CHAPTER 19

THE ACOUSTIC ENVIRONMENT: RESPONSES TO SOUND

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19.1 INTRODUCTION

Sources of noise in an office environment include heating, ventilating, and air-conditioning (HVAC) systems, speech, and office equipment. These can have effects on annoyance, speech intelligibility, and performance, and could be a factor in sick building syndrome. The emphasis here is on the effects of noise, which is usually defined as unwanted sound. This chapter will be limited to the office environment, and so will not consider effects such as hearing loss or other physiological effects resulting from exposure to high levels of noise. Nor will it consider the effects of vibration.

HVAC systems produce noise of fairly low frequency, extending into the infrasound region. The biological effects of infrasound have been studied mainly with respect to very high levels for short durations. Currently there is no information available on the long-term effects of lower levels, such as those encountered by office workers. A comparison of the literature on infrasound and on sick building syndrome shows a similarity in the description of symptoms. Therefore infrasound is potentially a cause of some of the symptoms of sick building syndrome.

Many people involved in building investigations have little expertise in acoustics, and so this aspect is often overlooked in a building investigation. Most investigators would like a simple, single-figure measure of the acoustic environment. The A-weighted decibel scale (dBA), first derived in 1927, is the most commonly used figure. In the right circumstances, and as long as its limitations are understood, dBA can provide a useful indication of the acceptability of the acoustic environment. But it does not take account of low frequencies and infrasound. Thus a measure that has been useful for decades is now beginning to show weaknesses in modern buildings, and new measures are needed to account for the characteristics of new, technically sophisticated buildings.

19.2 ACOUSTIC FUNDAMENTALS

Sound Propagation

Sound consists of energy generated by a source and transmitted by pressure fluctuations of the medium through which it travels. The pressure fluctuations can be described in terms of the velocity, frequency, and wavelength. The number of fluctuations (cycles) per second is the *frequency* in hertz (Hz). Subjectively, it is the pitch of a pure tone: The greater the frequency the higher the pitch. The distance between points of equal pressure is the *wavelength.* The *velocity* of the pressure wave is given by:

$$v = f\lambda \tag{19.1}$$

where v = velocity, m/s
f = frequency, Hz
λ = wavelength, m

The velocity of sound in air is proportional to the square root of the absolute temperature, but almost independent of air pressure. For air, it is normally taken as 340 m/s (the value at 14°C). The wavelengths of various frequencies at this temperature are given in Table 19.1. Note the long wavelengths in the infrasound region below 20 Hz: A 20-Hz wave is 17 m (56 ft), and lower frequencies are longer.

Octave Bands

An octave band is a frequency band with the upper frequency twice that of the lower frequency. Thus for a center frequency of f, an octave band ranges from $f/\sqrt{2}$ to $f \times \sqrt{2}$; e.g., the octave band centered on 1000 Hz ranges from 707 Hz to 1414 Hz. Once one band is fixed, the rest become fixed. The International Organization for Standardization (ISO) has agreed on centering the octave bands at 1000 Hz, which gives the center frequencies shown in Table 19.1. The octave bands can be further divided into one-third-octave bands.

The normal range of human hearing covers roughly 10 octave bands, from 20 to 20,000 Hz, although the frequencies are not cut off sharply at each end. The sensitivity of the ear

TABLE 19.1 Wavelengths of Various Frequencies of Sound in Air at 14°C

Frequency, Hz	Wavelength, m	Wavelength, ft
8	42.5	139.44
16	21.25	69.72
31.5	10.79	35.41
63	5.40	17.71
125	2.72	8.92
250	1.36	4.46
500	0.68	2.23
1,000	0.34	1.12
2,000	0.17	0.56
4,000	0.09	0.28
8,000	0.04	0.14
16,000	0.02	0.07

varies with frequency, and higher levels are required at the frequency extremes for a tone to appear equally loud as a tone at 1000 Hz. The normal audible range is shown in Fig. 19.1.

Weighting Curves

The sensitivity of the ear varies also with the loudness of a sound. Three weighting curves, the A, B, and C curves, have been devised to approximate the ear's varying sensitivity with frequency over three ranges of loudness, Fig. 19.2. (Another curve, the D-weighting curve, was later added for aircraft noise.)

The A-weighting curve is based on loudness curves measured by Bell Laboratories in 1927. It is defined by standards such as those set by the International Electrotechnical Commission (IEC) in 1961 and 1973. Originally it was meant only for low sound levels, below 55 decibels (dB). B-weighting was for levels from 55-85 dB, and C-weighting for levels over 85 dB (Porges 1977). In practice, A-weighting (dBA) is now used in most noise regulations, and C-weighting is used with sound reproduction systems. The C-weighting scale is similar to the linear scale (dBLin) with no weighting.

One of the reasons A-weighting has become so popular is that it provides a single-figure measurement of the acoustic environment that approximates the sound heard by the ear. For many applications, this is enough. But a dBA reading does not closely resemble the loudness of complex sounds. Also, Fig. 19.2 shows that the A-weighting curve gives large attenuations at low frequencies. Therefore A-weighting should not be used in noise assessments of mechanical ventilation systems, which have strong components in the low-frequency and infrasound regions. Using the A-weighting scale can show a reduction in noise levels when silencers are fitted or other remedial measures are taken; often the energy has merely been shifted to a lower frequency, outside the range of A-weighting.

Because of the limitations of weighting networks, a more detailed knowledge of the frequency spectrum is needed for analytical work. There have been many attempts over the years to devise methods that consider the frequency spectrum and still allow the acoustic environment to be expressed with a single value (Warring 1983, Blazier 1995). The result has been a confusing number of acceptability criteria. The various curves are often at odds, especially in the low-frequency region (if they even extend that far). They apply only to

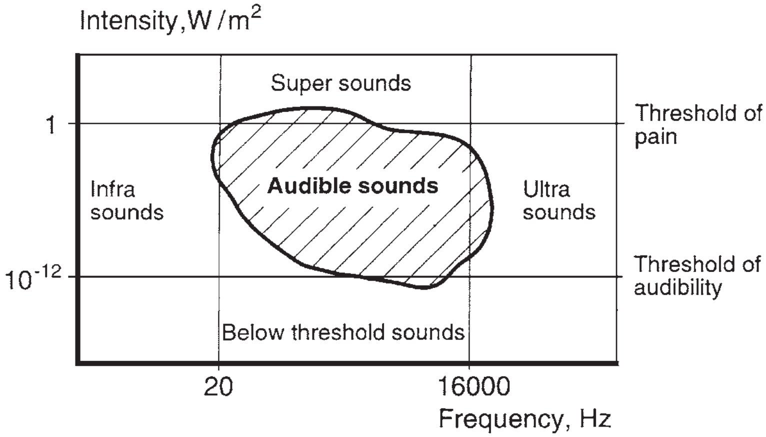

FIGURE 19.1 Normal audible range, showing how the sensitivity of the ear decreases toward the frequency extremes. Adapted from Szokolay (1980).

