent intervals. Instructions and precautions in the use of sound level meters are given in Reference 2.

APPROACHES TO THE GENERAL PROBLEM OF NOISE CONTROL

It is usually necessary to think of noise control problems as composed of three parts: (1) the source, (2) the path, (3) the receiver.

It is sometimes possible to reduce the noise at any or all of these parts. However, in construction design, the engineer is usually able to do something only with the path.

The source may be any piece of equipment or person generating audible noises. The transmission path may be a path directly through air or may be a path which includes solid structure such as walls, floors, pipes, duct walls, or air within ducts in various combinations. The receiver is usually a person who might be disturbed by the noise; however, the receiver might also be a delicate machine or manufacturing process that must be isolated from vibration.

The acoustic output of a source is ideally specified by its total sound power level and the sound power level in each of a group of frequency bands, preferably octave frequency bands. Where the source is not confined to a duct or the like, it may also be necessary to specify the source directivity, i.e., the relative amount of sound radiating in each direction of interest. In general, the specification of the acoustic output of a source by a single number is not adequate for engineering design of noise control measures. The sound power outputs of fans and grilles as noise sources are discussed in later sections.

Acoustic losses along a path from source to receiver normally exist in any building structure. These losses are a function of frequency and can be defined adequately when expressed as losses in each of eight octave bands. Losses for common structures, and for ducts of various sizes and shapes, as well as for some packaged sound attenuation devices, are published. Some values particularly applicable to ventilating problems are given in a later section.

The response of a person as a receiver has been determined under certain conditions. Noise levels which are found acceptable to the average person under specified conditions are called *noise criteria*. Several frequently used noise criteria are summarized in a later section. The noise criteria to be used must be chosen with regard to the type of activity to be carried on in the space being considered. Where delicate machines or manufacturing processes are the receiver, special noise criteria must be determined to fit the need. Noise criteria should best be specified as sound pressure levels in octave frequency bands.

A good procedure for attacking a noise control problem in a ventilating system will be illustrated by reference to Fig. 1. The sound power level of the fan is expressed in dbe. Sound attenuation in the duct is composed of losses in the unlined and lined portions of the duct, losses at the bend, and end reflection losses. Added attenuation of the fan noise is achieved by adding additional lining to the duct or providing package attenuation units. Noise is also produced at the grille and is expressed in dbe. All losses (attenuation) are expressed in decibels. The procedure follows:

Step 1. Determine the sound power level of the grille noise either from published data, or from actual measurements, or *from approximate data given in the section on Noise Generated* by Grilles.

Step 2. Determine the sound pressure levels in octave bands at a specified listener's position due to grille noise alone which is radiated from the end of the duct, using the acoustical properties of the room and the position of the listener (see the following section on Determination of Room Levels).

Step 3. Determine the allowable sound pressure level in octave bands (the criterion) at the listener's position either from published standard data (see the following section on Criteria for Noise Control) or from discussions with the architect or the ultimate user of the room under design.

Step 4. Subtract the criterion levels from the sound pressure levels at the listener's position (in decibels) to determine that *the levels at least meet the criterion* in each octave band. If the grille noise is higher than the criterion in any octave band, a larger grille size must be used.

Note: The total noise in the room is due to both the grille noise and the fan noise. If the grille noise levels just meet the criterion, then the fan noise emitted in the room must be at least 5 db below the criterion. Alternatively, the grille noise levels and the fan noise levels in the room could each be 3 db below the criterion, because when two noises of the same intensity are combined, the total level is 3 db higher than either. As a third choice, the fan noise could just meet the criterion, and the grille noise be at least 5 db below the criterion.

Step 5. Obtain the sound power level in octave bands of the fan, either from published data, or from actual measurements, or from approximate formulas given in the following section on Noise Generated by Fans.

Step 6. Determine the existing attenuations in the path, for example, natural duct losses, losses at bends, and reflection losses at the outlet (see the following section on Sound Attenuation in Ducts).

Step 7. Determine the net source power levels by substracting values from Step 6 from Step 5.

Step 8. Determine the sound pressure levels in octave bands at a specified listener's position using as basic data the net source power level from the duct, the acoustical properties of the room, and the position of the listener as done in Step 2.

Step 9. Subtract the criterion levels from the sound pressure levels at the listener's position (in decibels) as done in Step 4 to obtain the required amount of noise reduction NR in each of the eight octave bands (refer again to note following Step 4).

Step 10. Choose an economical means of providing the required NR. The noise reduction required usually must be obtained by treating the ducts between the source and the receiver either by adding an absorbing lining or by inserting a package unit (see Fig. 1) of known attenuation as a function of frequency. Because noise may be induced by vibration, a consideration of the fan mounting may be necessary. Also, if the fan room is adjacent to a quiet space, the construction of the fan room walls to provide adequate noise reduction should require attention. It is usually good policy to provide slightly more acoustical treatment than is necessary, thus obtaining a safety factor. A safety factor often used is 5 db greater noise reduction than would be indicated by the above procedure.

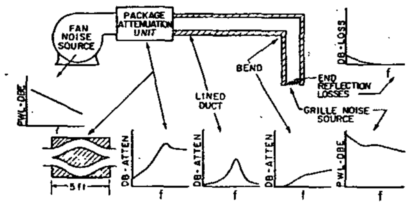

Fig. 1 . . . . Typical Ventilation System Problem

Frequently the controlling noise source in a building with a central station system is sound transmission through the walls of the apparatus room or from a duct plenum. Where such a room or plenum is near occupied rooms, the noise transmitted through the walls must be determined. The combined sound pressure levels resulting at a listener's position should be compared with the criteria as done in Step 4 for noise produced by grilles.

CRITERIA FOR NOISE CONTROL

Criteria for noise control in building spaces have evolved in the United States from several large scale studies and from the experiences of engineers who have recorded favorable and unfavorable reactions to known background noises in many types of rooms.[6]

The acoustical engineer should carefully question the user of the building to make certain of the kind of uses that he has in mind. For example, a coliseum used for sports only, need not be as quiet as a coliseum also used for concerts. As another example, a hall for band concerts need not be as quiet as one for chamber music. In fact, some rooms are better if they are not too quiet. It has been found that libraries, drafting rooms, and study rooms that are too quiet are not so desirable as they would be with moderate noise levels. In very quiet rooms of these types, sounds such as whispering, turning of pages, creaking of the floor, coughing, closing of doors, etc., act to distract the occupants and to make them complain of *noise*.