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ASSESSMENT OF THE TONALITY OF AIRCRAFT TAXIING NOISE

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1. INTRODUCTION

The presence of an audible tonal component in an otherwise broadband noise will cause that noise to be more annoying than the broadband noise would be on its own, even though the tonal component may not make a significant contribution to the A-weighted noise level. When assessing human reactions to noise, it is therefore important to detect the presence of audible tonal components and to take account of their likely effects. Noise from taxiing aircraft usually contains tonal components generated by rotating turbomachinery of the aircraft jet engines. An assessment of the tonality of aircraft taxiing noise has provided an opportunity to compare subjective and objective assessments of tonality.

2. NOISE RECORDING AND ANALYSIS

2.1 Noise recording

Digital Audio Tape (DAT) recordings of aircraft taxiing noise were made outdoors at two residential sites using B&K 2235 and CEL 393 sound level meters. The sites are situated approximately 650 metres to the north west of the western end of the southern runway at Heathrow airport.

2.2 Site observations

The aircraft taxiing noise heard comprised three constituent types. These were (i) high frequency whine, (ii) medium frequency whine, and (iii) broadband roar. At any one time, one or all of these could be present in total taxiing noise from one or more aircraft. Whereas the high frequency whine and broadband roar were nearly always heard, the medium frequency whine was heard only intermittently. The high frequency whine and medium frequency whine were subjectively unpleasant.

2.3 Frequency analysis using B&K analyser

Preliminary frequency analysis was carried out using a B&K 2123 Real-Time Analyser. 1/12 octave frequency analysis was carried out on selected 15 seconds periods of the DAT tape. The analyser was set to Linear averaging. The 1/12 octave spectra revealed medium frequency tonal components[1], but failed to show clearly the high frequency tonal components. Figure 1 shows a prominent tonal component in the 307 Hz 1/12 octave band.

[1] The term "tonal components" is commonly used to refer to discrete protrusions in the spectrum. It may be more accurate to refer to such protrusions as spectral prominences, which, in general, may or may not relate to tonal components. The presence or absence of tonal components is a matter for the subjective opinion of a listener.

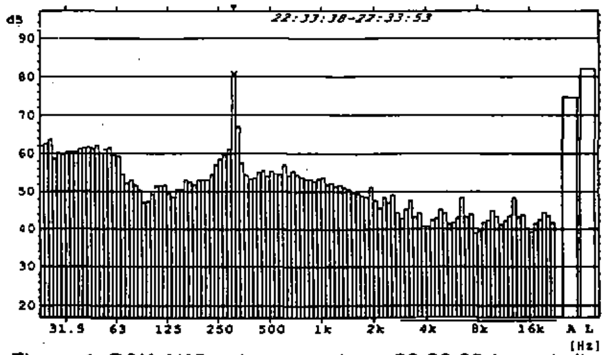

Figure 1: B&K 1/12 octave spectrum 22:33:38 hrs. at site 1

2.4 Frequency analysis using FFT analyser

Subsequent frequency analysis was carried out using an ONO SOKKI CF-4220 Fast Fourier Transform (FFT) Analyser. The analyser was set to HANNING window, MAX overlap and POWER SUM averaging. Narrow-band spectra were measured using a frequency range DC to 10 kHz, with 400 lines giving 25 Hz per band. A measurement time of approximately 15 seconds was obtained by using 1000 periods. The analyser also measured 1/3 octave spectra corresponding to the narrow-band spectra.

The narrow-band spectra successfully demonstrated the presence of high frequency spectral prominences, which were found in the range 1.1 to 5.6 kHz. It is worth noting that human hearing is particularly acute in this general range of frequencies. Figure 2 shows a background noise spectrum and a superimposed taxiing noise spectrum containing a series of spectral prominences between 2.3 and 5.6 kHz.