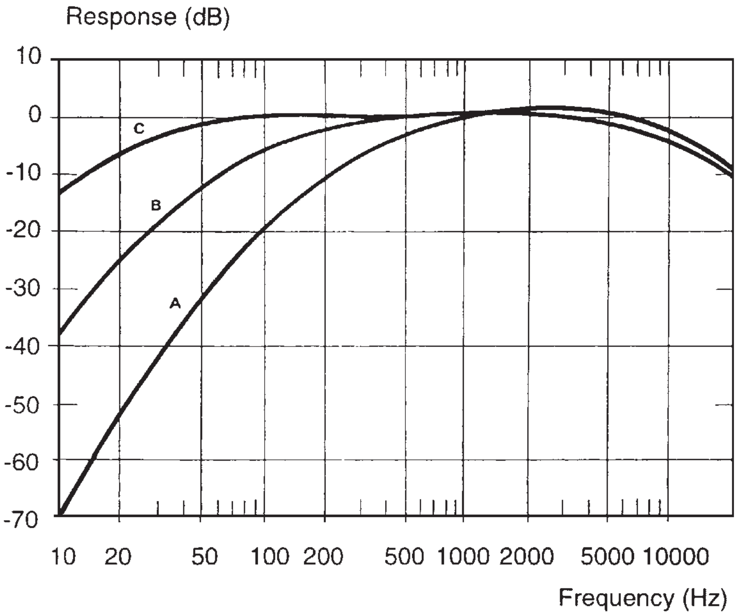

FIGURE 19.2 Weighting curves, from Iqbal et al. (1977). Note the large attenuation given by A-weighting at low frequencies (50 dB at 20 Hz, more at lower frequencies).

continuous noise, with no fluctuations and no unusual shapes in the spectrum. In spite of more sophisticated techniques for indicating loudness, dBA measures are as good as any unless there are unusual spectra (Porges 1977).

Unusual spectra include the low frequencies produced by HVAC systems (Hegvold and May 1978). Some information about the low-frequency content of a sound is given by (dBLin − dBA). If this value is greater than 20 dB, then complaints are likely to occur (Leventhall 1980, Broner 1994). More detailed information about the low-frequency content and unusual spectra are best obtained by plotting the frequency spectra, rather than by using single-figure criteria. Spectra can be plotted by attaching an octave band or one-third-octave band filter to a sound level meter, and recording the levels in the different bands.

Sound Levels

The magnitude of sound energy may be expressed either as power, intensity, or pressure. Sound *power* is the total rate of acoustical energy produced by a source, in watts (W). This is the value quoted by equipment manufacturers for their products. Sound *intensity* is the rate of energy flow through an area normal to the flow, W/m^2. It is a vector quantity that describes both the magnitude and direction of the energy flow. Sound *pressure* is the value of the pressure variation, in pascals (Pa). It has magnitude but no direction. Because the pressure fluctuates above and below a static value, the sound pressure level is taken as the root-mean-square pressure of a full cycle.

The three quantities vary over wide ranges; e.g., sound power varies from 10^{-12} W for the threshold of hearing to 10^4 W for a turbojet engine. Therefore logarithmic ratios are used so that all three terms can be expressed as *levels* in decibels:

$$\text{Sound power level} = 10 \log_{10}\left(\frac{P}{P_0}\right) \text{dB} \tag{19.2}$$

$$\text{Sound intensity level (SiL)} = 10 \log_{10}\left(\frac{I}{I_0}\right) \text{dB} \tag{19.3}$$

$$\text{Sound pressure level (SpL)} = 10 \log_{10}\left(\frac{p}{p_0}\right)^2 = 20 \log_{10}\left(\frac{p}{p_0}\right) \text{dB} \tag{19.4}$$

where P = sound power, W
I = sound intensity, W/m^2
p = sound pressure, Pa
I_0 = reference intensity = 1 pW (10^{-12} W) (10^{-13} W has been used in the United States)
p_0 = reference pressure = 20 μPa (20×10^{-6} Pa = 20×10^{-6} N/m^2)

A decibel figure must always have a reference value. If it is not stated, it is taken as 20 μPa for SpL.

The sound pressure level, SpL, is the measure most often encountered in guidelines and regulations. Sound intensity (as distinct from sound intensity *level*) is measured as the product of the instantaneous SpL and particle velocity of an imaginary particle in the sound field. It is only recently that instruments have been developed to measure intensity. The sound intensity *level* has the same numerical value as the sound pressure level in air.

An office environment has continuous noise, such as HVAC noise, and fluctuating noise, such as speech and office machinery. Fluctuations can even arise in HVAC noise from unstable fan operation, or “beats” between two fans operating at nearly the same speed. Fluctuating noise is difficult to measure on a sound level meter. Various methods have been proposed for recording the noise over periods of time, and integrating the results in different ways. A bewildering number of measures and acceptability criteria have been proposed. Possibly the most useful measure of the acceptability of fluctuating noise is L_{eq}, the equivalent (continuous) sound level, recommended by the ISO. It is the level of steady sound that would contain the same energy as the time-varying sound. It usually refers to A-weighted energy, but not always. If the sound is steady, continuous, and has no unusual frequency spectra, then L_{eq} is similar to dBA. For its measurement, an *integrating sound level meter* is needed (Warring 1983).

The noise sources in an indoor environment can thus be measured by using a sound level meter with an octave band filter for steady noise, and an integrating sound level meter for fluctuating noise. HVAC systems can generally be considered as steady noise sources, and the levels should not exceed, e.g., 40 dBA in offices in Sweden. Typical noise levels in offices are fluctuating noises of 50 to 70 dBA, although short-term peaks of over 80 dBA occur (Keighley 1970). Most of this has its source within the room, and consists of noise due to speech, the peaks being due to noise from machinery, e.g., telephones ringing.

19.3 NOISE FROM HVAC SYSTEMS

HVAC Noise Sources

The noise in an HVAC system comes from the fan unit, the ductwork, and the terminal devices. Terminal devices at the end of supply ducts are called diffusers, those at the beginning of exhaust ducts are registers, grilles, or mushrooms. Most HVAC noise is due to turbulent flow acting on blades, vanes, and casings (Neise 1992). The components that generate the most noise are the supply and exhaust fans (Hoover and Blazier 1991).

The fan should be selected to operate at the point of maximum aerodynamic efficiency, which is also the optimum point acoustically (Iqbal et al. 1977, Graham and Hoover 1991). Designers often try to use large, slow-moving fans to reduce noise. But fan noise is not just a function of the rotational velocity, it is also a function of the tip speed, which increases with increasing diameter. Undersized fans with high shaft speeds are noisier than fans operating at maximum efficiency; oversized fans with low shaft speeds produce more low-frequency noise.

In the fan unit itself, the noise comes from several sources (Neise 1992):

- The effect of the fan blade displacing air—the blade thickness noise
- Pulsation as moving blades pass stationary cutoffs at the outlet—the blade frequency
- Vortices from the trailing edge of the fan blades
- Mechanical noise, e.g., worn bearings
- Rotating stall

Rotating stall occurs when the flow rates are low across the fan blades. The side of the blade facing the flow is the pressure side, the other is the suction side. The flow stops on the suction side of one blade, which changes the angle of attack on the next blade and stalls the flow there as well. A stall cell builds up that moves around the blade in the opposite direction to rotation and produces low-frequency pressure pulsations.

A fan can be fitted in a scroll or a plenum chamber, Figs. 19.3 and 19.4. A plenum chamber has a slightly lower efficiency than a scroll, but it is physically shorter and can therefore fit in confined spaces. The choice of fan is greater so that more efficient and therefore quieter fans can be selected. Noise is further reduced by lining the plenum box with acoustic absorbing material.

Noise can also radiate out from ducts (breakout noise) and be transmitted from room to room via the HVAC ductwork (flanking transmission), Fig. 19.5. Any tees, bends, struts, or other features close to the fan inlet or outlet increase turbulence and thus increase noise levels. Diffusers at the end of supply ducts produce a fairly high-frequency hissy noise. Dampers placed behind diffusers result in more noise. Variable air valves (VAV) are a dominant source of noise, due to the pressure drops; the levels can be high enough for speech interference. They produce broadband noise peaking at 125 Hz.

