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SOUNDS WITH TONAL FEATURES - RESEARCH METHODS AND ASSESSMENT

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INTRODUCTION

The presence or absence of tonal components in a sound is a matter of subjective opinion. Continuous discrete single frequency components will almost always be judged as 'tonal' but narrow frequency band spectral prominences caused by random excitation of particular resonances or by closely spaced discrete frequency components will not always be judged as 'tonal', depending on the proportionate frequency bandwidth, and individual listeners will not always agree. In addition, harmonically related discrete frequency components will usually be judged as 'tonal', whereas inharmonic frequency components might not be. Wideband random signals without spectral prominences will not usually be judged as 'tonal'.

GUIDANCE AT EXISTING STANDARDS

Tonal components in environmental sounds often (but not always) enhance the noticeability or intrusion of those sounds within the general background of other non-tonal sounds. Examples of tonal sounds given at BS 4142:1990 (1) are as follows; '*whine, hiss, screech, hum*'. BS 4142 specifies that a 5 dB correction should be added to the measured noise level to account for the subjective effects of the tonal components.

There is no guidance given to help determine the presence or absence of tonal components by objective measurements, although the corresponding international standard BS 7445:1991 (2) suggests that 1/3rd octave band frequency analysis or narrow band frequency analysis can be used to demonstrate the presence or absence of clearly audible tonal components '*In some practical cases, a prominent tonal component may be detected in one-third octave spectra if the level of a one-third octave band exceeds the level of the adjacent bands by 5dB or more, but a narrow band frequency analysis may be* *required in order to detect precisely the occurrence of one or more tonal components in a noise signal*. This guidance is clearly not a precise specification.

The aeronautical community have developed a somewhat complex procedure for taking the presence of tonal components in aircraft flyover noise into account ISO 3891:1978 (3). The perceived noise level (L_{PN}) is computed from a weighted sum of noy values of 'perceived noisiness' in each one third octave band from 50 Hz to 10 kHz. A standardised tone correction is added to the perceived noise level whenever the 1/3rd octave band containing the tone protrudes by more than 2.5 dB above the level of the non-tonal noise in the same 1/3rd octave band. This is estimated by taking the average level of the 1/3rd octave bands either side. It is acknowledged that this procedure is capable of indicating the presence of tones when there are in fact none, for example when ground reflection effects lead to a typically 'combed' spectrum, and the standard states that '*if the tone correction is due to spurious effects, then it should be ignored*'. Again this is of limited value as a precise specification, notwithstanding the fact that the procedure for determining the tone correction is quite complicated.

A recently published American National Standard (4) sets out a test for the presence of a prominent discrete tone. This suggests that the 1/3rd octave band containing the tone needs to protrude above the average level of the 1/3rd octave bands either side by more than 15 dB for low frequencies (25 to 125 Hz), by more than 8 dB for mid-frequencies (160 to 400 Hz) and by more than 5 dB for high frequencies (500 to 10,000 Hz) for a prominent discrete tone to be identified as present.

It is clear that there is no agreement in the literature as to the best way to determine the presence or absence of tonal components from objective measurements of the frequency spectrum of the noise. The recent ANSI S12.9 Part 3 tone detection procedure sets the threshold quite high such that tonal components are unlikely to be identified when there are none, but weak tonal components could be missed. On the other hand, the ISO 3891 procedure sets the threshold so low that tonal components are often identified when they are not in fact present.

There is general agreement that some form of tonal correction or adjustment is justified, but there is no agreement as to the precise magnitude of this correction, some standards suggesting a blanket 5 dB correction, and others suggesting merely that the magnitude of the correction should be stated if applied.

FREQUENCY RESOLUTION

The main problem with the various methods set out in standards is that they are mostly based on 1/3rd octave band frequency analysis, which is actually too coarse to identify anything other than very prominent tonal components. 1/3rd octave band frequency analysis provides a good indication of general spectrum shape and corresponds reasonably well with the approximately logarithmic frequency resolution of the ear. In addition, 1/3rd octave band frequency analysis using a traditional type switched (serial) filter set can be implemented at relatively low cost, and this facility often appeals to standards committees. Narrower band serial filters require an excessive time to complete a single spectral analysis, which is particularly inappropriate for non-stationary sounds. This means that narrow band analysis is only really viable where each filter operates in parallel.

On the other hand, the frequency discrimination of the ear is obviously much narrower than 1/3rd octave. The just noticeable difference for frequency in the mid-frequency range can be better than 0.5% under laboratory conditions, which at 1 kHz is a lot narrower than the frequency resolution of a standard 1024 point FFT frequency analyser set to 10 kHz overall bandwidth. Of course, the real problem in tonal noise assessment is not normally the precise frequency of the offending tone, but the extent to which it protrudes above the surrounding background sound, and the extent to which this protrusion might advertise the presence of the tonal sound to a listener and thereby contribute to increased annoyance or noisiness under some circumstances. The subjective protrusion, or the sensation level, of the tonal component (the level by which the tonal component exceeds the masked threshold level) can normally be predicted quite well by reference to classical critical band theory. Critical bands model the frequency selectivity of the ear in terms of the equivalent masking bandwidth of each section of the basilar membrane in the inner ear.