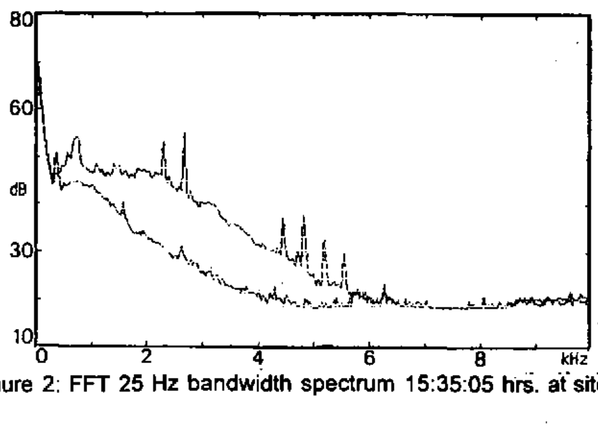

Figure 2: FFT 25 Hz bandwidth spectrum 15:35:05 hrs. at site 2

3. ASSESSMENT OF TONALITY

3.1 Subjective assessment

Subjective assessment was carried out using the guidance of BS 4142:1990 [1]. Clause 7.2 of the standard states that a 5 dB character correction should be applied: *"If the noise contains a distinguishable, discrete, continuous note (whine, hiss, screech, hum, etc.)...."*

3.2 Assessment using BS 7445

Clause 4.1.3 of Part 2 of BS 7445 [2] suggests that a prominent tonal component may be detected in 1/3 octave spectra if the level of one band exceeds the level of the adjacent bands by 5 dB or more. It gives the following advice on tone adjustment: *"If tonal components are clearly audible and their presence can be detected by a one-third octave analysis, the adjustment may be 5 to 6 dB. If the components are only just detectable by the observer and demonstrated by narrow-band analysis, an adjustment of 2 to 3 dB may be appropriate."* The criteria therefore distinguish between two categories which, for convenience, will be referred to as "strongly tonal" and "mildly tonal" as summarised in Table 1. The BS 7445 1/3 octave tests were carried out using the 1/3 octave spectra measured by the FFT analyser.

TABLE 1
BS 7445 criteria for assessing tonality

Criteria	Tone adjustment	Assessment
tonal components "clearly audible"	5 to 6 dB	STRONGLY TONAL
1/3 octave exceeds by 5 dB or more		
tonal components "just detectable" by observer	2 to 3 dB	MILDLY TONAL
1/3 octave does not exceed by 5 dB or more		
tonal components demonstrated by narrow-band analysis		

3.3 Assessment using principles of ANSI S12.9

Appendix C.1 of ANSI S12.9/Part 3 [3] gives the following test for the presence of a prominent discrete tone: *"For a prominent discrete tone to be identified as present, the equivalent-continuous sound pressure level in the one-third octave band of interest is required to exceed the average equivalent-continuous sound pressure level for the two adjacent one-third octave bands by some constant level difference, K_T."*

ANSI Appendix C.1 refers to the constant K_T and states: *"This constant may vary with frequency. Possible choices for the level difference are: 15 dB in low one-third octave bands (25-125 Hz), 8 dB in middle-frequency bands (160-400 Hz), and 5 dB in high-frequency bands (500-10000 Hz)."*

The ANSI 1/3 octave tests were also carried out using the FFT 1/3 octave spectra. These spectra were each measured over a single 15 seconds period, which is a form of measurement not strictly in accordance with ANSI. The 1/3 octave tests are therefore based on the principles of ANSI rather than being in strict conformance with ANSI.

3.4 Summary of tonality assessments

The tonality assessments are summarized in Tables 2 and 3. With the exception of one tonal component in one spectrum for site 1, all tonal components for the sixteen spectra assessed were above 1 kHz.