Noise estimations for HVAC systems are usually based on:

- The sound pressure level quoted by the manufacturer
- The silencer attenuation according to the manufacturer's data
- The effects, both positive and negative, of the ductwork and fittings, usually calculated from a textbook

The difference between this calculated noise and the actual noise of the installed HVAC system is called the *installation effect* (Bolton 1992). Nowadays fan manufacturers are required to provide noise levels both under standardized conditions and in systems. Even so, acoustical ratings of HVAC products are more useful for comparing products than for investigating performance in installed systems (Ebbing and Blazier 1997). A difference between the installed noise and the fan test standard can be due to factors other than the installation effect:

- Measurement technique and accuracy
- Manufacturing tolerances (the installed fan may be different to the tested fan)

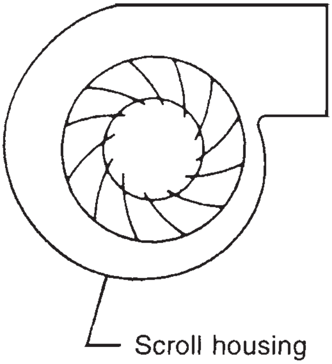

FIGURE 19.3 A scroll fan, centrifugal with backwardly curved blades.

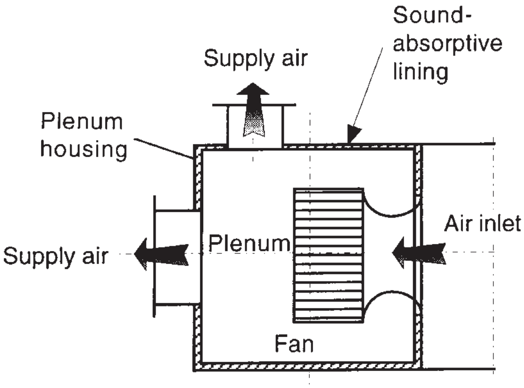

FIGURE 19.4 A plenum fan.

- Data limitations, e.g., the frequency range below 100 Hz is often not given
- Variability between testing laboratories

Control of HVAC Noise

Because A-weighting attenuates low-frequency noise readings, dBA is not recommended as a diagnostic tool for HVAC noise. Complaints about HVAC noise are related more to the quality of sound than the level, e.g., unbalanced spectra producing rumble or hiss, and using time-averaged A-weighted sound levels may not identify the reason for complaint (Blazier 1995).

Noise reduction is usually aimed at either reducing turbulence, or reducing the fan's response to turbulence. Solutions are usually specific for one type of fan, so general recommendations cannot be made (Bolton 1992). Sound transmission in ducts needs to be reduced without reducing or altering the flow. *Passive* noise control involves adding damping material and silencers. It is not effective at low frequencies because of their long wavelengths.

Active noise control feeds a counteracting signal into the duct to cancel the main signal. Active control allows the most effective fan configuration to be chosen, and the noise to be attenuated afterward. The system can adapt to changing frequencies (Mendat et al. 1992).

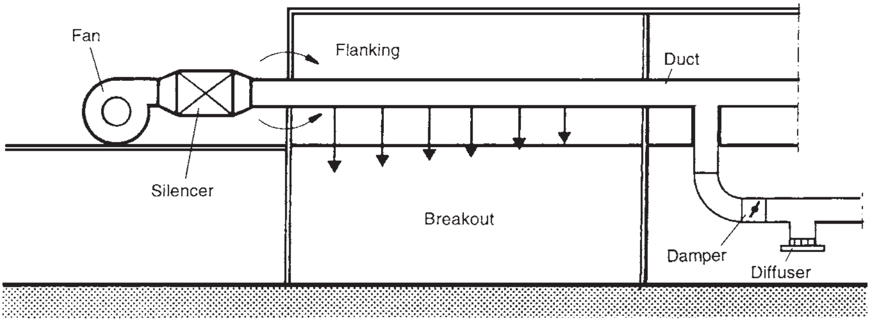

FIGURE 19.5 Breakout and flanking noise from ducts, and diffuser noise.

The effect is limited to waves that have a wavelength greater than the largest duct diameter, which usually means frequencies below 250 Hz. Active noise control systems can attenuate both broadband and narrowband (blade) frequencies. To work effectively, however, the airflow must have a low velocity (<8 m/s) and minimal turbulence, conditions which are often not met in modern HVAC systems.

The most effective way of reducing HVAC noise is by good system design. Corrections carried out after installation are often difficult and expensive. Good design includes selecting the best fan and designing for low pressure drops (Guenther 1998). From the viewpoint of both noise and efficiency, it makes more sense to adjust fan speeds than to throttle the flow with VAV dampers. Diffuser noise can be reduced by increasing duct diameter or increasing diffuser size (Hoover and Blazier 1991).

19.4 INFRASOUND

HVAC systems produce noise in the low-frequency and infrasound regions. The levels involved vary, but occupants can be exposed to 80 to 90 dB. Whether long exposures to such levels is harmful is still not known; most research into the biological effects of infrasound has been carried out at higher levels. Some investigators reported symptoms such as fatigue, dizziness, irritation, and nausea from exposure to infrasound, and implicated infrasound as a cause of allergies and nervous breakdown (Gavreau 1968). The descriptions seem remarkably similar to some descriptions of sick building syndrome (Finnegan et al. 1984). Review articles on the effects of infrasound have been produced by Händel and Jansson (1974), Westin (1975), Harris et al. (1976), and Broner (1978), and a book has been edited by Tempest (1976). Infrasound has been a controversial subject, with some authors reporting alarming effects from exposure to infrasound, and others saying the effects have been exaggerated.

The Nature of Infrasound

Although the audible range is usually quoted as 20 to 20,000 Hz for humans, there are no sharp cutoffs at the frequency extremes. The ear becomes progressively less sensitive to lower frequencies, so that the threshold is about 70 dB for a 20-Hz sound. Below 19 Hz, tonal quality is lost as tones lose their smoothness (analogous to flicker in vision). Below about 15 Hz, the sound is perceived as a pumping noise. Below 10 Hz, there are only tactile sensations in the ear. Curves of equal loudness, equal annoyance, and hearing thresholds for infrasound have been determined (Whittle et al. 1972, Yeowart 1976, Møller and Andresen 1983); see Fig. 19.6. The curves converge somewhat in the infrasound region and the slope flattens out; i.e., once the auditory threshold is reached, slight increases seem very loud and annoying. Equally, modest reductions may be all that is needed to remove the effects. Various attempts have been made to produce the best weighting curves for low frequencies (Brüel 1980), but there is still no standard.

Natural infrasound is mostly below 2 Hz, and is produced by thunder, earthquakes, and volcanoes. The energy can be propagated over large distances. One of the few attempts to study the effects of natural infrasonic waves was carried out in Chicago, to see if there were any effects on traffic accidents or absenteeism among schoolchildren. Some correlation was found (Green and Dunn 1968). The effects of natural infrasound on humans are probably minimal, because the wavelengths at 1 Hz are so large in relation to human size (Westin 1975). At one time Sweden had working limits of 110 dB for the 2- to 20-Hz range. Such a limit is rather impractical, as it could result in work stoppages just because a strong wind is blowing against a building (Brüel 1980).

Artificial infrasound can occur in many settings. A car travelling on a motorway with the window open can have a sharp peak at 16 Hz. A bus typically produces a spectrum with a peak in the 63-Hz band at around 90 dB, which translates into a 10- to 20-Hz band indoors when the bus is passing at 50 km/h. Trains produce around 100 dB at 100 Hz, which can affect the driver's alertness, although it is not usually a problem for the passengers. Indoors, the main source is HVAC systems (Leventhall 1980).

