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Making Noise Comfortable for People

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ABSTRACT

Typical HVAC noise may produce an uncomfortable environment, leading to the associated problems of general dissatisfaction and reduced productivity. It is not sufficient to have good thermal, lighting, and air cleanliness conditions if the noise is disturbing.

In this paper, noise comfort is considered, with special emphasis on the developing criteria for low-frequency noise.

INTRODUCTION

The current interest in indoor air quality (IAQ) stresses thermal comfort and the requirements for clean, unpolluted air but often neglects the noise that is a by-product of distributing this air around a building. It is not sufficient to have all other aspects under control if the associated noise remains disturbing. While much has been done to reduce HVAC noise, either by fan and duct design or by noise mufflers, there is often a residual low-frequency noise that is difficult to control, while a hiss may occur at high frequencies. Conventional means of control using absorptive materials introduces a potential for both loose fibers and a breeding ground for microorganisms. Restrictive mufflers also introduce an energy penalty through their pressure losses.

Noise and Comfort

An uncomfortable person may not work at peak level. "Comfort" in this context covers all aspects of the work environment, thermal, visual, ergonomic, and auditory, as well as relationships with colleagues, company ethos, etc. Dissatisfaction with surroundings has a negative impact on productivity (Lomonaco and Miller 1997). The wrong sort of noise leads to dissatisfaction, and the authors contend that because of its intimate connection with air-moving systems, noise should be regarded as a negative contributor to indoor air quality.

A RESPONSE MODEL

A way in which we might develop our response to noise is shown in the simple illustrative model in Figure 1, where physical inputs to the ear lead to subjective reaction. There are three stages to the model: detection, perception, and response.

Detection: The noise input is detected and transformed into the form that is necessary to give the sense of perception.

Perception: It is concluded that there is a noise and we analyze some of its attributes, such as loudness, frequency components, location, fluctuations, whether there is any personal association with us, etc.

Response: We react to what we have perceived. The response is conditioned by parameters in addition to the physical attributes of the noise alone, including personal and situational elements, which may vary from time to time. The subjective "quality" of the noise is influenced by our perception and response reactions. The response may also be influenced by a number of other factors in the internal environment through additive, synergistic, or antagonistic relationships.

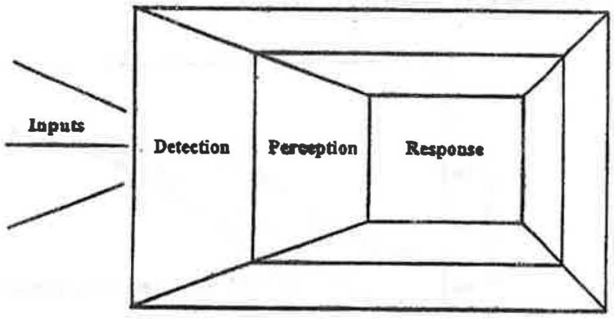

Figure 1 *Simple response model.*

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Some Contributory Factors

Spectrum Balance. It has been proposed that the spectrum slope, i.e., rate of fall-off from low to high frequencies, is a major element of perceived sound quality (Bryan 1976; Tempest 1973). This is illustrated in Figure 2. However, later work has questioned the effect (Goldstein and Kjellberg 1985), and it is possible that both spectrum slope and sound level interact to give the total effect.

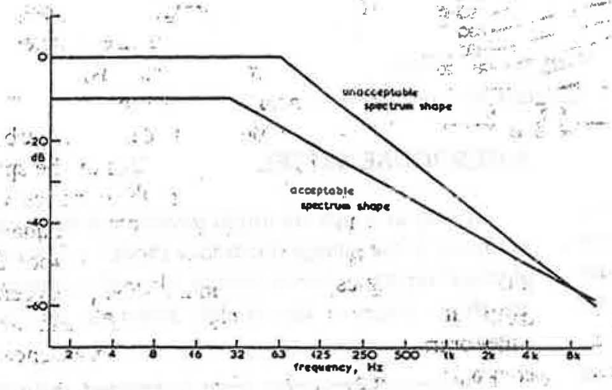

Figure 2 Shapes of noise spectra based on measured acceptable and unacceptable noises.