TABLE 2
Taxiing noise tonality assessments for site 1

spectra assessed	subjective assessment	BS 7445 1/3 octave	BS 7445 narrow-band	ANSI S12.9 1/3 octave
4	clearly audible h/f whine	not strongly tonal	mildly tonal	no prominent discrete tone
1	clearly audible m/f * & h/f whine	strongly tonal	n/a	prominent discrete tone

* medium frequency (m/f) tonal component in 307 Hz 1/12 octave

TABLE 3
Taxiing noise tonality assessments for site 2

spectra assessed	subjective assessment	BS 7445 1/3 octave	BS 7445 narrow-band	ANSI S12.9 1/3 octave
2	clearly audible h/f whine	not strongly tonal	mildly tonal	no prominent discrete tone
6	clearly audible h/f whine	not strongly tonal	mildly tonal	prominent discrete tone
3	clearly audible h/f whine	strongly tonal	n/a	prominent discrete tone

4. DISCUSSION OF TONALITY ASSESSMENT METHODS

4.1 Differences between BS 7445 and ANSI S12.9

These standards use an objective test based on whether 1/3 octave band levels exceed by 5 dB or more. With BS 7445, a 5 to 6 dB tone correction is deemed necessary if the level of a 1/3 octave band exceeds the level of **both** adjacent 1/3 octave bands by 5 dB or more.

With ANSI, a prominent discrete tone is deemed present if the level in a 1/3 octave band exceeds the **average** level of the two adjacent 1/3 octave bands by 5 dB or more (for 500-10000 Hz). Therefore, the ANSI test is more likely to be met than the BS 7445 test.

4.2 Discussion of critical band analysis

Critical band analysis is explained in ISVR report 202 [4]. The masked threshold level of a tone bears a fixed relation to the level of the auditory critical band of the noise surrounding the tone. This relation is defined as:

$$L_{At0} - L_{Afcrit} = -4 \text{ dB} \tag{1}$$

In this equation, L_{At0} is the A-weighted threshold level of a tonal component having frequency f, and L_{Afcrit} is the A-weighted level of the background noise in the critical band centred on frequency f. In this context, "background noise" refers to the local broadband masking noise within the spectrum. Critical bandwidths are given in ISO 389:1994, Part 4 [5]. Subject to reservations expressed below, and for illustrative purposes, one example of elementary critical band analysis is given for a tonal component which has a relatively narrow bandwidth (measured as less than 1/9 octave). The original FFT 25 Hz bandwidth spectrum was reanalysed using 10 Hz bandwidth. It was then imported into a spreadsheet to give the spectrum of Figure 3. The background critical band level L_{Afcrit} was calculated as 53.7 dB, giving a threshold level L_{At0} of 49.7 dB. The tonal component had a centre frequency in the 1910 Hz 10 Hz band, and had a level L_{At} calculated as 59.3 dB. This gives a sensation level of 9.6 dB, which suggests that the tonal component should be detectable by a listener.

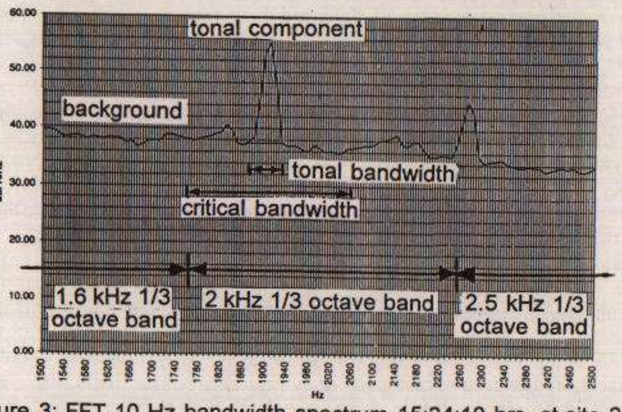

Figure 3: FFT 10 Hz bandwidth spectrum 15:24:10 hrs. at site 2

Bullmore and McKenzie [6] describe the development of an objective procedure, based on practical critical band analysis, for identifying and rating tones in noise from wind farms. It was found that variations in the parameters (eg. tone identification, tone level evaluation, time weighting and frequency resolution) used for the critical band analysis could result in variations in tone level differences in excess of 5 dB for the same data. It was therefore necessary to tightly specify all the critical band analysis parameters in the objective procedure. The objective procedure was developed and validated specifically for noise from wind farms.