Effects of Infrasound

Although some work was done on the biological effects of infrasound in the 1930s, e.g., by the Nobel prize winner George Von Békésy in 1936, interest in the field then

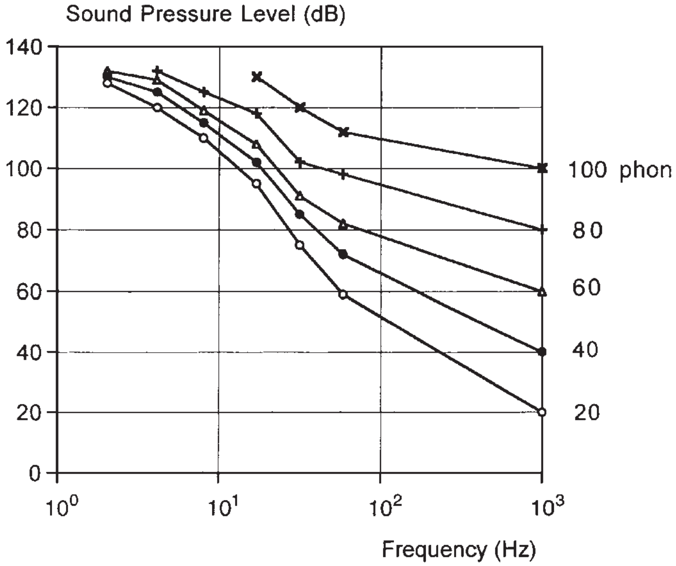

FIGURE 19.6 Curves of equal loudness for the infrasound region (Møller and Andresen 1983). The phon is a unit of subjective loudness whose values have been standardized to coincide with the decibel scale at 1000 Hz.

declined. Revival in interest came with the advent of supersonic aircraft and sonic booms, and with concerns about the effects of rockets used in the space programme. This resulted in several studies over about a decade starting in 1965. Many articles appeared in the nonscientific press during this period, resulting in some skepticism about the effects that persists to this day. Even the results from scientific studies were inconsistent, because infrasound is difficult to produce under experimental conditions and difficult to measure.

The first experiments (Mohr et al. 1965) showed that exposures up to 150 dB could be tolerated for short periods (2 minutes). Sources included loudspeakers in a reverberation chamber and a J57 turbojet engine with afterburner in an F102A aircraft. Some of the effects reported from very low frequencies (5 to 10 Hz) were chest wall vibration, gag sensations, and changes in respiratory rhythms. Exposure to frequencies of 50 to 100 Hz resulted in mild nausea, headaches, choking, coughing, visual blurring, and fatigue. Although there was much individual variation, all subjects reported severe postexposure fatigue that could only be resolved by a night's sleep.

Studies showed that infrasound is transmitted poorly via air to the body organs (von Gierke and Nixon 1976), and that any possible effects are mostly due to pressure effects in the ear (Westin 1975). Comparisons of deaf people with normal people indicated that low-frequency noise affects the cochlea (Yamada et al. 1983).

Tests carried out at more moderate intensities around 125 dB produced drowsiness, lack of concentration, nausea, postexposure fatigue, and headache (Evans 1976). Frequencies of 15 to 20 Hz produced respiratory difficulties, sensations of fear, and cutaneous flushing. In one study, levels as low as 85 to 110 dB could produce violent and sudden attacks of nausea at 12 Hz, even in people who were skeptical about the effects of infrasound (Brown 1973). There is even some anecdotal evidence of complaints at levels as low as 65 dB (Tokita 1980), and it is still possible that such low levels can have psychological rather than physiological effects.

These reports were some of the more worrisome about infrasound to come out, because they suggested that everyday levels of infrasound could cause problems in some people, especially those with balance disturbances or other middle ear problems (Tempest 1976). Levels of 115 dB can occur in a car on a motorway, and it was postulated that some motorway accidents were the results of increased reaction times, lethargy, drowsiness, and euphoria produced by infrasound.

Several investigators began to suggest that the effects had been exaggerated (Harris and Johnson 1978). Tests carried out at 144 dB for 8 minutes had failed to show detrimental effects (Slarve and Johnson 1975), although some subjects reported drowsiness and a decreased ability to concentrate. One reason for the controversy may be the assumption that the effects due to infrasound increase linearly with increasing levels. However, there is some evidence to the contrary. Levels below 120 dB may have a depressive effect, and higher levels an arousal effect (Broner 1978). A typical office environment has the lower levels. The depressive effects at lower levels could account for symptoms such as fatigue and lack of concentration.

Sensitive people have a lower threshold to infrasound, a phenomenon reproducible under laboratory conditions, and show changes in respiration rate and the alpha wave rhythm. People with a cold can experience nausea and vomiting when exposed to infrasound (Okai et al. 1980). People who develop an allergy whereby they become sensitive to very low levels of a stimulus frequently have a spillover effect and become sensitive or allergic to other stimuli. Allergic people should therefore be considered a risk group for sensitivity to infrasound, until more information is available (Burt 1998).

By 1980, more buildings were being constructed with tight sealing and mechanical ventilation to save energy. People thus began to spend more time in closed spaces ventilated by low-frequency pulsed air (Borredon 1980). Unfortunately, interest in infrasound began to decline at about the same time. The acoustic environment in modern, tightly sealed buildings with mechanical ventilation has received little study, and almost none with respect to sick building syndrome.

To this day there have been very few studies about the effects of longer durations of infrasound at more moderate intensities, such as those encountered by many office workers. One study tested subjects for two working weeks (8 hours a day for 10 days) at levels of 70 to 125 dB, and frequencies of 3 to 24 Hz, both pure tone and band. Measurements were made of several physiological parameters such as ECG, blood pressure, respiration, and epinephrine and norepinephrine in urine. The physiological parameters were not significantly altered, but several subjects reported subjective effects such as reduced concentration, increased tiredness, headache, and tenseness (Ising 1983).

19.5 THE EFFECTS OF INDOOR NOISE

In addition to noise from HVAC systems, the indoor environment has other sources of noise. These include speech, noise from equipment, and outdoor or community noise.

Community noise includes the noise from aircraft, trains, and traffic. In an indoor environment, such noise becomes a problem only if it penetrates the building envelope. In modern, well-sealed buildings, this usually only occurs if the windows are opened. If the windows are kept closed to shut out community noise, then it becomes important that the HVAC systems are working as intended, and that their noise levels are not excessive. There have been reports where shutting the windows and turning on HVAC systems resulted in higher noise levels than with the windows open and the HVAC system switched off (Lee and Khew 1992).

Community noise is a large field, with specialists for aircraft noise, traffic noise, noise assessments of building sites, etc. Modern, well-sealed buildings with double or triple glazing are fairly well insulated from outdoor noise, and so the effects will not be considered further here.

Most standards and recommendations for noise were made for industrial environments, as were most of the noise reduction measures. The number of places with high noise levels is now decreasing, but the number of places with moderate levels is increasing. These include office buildings, where average noise levels vary from about 50 to 80 dBA (Keighley 1970). At these levels, the risks for hearing damage and physiological effects are slight. Instead, the effects of noise on psychosocial factors like *annoyance, speech,* and work *performance* become important (Guignard 1965, Kjellberg 1990).

Annoyance

Annoyance to noise is a subjective reaction, and therefore needs to be measured by human opinion. Annoyance is due to the degree of noisiness plus the respondent's assessment of other factors like fluctuations, emotional content, visual cues, and novelty (May 1978). Because of individual differences, annoyance assessments need to be based on surveys of many people rather than studies of a few individuals (Borredon 1980).

The view has been expressed that annoyance responses are little more than fickle responses of cranks or unstable persons. But there is a large body of evidence now available showing consistent increases in reported annoyance with increasing noise. Moreover, these surveys have shown that there is little relationship between annoyance and personality traits such as neuroticism or stability, or factors like type of employment and income.

Even directing attention to a noise source, e.g., by a survey or by media exposure, has little effect on the results. Nor does directing attention away from noise, e.g., by using a "concealed" questionnaire which purports to be about other environmental matters (Large et al. 1982).

Annoyance to a noise usually increases with time, contrary to the popular belief that adaptation takes place (Kjellberg 1990). It is often assumed that annoyance increases with increasing loudness, but a noise need not be loud to be annoying, e.g., an insect buzzing around one's head. Also, loud noises can be regarded as pleasurable, e.g., loud music. Thus the type of noise is probably more important than the noise level in determining annoyance.