Frequency Composition. Some work has indicated that sounds in the frequency range 30 Hz to 60 Hz are less acceptable than sounds of the same level at immediately lower and higher frequencies (Broner and Leventhall 1984, 1985). The definition of a low-frequency weighting scale for sound level meters included an allowance for this, as shown by curve LF2 (Inukai et al. 1990) in Figure 3. Again, there is an uncertainty as to the influence of sound level. A sound that contains a high level of low-frequency noise may have the same criterion value (e.g., NR or NC) as a noise without this low frequency. A pilot study has shown that low-frequency air-conditioning noise may have an adverse effect on comfort and productivity (Persson-Waye et al. 1996).

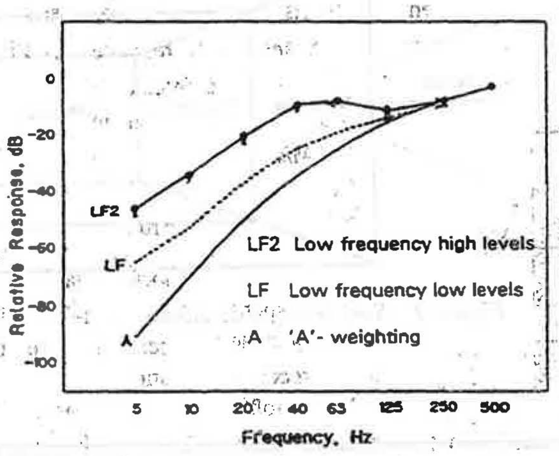

Figure 3 Relative response of A-weighting and SLM low-frequency weighting.

Fluctuations. A sound that is fluctuating in level is more annoying than a steady level of the same frequency and magnitude. Fluctuations may result from beating between adjacent frequencies, (e.g., two machines of slightly different speed), inherent time variations (e.g., some combustion noises), poor airflow conditions, and band-limited effects of a narrow band of noise or propagation irregularities. Fluctuations may be perceived as "rumble," a well-known effect in air-conditioning systems. Bradley (1994) conducted laboratory tests that quantified the decibel penalty to be associated with fluctuations as 5 dB - 12 dB.

CRITERIA

Criteria are devised to restrict environmental variables, such as temperature and noise, to within a comfortable range or to a permitted maximum. Some criteria are subjectively deficient, as the economic consequences of their implementation may have led to a dilution of the requirements. This has occurred with criteria for limiting the maximum levels of noise, for example, for worker protection in the manufacturing industry.

A number of criteria, intended as full audible band criteria, give some attention to the low frequencies. These are NR (ISO 1971), NC (Beranek 1987), PNC (Beranek et al. 1971), RC (Blazier 1981), and NCB (Beranek 1989). They all permit increase of level as the frequency decreases, but at different rates, so that the criteria show their main differences at the lower frequencies. This is illustrated in Figure 4 from which it can be seen that at 31.5 Hz the NR35 curve (still used in Europe) is nearly 20 dB more lenient than RC35 (recommended by ASHRAE).

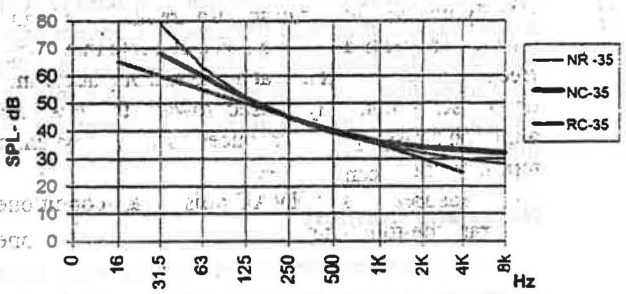

Figure 4 Comparison of criterion curves NR35, NC35, and RC35.

Other criteria have been designed specifically for low-frequency noise (Dawson 1982; Broner and Leventhall 1983; Broner 1994), imposing a more stringent limit on the low-frequency levels than is given by the wide band general criteria. The LFNR curves are similar to the NR above 125 Hz but take account of the range of increased sensitivity below this frequency. The room sound quality (RSQ) curves shown in Figure 5 (Broner 1994), are similar to the RC curves, but they level off below 31.5 Hz. LFNR and RSQ both control the maximum permitted level of the low-frequency noise components of the spectrum.