The precise bandwidth of a critical band varies depending on the method of measurement and the various assumptions made. However, 1/3rd octave bands provide a good approximation to critical bands over much of the mid-frequency range, and have the clear advantage of being easily defined mathematically. In general, a single discrete frequency component will be just detectable under ideal listening conditions when the sound level of the discrete frequency component is greater than around 4dB less than the aggregate sound level of the surrounding critical bandwidth of the background noise with the effects of the discrete frequency component removed.

ALTERNATIVE APPROACHES

The 4dB rule sounds like a precise specification, but it is not usually quite as simple as that. The first problem is that standard 1/3rd octave filters do not overlap, whereas the equivalent filters in the ear are distributed continuously right through the audio frequency range. In practice, the discrete tone level has to be compared against the summed level within the critical band or 1/3rd octave bandwidth surrounding the discrete tone frequency. Fixed 1/3rd octave filters are of little use if they cannot be swept up or down so that they can be centred on the discrete tone frequency. In practice, fixed parallel filter sets can be used, but only if there are a minimum of around eight separate filters within each classical critical band or 1/3rd octave band. This means using either 1/24th octave band frequency analysis or narrow band FFT (Fast Fourier Transform) and then summing band levels above the below the discrete tone frequency.

The next problem is that real tonal noise problems found under field conditions often present with a multiple frequency modulated tone complex, which might spread over more than one critical bandwidth. There is a considerable amount of research in the psychoacoustic literature relating to multiple tone complexes, but very little of this is directly relevant to tonal noise assessment problems in the community noise and sound quality fields. To some extent, each discrete tone frequency present contributes to the masking effect against all the others. In addition, multiple tone complexes can introduce numerous technical artefacts, such as beating between two closely similar frequencies. Finally, it is not clear to what extent a narrow band filtered noise component could be distinguished from a similarly narrow band multiple tone complex. All of these factors could require changes from the general 4dB rule.

The critical band approach to tonal noise assessment requires that the sound level of the tonal component should be compared against the sound level of the masking signal, as measured over the surrounding critical band. Providing that the offending tonal noise can be switched off at source or otherwise prevented from having any influence, then it is relatively simple to measure the level of the background noise in the surrounding critical band. This cannot be done where the offending tonal noise cannot be switched off without otherwise affecting the background noise (e.g. a fan with both broad band and narrow frequency band components). There are various 'rules' which can be devised for estimating the level of the surrounding critical band from the band levels of the immediately adjacent critical bands up and down in frequency, but these are often limited in application, as they invariably depend on assumptions as to how the band level of the background noise at the tone frequency depends on the band levels either side. Such 'rules' can be very difficult to apply where the tonal 'feature' spreads over more than one critical bandwidth, or where there is significant modulation present. In the case of modulated tones, there seems to be some differences in both the detection thresholds and the basic perceptual mechanisms involved in resolving amplitude as opposed to frequency modulated tones. Many real sounds have a mixture of both amplitude and frequency modulation present, which can create difficulties under the current state of knowledge.

THE SEPARATE FEATURE VS THE OVERALL MEASURE APPROACH

The essence of the separate feature approach is that it attempts to mirror human auditory function more closely than 'traditional' methods of tonal assessment (5). Perhaps the main functions of the auditory system is to extract useful information from the auditory environment. This information is contained not so much in the overall sound but in terms of the various component parts which contribute to it. Each component indicates the presence of a particular source or source mechanism. For example, speech intelligibility depends on resolving individual components within a complex speech signal, not on being able to judge the overall loudness of the speech.

The main purpose of most tonal assessment procedures seems to be to provide an objective method to determine whether or not a tone correction or adjustment should be added to the overall measured sound level. The human auditory system is biologically adapted to resolving individual components from the overall sound rather than aggregating the whole sound together. There is increasing evidence that individual components can be more important than the ensemble in terms of subjective reaction, particularly in the field of sound quality research, which is closely related to environmental noise assessment. This means that the acoustic feature approach, whereby the main purpose of measurement is to determine the relative sensation level of each different component within the overall sound must have some merit. However, the acoustic feature approach is really a philosophy of the basic purpose of the measurement, rather than being just another yet more complicated dB scale, and this means that it is difficult to devise scientific 'proof' of the approach. Ongoing and future research in this area tends to assume that the acoustic feature approach is implicitly meritorious, in order to be able to concentrate on the details of determining objective measures for the calculation of masked threshold levels and the corresponding sensation levels of individual features.

Having taken apart an objectionable sound into its component parts or features, what does this mean for assessment purposes? There is probably no direct relationship between any aggregate sum of the sensation levels of all the identified features and overall annoyance or noisiness. This is where human preference comes in, which is of course, subject to considerable variation. The most important role for acoustic feature research in relation to tonal (and other) components or features is to provide directly useful engineering data. Feature sensation levels might not directly predict annoyance, but they can be used to calculate the precise amount of noise reduction required to mitigate against particular complaints.

FUTURE RESEARCH

The research field is actually quite open at this time. Whereas the single discrete tone frequency in a well behaved broad band background sound might actually present relatively few problems for assessment, provided that the right equipment is available, most real-life sounds are considerably more complex than this. Future research should be addressed to developing objective measures which correspond to feature sensation level rather than to any overall measure.

REFERENCES

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