Three kinds of annoyance can be described (McLean and Tarnopolsky 1977):

- Subjective, or feelings of being bothered, angered, or having privacy invaded
- Interference, or disruption of activities
- Stress annoyance, resulting in the symptoms of stress such as headache, tiredness, irritability, and lowering of morale

Other factors affecting annoyance are fluctuating, unpredictable, and uncontrollable noise. An important factor in controlling noise is the *perception* of control, i.e., the feeling "I can do something about it" (Hirsch 1973). If people know that they can turn the noise off, the noise is more acceptable. A person operating a machine controls the noise it makes, and therefore can deal with the noise better than someone else hearing the same noise. The two people will also have different attitudes to the noise. Surveys showed, for example, that those who were in favor of the Concorde project were less annoyed by its noise than those who were opposed (Kjellberg 1990).

Infrasound and low-frequency noise become annoying when the masking effect of higher frequencies is absent (Leventhall 1980). This can happen with the transmission of signals through walls, which attenuates the high frequencies. Accommodation to such low-frequency noise seems more difficult than to noise of higher frequencies, and can produce typical stress symptoms of headache; pains in neck, arms, and legs; and digestive disorders. Susceptible people are more sensitive to the annoyance effects (Broner 1978) and so annoyance can be considered a feature of infrasound.

Speech

Background noise can interfere with speech communication, and the higher the noise the more the voice has to be raised for satisfactory communication. Background noise includes irrelevant speech, which can be disruptive because of its informational content. However, even incomprehensible speech is annoying (Kjellberg 1990). This has been demonstrated with unknown foreign languages, or even with tapes played backward (Jones and Broadbent 1991). There appear to be some aspects of speech that distinguish it from other kinds of noise. Thus vocal music is more disruptive than instrumental music. The effects of irrelevant speech are independent of the level once it is higher than 55 dBA (Jones 1990).

Speech consists of vowel sounds, mostly at frequencies of 125 to 2000 Hz, and consonants, which are at higher frequencies of 3000 to 6000 Hz. The effective speech frequency range is 600 to 3000 Hz, and a loss of information outside this range does not severely reduce intelligibility (Guignard 1965). Unfortunately, noise-induced hearing loss affects frequencies around 3000 to 4000 Hz, thus affecting the ability to hear consonants.

The level of speech depends on vocal effort and is different for male and female voices. The maximum loudness of male voices occurs around 400 Hz, and for female voices around 900 Hz. Normal speech, when measured at intervals of $^1/_8$ second, covers a range of nearly 30 dB. However, speech levels are usually measured and expressed in terms of the long-time (60 seconds) root-mean-square pressure (Kryter 1970). Typical levels are given in Table 19.2.

Speech must be clearly articulated, and the listener needs good hearing, in order to be intelligible. Articulation indices exist, although they can have a lot of correction factors and still not accurately predict the intelligibility of a speaker; some voices have spectra that are harder to understand than others. Therefore indices are seldom used today.

Speech interference levels (SILs) were devised as long ago as 1956 (Beranek 1956). The SIL is the maximum level of noise that allows speech without interference. It is measured as the average sound pressure level of the three octave bands centered on 500-, 1000-, and 2000-Hz octave bands. More bands have been tried, but the results are almost identical to three bands. A common recommendation is that the SIL should be more than 12 dB below the level of speech to avoid interference (McLean and Tarnopolsky 1977).

Background levels of 30 to 40 dBA have a minimal effect on the speech level required for clear articulation, and the maximum recommended background level for classrooms, for example, is around 47 dBA (Lee and Khew 1992). After that, a speaker needs to raise the voice by about 0.5 dB for every 1-dB increase in background noise. Loud speech above 75 dBA becomes less intelligible than normal speech. Also, at this point the background level would be above 60 dBA, and high background levels also reduce intelligibility (Keighley 1970).

People with hearing losses are more affected by irrelevant speech than those with normal hearing; i.e., they have more difficulty in a “cocktail party environment.” Also, they are usually more annoyed than people with normal hearing. Thus the idea that they won’t be annoyed if they cannot hear the noise is wrong (Kjellberg 1990).

The above guidelines are for a steady situation. In the real world, sounds vary with time, resulting in time-varying interference with speech. There can also be effects involved other than pure masking. For example, a noise can force a listener to concentrate more on receiving the signal correctly, and less on comprehension (Hockey 1978). The effects on acceptability are difficult to determine, but the Environmental Protection Agency in the United States describes L_{eq} = 45 dBA as an acceptable level for speech indoors.

Performance

Performance effects are distinct from annoyance effects. The effects of noise on performance can be positive or negative, depending on the type of noise, task demands, familiarity with the task, whether the task is verbal or not, conflicting demands, duration of the task, and effects on morale as a result of managers’ concern for workers. Sudden changes in noise levels produce a temporary performance loss, as do noise bursts and unfamiliar noise. Continuous or familiar noise has little effect on familiar tasks. Irrelevant noise, rather than

TABLE 19.2 Typical Sound Pressure Levels, dBA, for Speech at a Distance of 1 Meter

Type of speech	Male voice	Female voice
Whisper	20–30	20–25
Low voice	50–60	45–55
Normal voice	65–68	60–65
Raised voice	70–75	68–70
Loud voice	75–80	70–75
Shouting	>85	75–85

Source: Adapted from Warring (1983).

noise that is part of the work, reduces efficiency. High frequencies affect performance more than low frequencies do (Jones and Broadbent 1991).

Performance is usually measured by various short-term psychological task tests carried out in a laboratory. The results do not always translate well into actual working places and over 8-hour working days (Hockey 1978). Nevertheless, several investigators have shown that noise (excluding speech) need not affect performance, or that the effects are surprisingly small. The performance of simple tasks may actually be improved by noise, but performance is impaired in complex or high-information-load tasks. Cognitive tasks (verbal learning, memory, mental arithmetic, etc.) can be affected by 70 to 80 dB, i.e., the levels found in offices.

A subject can compensate for raised noise levels by concentrating harder. However, there is usually a price to be paid. The extra effort can be demonstrated as physiological stress. If the stress levels stays the same, then the work rate worsens. If the work rate stays the same, then more mistakes are made, judgment is impaired and irritability increased (McLean and Tarnopolsky 1977).

Noise can affect the rate or process of learning. During a lecture, more learning takes place when the narrator implies some emotion, regardless of visual or other supporting media. The kind of emotion is irrelevant; more learning can be shown to occur even when the speaker is contemptuous of the subject matter. Music can also assist in learning, because it elicits an emotional response. Again, the process is effective whether the subjects like the music or not. Audio stimuli are more effective than visual stimuli in inducing a response (Burris-Meyer 1971).

Office workers seldom pay attention to HVAC fan noise, but they are very relieved when it stops. Tests have shown HVAC noise can adversely affect performance, and that stopping the noise can lead to an improvement in performance (Kjellberg and Wide 1988). Exposure to infrasound at moderate levels (90 dB) has been shown to degrade performance gradually (Kyriakides and Leventhall 1977). However, other investigators have said that infrasound which is not perceived subjectively has no effect on performance, comfort, and general well-being (von Gierke and Nixon 1976).

Performance is adversely affected by a loss of control over the situation, and the effects are less if subjects know they can terminate the noise. The level of control affects a worker's attitude to both the noise and the work (Jones and Broadbent 1991). It was shown above that the degree of control can also affect annoyance. The level of individual control therefore affects many aspects of office work.

19.6 ACCEPTABLE INDOOR NOISE LEVELS

The above descriptions should indicate that it is no simple matter to recommend noise limits. Any given level will have different affects on annoyance, speech intelligibility, and performance, the difficulties being compounded by differences between individuals. Nevertheless, there have been several attempts to recommend acceptable noise limits indoors. Table 19.3 gives some examples of approximate instantaneous levels in dBA. For fluctuating noise levels, the figures can be regarded as reasonably accurate L_{eq} levels.