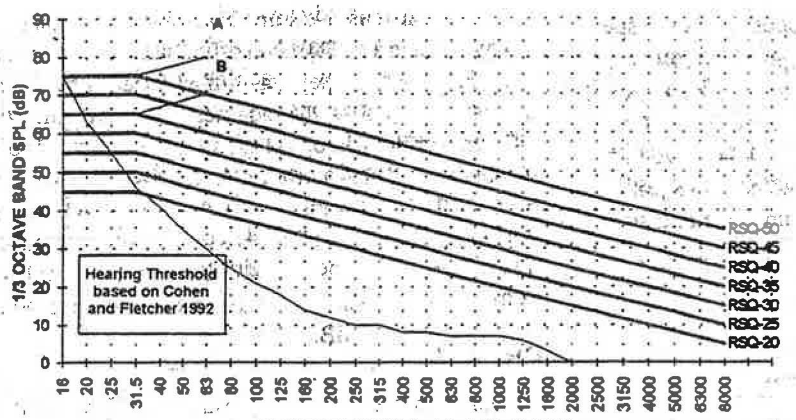

Figure 5 Room sound quality curves.

However, none of the criteria directly addresses the potential for level fluctuations. Indeed, fluctuations are averaged out in the measurement processes that produce the data for comparison with the criteria. Fluctuations are detected either by listening or by a statistical analysis of the levels of the fluctuating sound.

Blazier (1995) proposes an analytical methodology as a first step toward the assessment of the spectra of HVAC system noise in terms of particular sound quality attributes. He derives a Quality Assessment Index for low frequencies (16 Hz - 63 Hz), middle frequencies (125 Hz - 500 Hz), and high frequencies (1 kHz - 4 kHz). Blazier (1996) also considers temporal variations.

HVAC NOISES

Typical idealized fan spectra are shown in Figure 6. Most duct components attenuate noise at a rate that increases with frequency. The result is that at the end of a duct run, the residual noise is normally biased toward the low frequencies, although a hiss can be introduced as an aerodynamic effect at terminal units.

Measurements of HVAC noise in air-conditioned spaces illustrate the following:

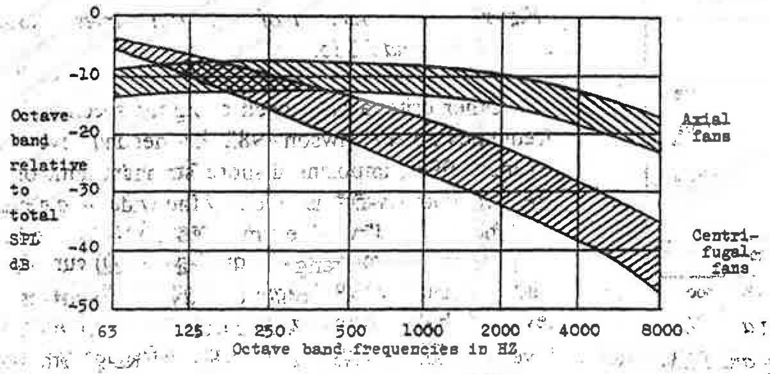

Figure 6 Typical fan spectra.

- The noise has its highest levels at low frequencies;
- The noise levels may fluctuate with time, often rapidly, to produce a "rumble" sensation.

The fluctuation may be caused by inherent variations in level (irregular variations) or by beating between closely spaced frequencies of machine components (regular variations).

In considering noise comfort, we are aiming to achieve a sound that does not disturb our activities. Noise comfort depends on the spectral and temporal variations of the sound, as well as on sound level. A comfortable sound quality occurs when the sound does not intrude upon us, that is, it is a "neutral" sound. This requires certain spectral characteristics ("spectrum balance") and appropriate temporal characteristics. There should be an absence of disturbance or irritation, but occupants must be "in touch" with their environment, which, by interaction with their own psyche, produces optimum arousal. In noise terms, this is likely to be achieved with either a neutral or a slightly stimulating (arousing) noise. Arousal is a very individual requirement, and it is not easy to develop an arousing sound other than through music; therefore, it is necessary to design a neutral background noise.