Flindell [7] refers to problems using critical band analysis with real tonal noise found under field conditions. These problems include the analysis of multiple tone complexes and sounds having amplitude or frequency modulated tones. The author states that many real sounds can create difficulties under the current state of knowledge.

It is clear from the work of Bullmore, McKenzie and Flindell that the application of critical band analysis to real-life sounds is far from straight forward. The present work shows that aircraft taxiing noise may contain multiple tonal components. Added to this is the fact that taxiing noise at any one time may be made up of taxiing noise from a number of different moving or stationary aircraft each emitting different tonal signatures. Furthermore, a taxiing noise tonal analysis method has to cater for the time variation of both taxiing noise and background noise. In view of these complexities, it is evident that practical critical band analysis techniques may not be sufficiently developed at the present time to assess reliably the tonality of aircraft taxiing noise.

4.3 Differences between subjective and objective assessments

The summary of results given in Tables 2 and 3 shows that subjective assessments of clearly audible high frequency tonal components were often not matched by objective assessments using 1/3 octave analysis. This is illustrated by Figures 4 and 5. The background noise spectrum and 1/3 octave band limits have been added in Figure 4. A number of clear spectral prominences are evident in the taxiing noise FFT narrow-band spectrum, whereas the taxiing noise FFT 1/3 octave spectrum is relatively flat. Subjectively, high frequency tonal components were clearly audible.

It is apparent from Table 1 that there is no provision in the BS 7445 criteria for the **combination** of (i) a subjective assessment of tonal components being "clearly audible", and (ii) a 1/3 octave spectrum in which none of the bands exceeds the two adjacent bands by 5 dB or more. There is, therefore, an inherent assumption that a subjective assessment of tonal components being "clearly audible" will necessarily be accompanied by a 1/3 octave spectrum in which at least one of the bands exceeds the two adjacent bands by 5 dB or more. Many of the results did not support this assumption.

The conclusions of ISVR report 159 [8] state that subjects with normal hearing can unequivocally distinguish between the presence of pure tones in noise and the presence of other narrow-band stimuli with bandwidths equal to or greater than 1/9 octave. The report indicates that currently recommended procedures for the objective detection of tonal components, based on 1/3 octave analysis, may be inadequate. Thus, the use of 1/3 octave analysis makes no distinction between pure tones and other narrow-band stimuli contained within the bandwidth of analysis. 1/3 octave spectral analysis may well be too coarse to identify reliably the presence of subjectively identifiable tones.

It seems possible that a test based on comparing noise levels in adjacent 1/3 octave bands may give unreliable results when the spectrum falls steeply with increasing frequency, or contains a number of spectral prominences which lie in adjacent 1/3 octave bands. The taxiing noise spectrum of Figures 4 and 5 is an example. Three spectral prominences in the 5 kHz 1/3 octave band are concealed by a steeply falling spectrum. Two spectral prominences lie in the 2.5 kHz 1/3 octave band. However, there is another spectral prominence in the 2 kHz 1/3 octave band.