Typical levels exceed most recommendations by about 5 to 10 dB. There usually has to be a compromise between maintaining performance and keeping costs reasonable (Warring 1983). HVAC noise should not exceed the levels in Table 19.3. Note that a noise can still be within a recommended value and be found to be disturbing by one or more occupants, e.g., fluctuating noise levels and unusual spectra. The figures in Table 19.3 are therefore to be used as a guide, and not adhered to rigidly. It should not be assumed that all is well if the measured values do not exceed recommended values.

TABLE 19.3 Some Recommended Acceptable Levels, dBA

Location	Beranek (1957)	ASHRAE (1967)	Kryter (1970)	Beranek (1971)
Private office	30–45	25–45	35	
General office	40–55	35–65	35–40	
Classroom	35	35–45	35	38–47
Lecture theatre	30–35	30–40	33	30–34
Assembly hall	35–40	30–40	38	30–42
Court room	40–45	40		42
Hospital	42	30–45	40	34–47
Church	40	25–35	40	30–42
Concert hall	25–35	25–35	28–35	21–30
Recording studio	25–30	25–35	28	21–34
Homes, bedrooms	35–45	25–35	40	34–47
Restaurant	55	40–55	55	42–52

Source: Adapted from Hegvold and May (1978).

19.7 ACOUSTIC MEASUREMENTS

Instruments

Sound Level Meters. A simple sound level meter consists of a microphone, an amplifier and a readout facility. Because sound consists of pressure fluctuations above and below a static value, the signal is usually rectified in the form of the root mean square of the averaged signal. An attenuator is fitted so that levels can be measured in 10-dB steps, thus a wide range of levels can be covered. All sound level meters have an A-weighting filter. More versatile instruments can have several weighting networks. An integrating sound level meter is the same as a basic sound level meter, but with the added facility of storing, or logging, measured values over a period of time. The signal is averaged to give the equivalent sound level L_{eq}.

Frequency Analysis. Many sound level meters have a facility for attaching an octave band filter set. A series of readings can then be taken at the different octave band settings to give a crude frequency analysis. For more accurate analysis, a one-third-octave filter can be used, which gives 3 times as many individual bands as an octave analysis. Even a third-octave analysis will produce a spectrogram with "steps" from one band to the next. Greater detail can be achieved by a narrowband analysis. This is often performed by using a single filter with a constant bandwidth, regardless of the frequency. The filter is swept slowly across the desired frequency range. Such analyses are more tedious to perform, and may not be justified in a routine analysis of building acoustics (Burns 1968). The narrower the frequency band chosen, the more time is needed for the analysis.

More recently, real-time frequency analyzers have become available. These can display the levels in all the chosen frequencies simultaneously. The analysis is quicker than with swept analyses, but the instruments are expensive and the resolution poorer. They are useful for measuring sounds with transient events, which may be missed by a swept analysis. They are not necessary for the measurement of continuous noise like HVAC noise.

Recording Results. A sound level meter, with or without a filter, may be connected to a graphic level recorder, which is usually calibrated with a logarithmic potentiometer to give the output in dB. Different kinds of chart paper can be used, including paper with a frequency scale. To obtain a frequency spectrogram, the speed of the paper feed is synchronized to the rate at which the frequencies are swept by the filter.

A sound level meter, frequency filter, and level recorder together can be bulky and difficult to use under field conditions. This was particularly true of earlier instruments. For a field study, the best procedure is to make tape recordings of the sound. These provide a permanent record of the acoustic measurements that can be analyzed under less pressing conditions in the laboratory. In recent years, portable digital audio tape (DAT) recorders have become available, with linear responses down to the infrasound region. They are no bigger than the familiar "Walkman" tape recorders. Their use allows much bulky equipment to be left in the laboratory, as the only items needed for the field measurements are the DAT recorder and the sound level meter. In using a tape recorder, a known sound level signal must be recorded first. During playback, the measuring level is set to the known signal level.

Combination Instruments. Over the past 10 years, computer technology has enabled great strides to be made in the development of acoustic instruments. Many sound level meters are manufactured as integrating meters that enable a large number of measurements to be stored. The meter can display the results individually in a display window, or be connected to a desktop computer with a suitable program (e.g., Excel from Windows). The results can then be read on the computer screen, or printed out with the computer's printer. These meters can measure several parameters simultaneously, e.g., dBA, dBC, L_{eq}, maximum, minimum and peak levels, plus various other parameters used in the measurement of community noise. More advanced versions incorporate third-octave filters and can give real-time analyses in the instrument's display window. The computer programs allow the results to be displayed graphically or as a table, and provide notification of noncompliance with standards. Thus the array of sound level meter, filter, and graphic level recorder can be reduced to a single hand-held instrument that can be connected to a desktop computer. These instruments are more flexible than older models and make it easier for acoustics to be included in building investigations.

A measure of low-frequency content is given by some meters as $L_C - L_A$ for steady noise, or $L_{Ceq} - LA_{eq}$ for fluctuating noise. However, because there has not been much interest in measuring infrasound since the early 1980s, many modern meters do not go lower than 20 Hz. This is likely to change if future investigations show that infrasound is a commonly occurring problem in building acoustics.

Examples

Figure 19.7 shows a tracing of a recording taken at an occupant's workstation in an office. The figure shows the audible range scanned in one-third octaves, followed by the various weighted values. Figure 19.8 shows a narrowband analysis of the same recording done with a filter covering the range 1 to 2000 Hz.

In Figure 19.7, there are 50-dB peaks in the audible range at 35 and 50 Hz, the A-weighted value is 46 dBA, the B-weighted value is 51 dBB, the C-weighted value is 60 dBC, and the unweighted (Lin) value is 64 dB (dBB is no longer used). The A-weighted level is above most limits for private offices, but within the limits for general offices; see Table 19.3. However, this is a recording of what is predominantly HVAC noise, and is probably too high for most occupants. The level is almost high enough to begin interfering with speech. Contributions from other noise sources are usually fairly easy to identify: the noise from a computer is shown by the peak at around 300 Hz.

The unweighted value of 64 dB is higher than any peak in the audible range, and provides the clue that there is some more energy outside the audible range. This energy can be seen in Fig. 19.8, with peaks of 65 dB at 8 and 18 Hz, in the infrasound region. The difference