In terms of frequency components, negative quality characteristics can be described by the following spectrum imbalances (Broner 1994):

- *Rumble:* high levels, below 125 Hz (vibration of lightweight building components may occur below about 20 Hz).
- *Roar:* high levels in the region 125 Hz - 500 Hz.
- *Whoosh:* high levels in the region 500 Hz - 2000 Hz.
- *Hiss:* high levels in the region 2000 Hz - 8000 Hz.

In temporal terms, sound quality characteristics include:

- *Fluctuation:* caused by a detectable variation in rumble sound pressure level.
- *Roughness:* fluctuations in overall level occurring at frequencies between 20 Hz and 300 Hz.
- *Throb:* a variation in rumble sound pressure level occurring at a rate of up to about 5 Hz.

A "neutral" sound does not have the unbalanced spectral components described above and does not exhibit detectable fluctuations.

In addition to spectral composition, the neutral sound should not be too noisy for its location. For example, the requirements are different for a high quality private office and a multi-occupation office.

It is of interest to compare these desirable characteristics with actual characteristics of typical

HVAC noises. In general, HVAC noise in the conditioned space has a spectrum that falls with increasing frequency, but spectral peaks, often at fan-blade frequency in the 125 Hz/250 Hz octave bands, may be added into the spectrum. The sources of the high-level low-frequency noise are the fans or ductwork vibration. Current trends are away from central plant rooms to distribution of smaller units on each floor or in the ceiling. This brings the noise sources closer to people.

In a wide-ranging study of HVAC noises Broner (1994) analyzed recorded noises in a number of ways, including

- the average spectrum in third octave bands over a two-minute period,
- the statistical data in third octave bands—giving an indication of fluctuation, and
- the variation with time of the level in selected bands.

The spectra were divided into subjective "quality" categories of "strong rumble," "rumble," "neutral/marginal," and "neutral," as shown in Figure 7, which gives spectra normalized to similar speech interference levels (average of levels at 500 Hz, 1 kHz, and 2 kHz octave bands).

The spectrum with "strong rumble" peaks at 31.5 Hz. Reduction of the low frequencies gradually produces a neutral spectrum.

In addition to the average levels, fluctuation must also be considered. These are illustrated in Figure 8 (Broner 1994), where it is shown that the standard deviation of the overall band levels are lowest for the neutral spectrum.

The RC criterion curves, as recommended by ASHRAE, have a slope of –5 dB per octave (Figure 9). The family of RC curves permits a noise to be designated by its subjective attributes of "rumble," "neutral," or "hiss" and also gives indication of the potential for causing vibration (ASHRAE 1995).