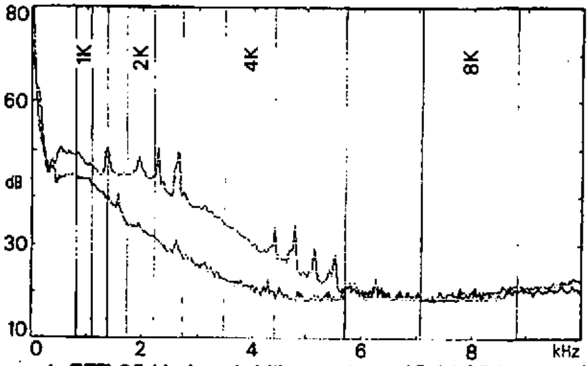

Figure 4: FFT 25 Hz bandwidth spectrum 15:14:05 hrs. at site 2

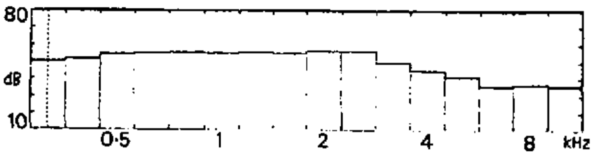

Figure 5: FFT 1/3 octave spectrum 15:14:05 hrs. at site 2

It also seems that the 5 dB 1/3 octave tests may not be fully consistent with critical band theory. This effect is illustrated using the spectrum in Figure 3. According to the elementary critical band analysis in Section 4.2 above, the tonal component at 1.91 kHz would be expected to be audible. Tonality was indeed observed subjectively at this time, although such tonality does not necessarily relate specifically or exclusively to the 1.91 kHz tonal component (since the full spectrum exhibited other spectral prominences). According to critical band theory, the audibility of the 1.91 kHz tonal component is determined by the noise level of the remainder of the spectrum across the bandwidth of the associated critical band. This critical band extends from 1.76 kHz to 2.06 kHz. The BS 7445 and ANSI assessments relate to whether or not the noise level of the 2 kHz 1/3 octave band exceeds the noise levels of the 1.6 kHz and 2.5 kHz 1/3 octave bands by the required 5 dB. The 1.6 kHz 1/3 octave band extends from 1.414 kHz to 1.760 kHz, and the 2.5 kHz 1/3 octave band extends from 2.250 kHz to 2.825 kHz. The 1/3 octave tests are therefore using noise levels for frequency ranges which, according to critical band theory, are not **directly** relevant to audibility of the tonal component.

The narrow-band analysis suggested in BS 7445 for tonal components which are "just detectable" to an observer can demonstrate spectral prominences. However, that analysis does not, by itself, provide an objective test of the audibility of tonal components which may, or may not be, associated with those spectral prominences. BS 7445 does not provide guidance on the degree of spectral protrusion necessary for audibility of such components.

5. CONCLUSIONS

1. Subjective assessments of a clearly audible high frequency whine were often not matched by objective assessments of tonality using 1/3 octave band frequency analysis. This indicates that the 5 dB 1/3 octave tests of BS 7445 and ANSI S12.9 may fail to give an objective demonstration of the presence of clearly audible high frequency tonal components.

2. Narrow-band FFT frequency analysis is useful for demonstrating the presence of high frequency spectral prominences but does not, by itself, demonstrate audibility of associated tonal components. Moreover, for complex noises, such as aircraft taxiing noise, currently available critical band analysis techniques may have limited utility for the objective demonstration of audibility of tonal components associated with such high frequency spectral prominences.

3. Objective methods of demonstrating the presence of audible high frequency tonal components do not appear to be sufficiently developed at the present time to deal with complex noises such as aircraft taxiing noise. In such circumstances, objective methods should inform subjective judgement rather than replace subjective judgement.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

[1] *"Method for rating industrial noise affecting mixed residential and industrial areas."* BS 4142:1990. (superseded by BS 4142:1997). British Standards Institution.
[2] *"Description and measurement of environmental noise."* BS 7445:Part 2:1991 (equivalent to ISO 1996-2:1987). BSI.
[3] *"Quantities and procedures for description and measurement of environmental sound. Part 3: Short-term measurements with an observer present."* ANSI S12.9/Part 3: 1993.
[4] *"Annoyance due to discrete tones in broadband background noise. Part II: Analysis."* D W Robinson. ISVR Technical Report No. 202, Jan. 1992.
[5] *"Acoustics - Reference zero for the calibration of audiometric equipment. Part 4 - Reference levels for narrow-band masking noise."* ISO 389:1994. ISO.
[6] *"Tonal noise immission from wind farms."* A J Bullmore and A R McKenzie. Inter-Noise 96, pp. 453-458. IOA, 1996.
[7] *"Sounds with tonal features - research methods and assessment."* I H Flindell. Inter-Noise 96, pp. 2473-2478. IOA, 1996.
[8] *"The detectability and tonal character of tones and other narrow-band stimuli in noise."* P R Williams and D W Robinson. ISVR Technical Report No. 159, Feb. 1988.