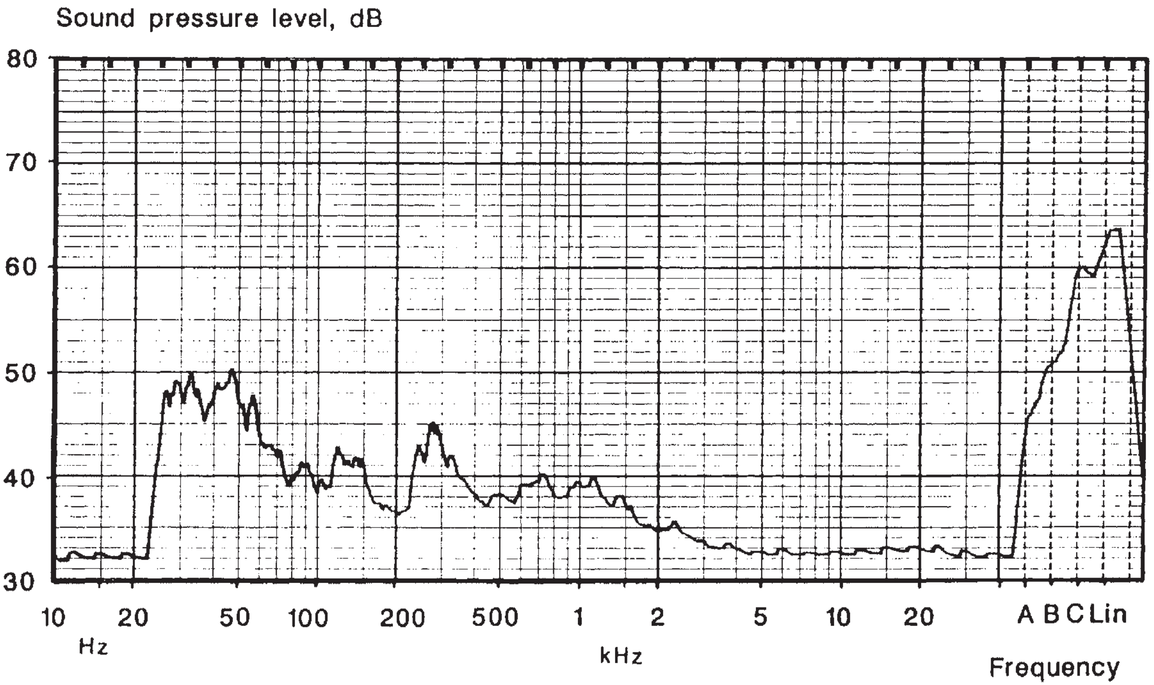

FIGURE 19.7 One-third-octave spectrogram of a recording at a desk in an office, showing the audible range (20 to 20,000 Hz) (Burt 1996). On the right are the dB levels for three weighted scales and one unweighted scale: dBA = 46, dBB = 51, dBC = 60, dBLin (unweighted) = 64.

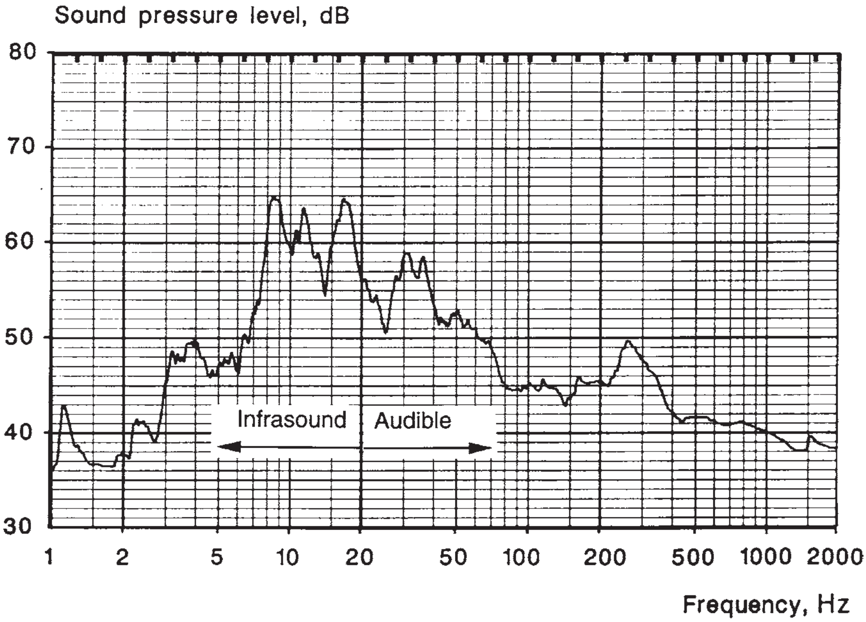

FIGURE 19.8 Narrowband analysis of the same recording as in Fig. 19.7, showing part of the audible range (20 to 2000 Hz) and the infrasound range (below 20 Hz) (Burt 1996).

between the unweighted and A-weighted levels is thus $65 - 46 = 19$ dB, i.e., close to the 20-dB limit suggested above as the level where low frequencies could become a problem.

Figure 19.9 compares tracings from adjacent supply and exhaust terminals in a system where the supply and exhaust fans are identical but working in opposite directions. Note that the levels are all unweighted. Levels at exhaust terminals are lower than at supply terminals, and there is less energy in the infrasound region. Experience has shown that exhaust-only ventilation systems are usually more acceptable than supply-and-exhaust systems, and this is one possible reason. The supply ventilation fans produce noise spectra typical of centrifugal fans, with most of the energy being in the region below 100 Hz. The energy is airborne and not structureborne. The effects on people will therefore be due only to pressure effects on the inner ear, and not vibration effects on the whole body or involving individual organs.

Figure 19.10 shows the effects of reducing fan speeds. There is some noise reduction that could be beneficial, although the effects in the infrasound range are slight. The effect is not general, as reducing fan speeds may cause a fan to operate outside the range of its optimum aerodynamic efficiency, which would increase the noise.

Figure 19.11 shows the effects of shutting the windows and doors to a room. Large reductions occur in the low-frequency and infrasound range. There are two reasons. One is that an open window can result in a room acting like a Helmholtz resonator. This effect occurs when a closed volume (the room) is connected to a much larger space (outdoors) by a duct (the window). Air movement in and out of the window causes a resonance to be set up in the room. Closing the window reduces the effect. The other reason is that the entire building can be acting as a resonance chamber for the noise. The wavelength of a 10-Hz wave is 34 m, see Eq. (19.1), so a building with this internal dimension will emphasize this frequency. Closing the door shuts the room off from the rest of the "resonance chamber." The result of closing both windows and doors is a reduction of 25 dB at around 10 Hz.

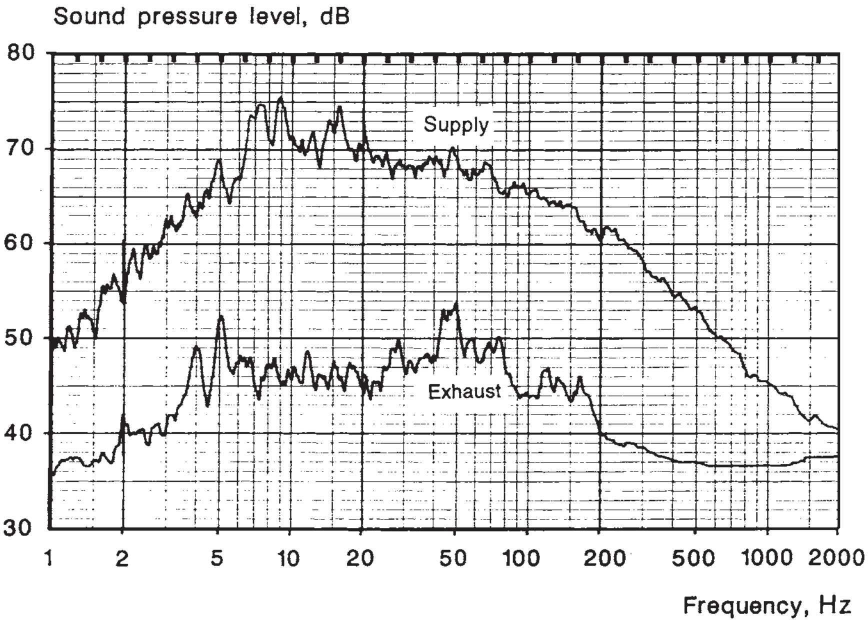

FIGURE 19.9 Narrowband spectrograms of recordings made at HVAC supply and exhaust terminals located in an office room (Burt 1998). The supply and exhaust fans in this system are identical, but working in opposite directions.

Figure 19.12 compares tracings at the supply grille and occupant's desk. The levels at 10 Hz do not decline much from the supply grille to the occupant's workstation. This is probably due to standing waves being set up in the long corridors in the building. Standing waves (as opposed to travelling waves) occur when sound waves are reflected. If two waves travelling in opposite directions are in phase, they will reinforce each other. The wavelength of the reinforced wave is the distance between the reflecting surfaces. The effects are seldom noticed in ordinary buildings, but unexpected resonances can be set up at low frequencies. The total length of this building is 68 m, with each half being supplied with air by a separate fan. Thus each fan supplies 34 m, which is the wavelength of a 10-Hz wave. The occupant in this room is being subjected to a 10-Hz wave of over 70 dB for the entire working day. The effects of long-term exposure to such levels are still unknown.