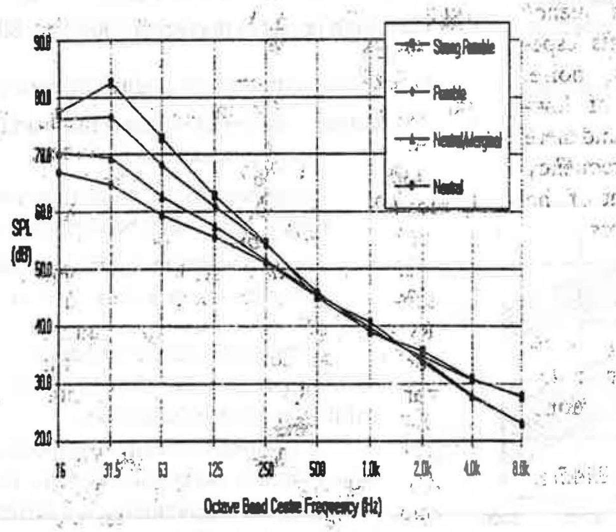

Figure 7 *Average normalized spectra for the sound quality categories.*

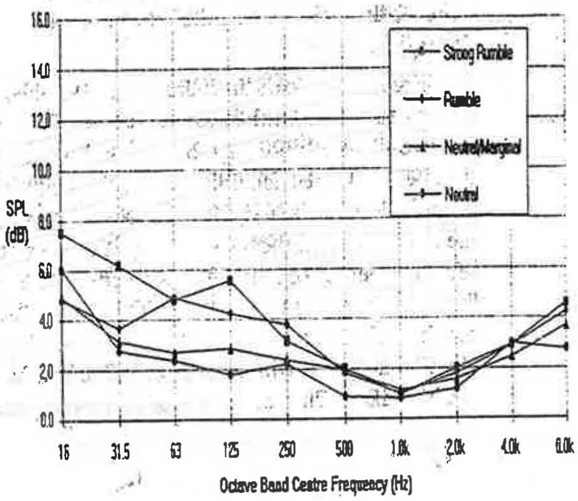

Figure 8 *Standard deviations of the normalized spectra.*

NOISE AND PRODUCTIVITY

Noise may be considered as one component of internal air quality and is a potentially detrimental factor on work performance. This is illustrated by a study of the comparison of subjective responses for air-conditioning noises of similar NC/NR/dBA ratings but different low-frequency content (Persson-Waye et al. 1996). In this pilot study of 14 healthy subjects, with an average age of 26 years, low-frequency noise interfered more strongly with performance than medium-frequency noise of similar rating criteria. The study indicated that low-frequency noise has an additional effect on

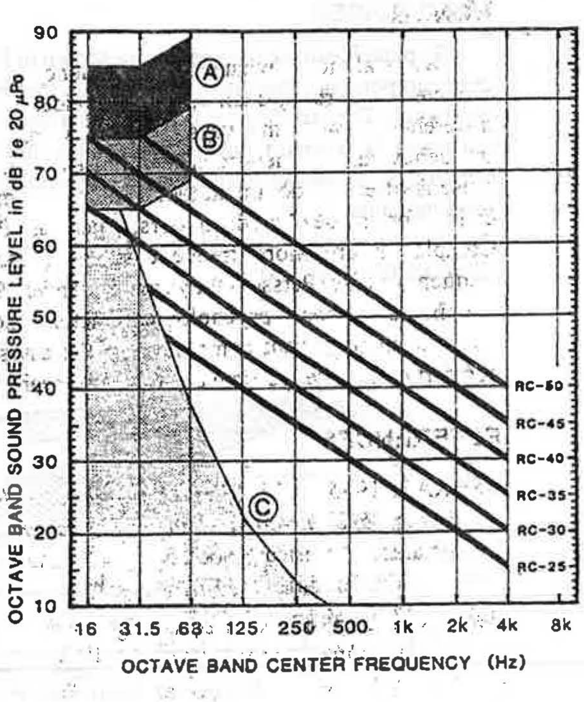

Figure 9 *Room criterion (RC) curves—recommended by ASHRAE.*

cognitive elements and that the effect develops over time to become apparent during the one-hour exposure periods of the test work.

Figure 10 shows an average value of the individual differences of response times for the same verbal reasoning test in the two air-conditioning noises. The x-axis is equivalent to a time scale where each unit is about four minutes. The response times in low-frequency noise were 10% - 20% greater than in the absence of the low frequency. Subjects also had a poorer "social orientation," in that at the end of the exposure period, they felt more disagreeable, irritated, and less cooperative or helpful. The noise comfort was degraded by the presence of low frequencies, which were not detected by the inadequate NR/NC/dBA criteria.

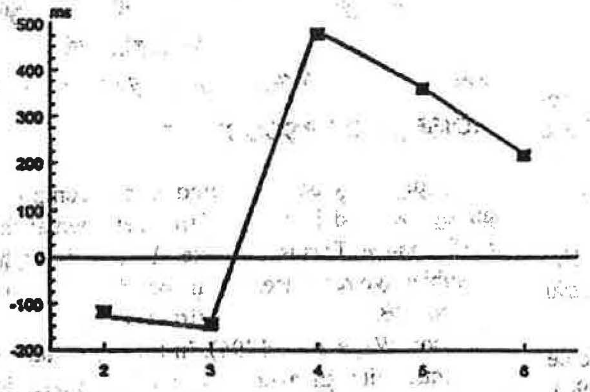

Figure 10 Comparison of response times in low-frequency and mid-frequency noise.

CONCLUSIONS

While all noise, whatever the frequency, has the potential to have a disturbing quality, there is evidence that there is a difference between the ways in which we respond to lower-frequency and higher-frequency noises. Low-frequency noise is often the dominant factor in noise complaints, especially for noise heard indoors, such as HVAC noise. Complaints are more frequent in the presence of low-frequency noise (Persson-Waye and Rylander 1988) and there are increased socio-psychological factors. Low-frequency noise is an important component in the assessment of the comfort of a noise, particularly for noise heard indoors.

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