19.8 CONCLUDING REMARKS

Modern HVAC systems often have long ducts and large pressure drops, so that large fans are needed to move air through them. Large centrifugal fans can produce considerable amounts of energy in the low-frequency and infrasound regions. A good idea of the amount of energy in the lower frequencies is given by the difference between the unweighted and A-weighted levels (or the difference between the C-weighted and A-weighted levels—they are almost the same). If the difference is greater than 20 dB, then the level of low-frequency noise is probably sufficiently high to cause complaints.

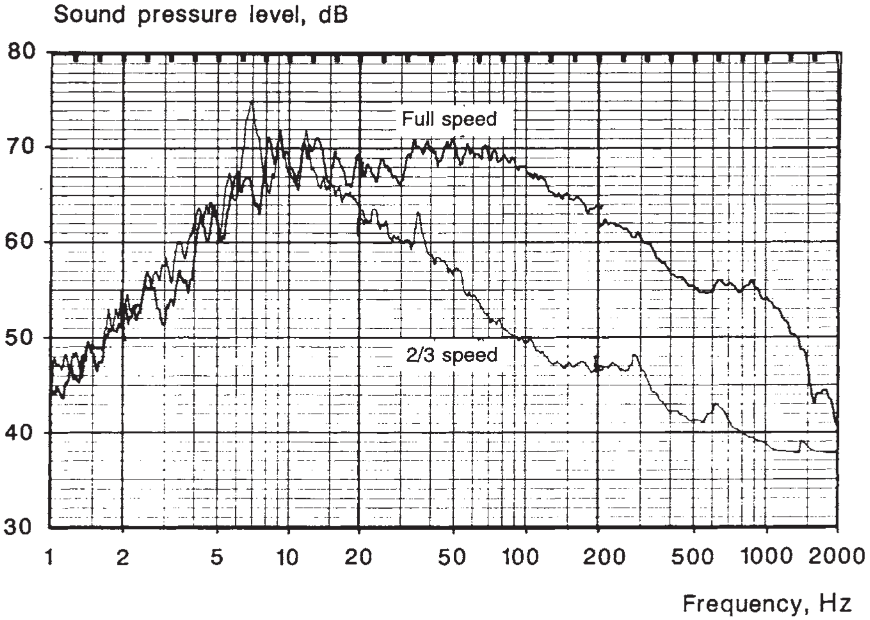

FIGURE 19.10 Spectrograms at supply terminal, showing effect of reducing fan speeds (Burt 1998). Most of the reduction is in the audible range, and the effect in the infrasound region is slight (with this system).

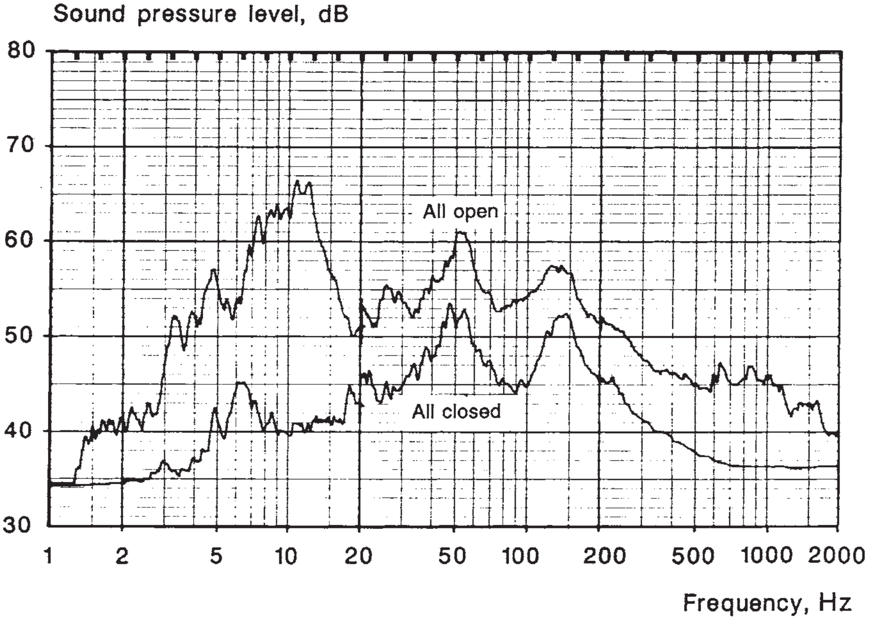

FIGURE 19.11 Spectrograms showing the effect at a desk of closing windows and doors (Burt 1998). The greatest reduction (25 dB) occurs in the infrasound region.

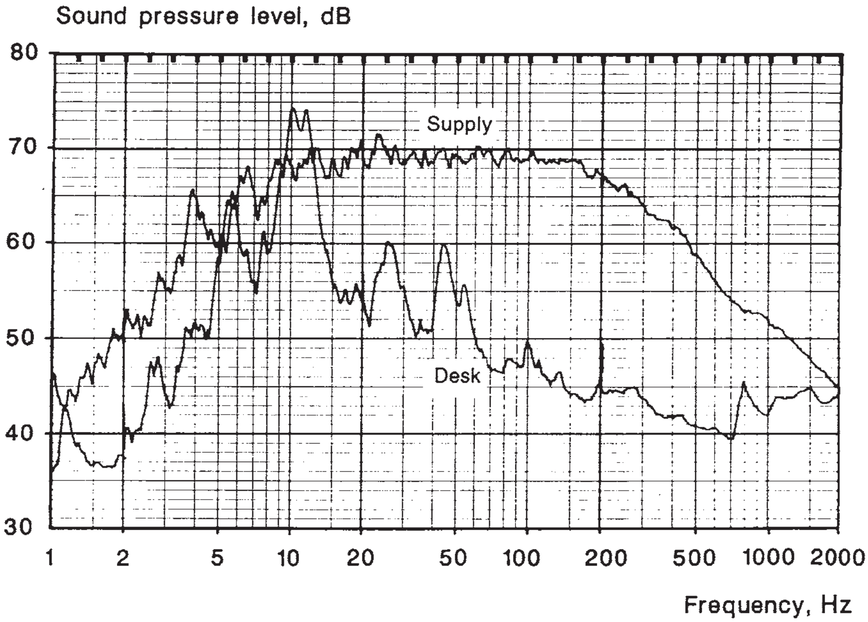

FIGURE 19.12 Spectrograms at supply terminal and desk in the same room (Burt 1998). The sharp peak in the infrasound region at around 10 Hz could be due to some dimensions of the building coinciding with the wavelength of this frequency.

A crude frequency analysis of the acoustic environment indoors can be carried out with a sound level meter equipped with an octave band filter and the results plotted manually. A one-third-octave filter will show more detail. A frequency spectrogram can be obtained by connecting the acoustic filter to a printer, both instruments sweeping the frequencies at the same rate. The shape of the frequency spectrum can provide some insight into the noise that would not be obtained by simply measuring dBA (Kryter 1970).

Control of low-frequency noise is difficult. Normal acoustic insulation has little effect at these frequencies. The two methods available are source control and active noise control. Source control may involve changing the ventilation fans, which may be an expensive and unattractive option for the building owner. Active noise control systems are still being developed, and are currently difficult for most people apart from the manufacturer to use. Even so, they offer one of the most promising methods of noise control in problem buildings, and represent a cheaper option than changing fans. They have a further advantage in allowing a greater choice of fans at the design stage. The quietest fan is the one working in the range of its optimum aerodynamic efficiency.

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