inter.noise HAMBURG 2016

Signal-based indicators for predicting the effect of audible tones in the aircraft sound at takeoff

Antoine MINARD[1]; Christophe LAMBOURG[1]; Patrick BOUSSARD[1]

[1] GENESIS, France

ABSTRACT

Audible tones in the sound of aircraft at takeoff, perceived at ground level, generally take the form of two components. The first one is a whistling sound at a frequency that corresponds to the fan rotation multiplied by the number of blades (blade passing frequency). The second one is a series of harmonic partials with a low fundamental frequency (buzz-saw noise). In the scope of the PARASOFT project, a former study showed that these two sound components, when heard at the same loudness, can have an effect on unpleasantness. Here, the results of this study were compared with different tonality indicators (EPNL tone correction factor, ISO1996-2 annex C, DIN45681, Aures' model), and an indicator of roughness. This comparison revealed that all four tonality indicators are well suited for quantifying the detrimental impact of isolated tones. However only Aures' model for tonality, because it is not limited to the highest emergence, and roughness are able to account for the effect of buzz-saw noise. Aures' model for tonality should thus be considered when trying to predict the negative impact of any kind of audible tones in aircraft sound at takeoff.

Keywords: Tonality, indicator, aircraft flyover, sound quality
I-INCE Classification of Subjects Number(s): 63.7,69.3

1. INTRODUCTION

Numerous studies identify noise as the main annoyance source, which indicates that the sound environment is becoming an important concern for most people. Among the different types of transportation noise, aircraft flyovers are considered as the most annoying (1). The sound of aircraft flyover comes from sources of different natures (aerodynamic turbulences, fan, jet, etc.). For contemporary aircraft, these contributions can be seen on a perceptual point of view as three main types of sound components:

- Isolated tonal components, such as blade-passing frequency tone (BPF) generated by the fan of turbojets.
- Harmonic series of tones with a low fundamental frequency ("buzz saw" noise – BSN – that is generated by turbulence at the tip of the blades when their speed becomes supersonic).
- Broadband noise encompassing many contributions.

The influences of these components on the perception by people living near airports are not entirely understood. To this day, recommendations from standardization organizations such as the International Civil Aviation Organization mainly refer to EPNL (Effective Perceived Noise Level) in order to limit the annoyance for people living near airports (2), although this indicator was introduced more than 50 years ago. EPNL consists in an estimation of loudness (ISO532A), with correction factors only accounting for flyover duration and possible isolated tonal emergence.

In the framework of the IROQUA program, the PARASOFT project, funded by FNRAE and collectively conducted by Université de Cergy-Pontoise, ONERA, INSA-Lyon and GENESIS, attempts to expand the comprehension of the relation between parameters of the flyover sound and the perception by people living near airports. For this purpose, psychoacoustic experiments were conducted in order to evaluate listeners' unpleasantness when confronted to flyover sounds (3, 4, 5). The results of these experiments revealed, at least in some cases, that some components of the flyover sound, which can be considered as tonal, had a significant influence on unpleasantness.

In order to objectify this influence, and in a purpose of unpleasantness prediction, several "tonality" indicators were calculated over the sounds used in the experiment dedicated to this aspect (3).

[1] aminard@optis-world.com

Moreover, because of the "rough" nature of the sound when considering the BSN component, a model of roughness was also tested. Section 2 details these different indicators, and section 3 deals with their ability to explain unpleasantness, for 2 sets of sounds corresponding each to a same aircraft flyover whose tonal components where reduced to different extents.

2. Tonality and roughness indicators

2.1 EPNL tone correction factor

The tone correction factor that is included in the EPNL calculation (2) is based on a sound spectrum description in 1/3-octave bands of each signal window of 0.5 s. "Spectral irregularities" are located by identifying bands whose levels are at least 5 dB higher than either of their 2 adjacent bands. The emergence "F" in each of these bands is calculated as the difference between the initial level of the band and that of a smoothed version of the curve of the 1/3-octave-band levels, obtained by averaging adjacent band levels. Each emergence F is then transformed, according to the center frequency of the band, into a tone correction factor C whose values stand between 0 (for F ≤ 3dB) and 6.67 dB (for F ≥ 20 dB and a center frequency between 500 Hz and 5 kHz). Finally, only the highest value of C throughout the spectrum is kept as the instantaneous decisive tone correction factor. In the subsequent analyses, the maximum value of C over time is considered[2].

2.2 Tonal Audibility (ISO1996-2 C)

The annex C of standard ISO1996-2 (6) is based on the Joint Nordic Method (7). It provides a procedure for automatic detection of tonal components. According to the importance of these tonal components, the method gives a measure of the degree of tonal emergence, called "Tonal Audibility", from which an adjustment between 0 and 6 dB is derived to be added to the measured A-weighted sound level. The procedure includes 4 stages:

- A-weighted spectral analysis in narrow bands over a signal window of 300 ms (corresponding to a frequency resolution of 3.33 Hz). The resulting spectra are then averaged over time (the standard recommends that the total duration of the signal be at least 1 minute).
- Procedure for automatic detection of tonal emergences (spectral emergences locally higher than 6 dB, and 3-dB bandwidth smaller than 10 % of the critical bandwidth centered on the emergence frequency).
- In each critical band where at least one emergence was detected, calculation of the tonal level L_{pt} (energy summation if several distinct emergences were identified in this band) and the masking noise level of this critical band L_{pn}.
- Calculation of the Tonal Audibility ΔL_{ta} in each critical band (center frequency f_c) while taking into account the masking index (8), which corresponds to the level difference at masking threshold between a pure tone and the noise critical band centered on it:

$$\Delta L_{ta} = L_{pt} - L_{pn} + 2 + \log_{10}\left[1 + \left(\frac{f_c}{502}\right)^{2.5}\right] \quad (1)$$

The maximum value of ΔL_{ta} in dB identifies the decisive critical band. According to the standard, an adjustment in dB to be applied on the measure of the A-weighted sound level is derived from the obtained value, but it is not considered here.

The standard recommends a minimum signal duration of 1 minute (during which it is supposed that the signal is stationary or at least that emergence frequencies do not vary much). Because of the particular nature of the sounds considered here, non-stationary by essence because of the Doppler effect, the used indicator is in fact an adaptation of the standard for non-stationary sounds. It calculates the Tonal Audibility in each window of 1 second of the signal, and the maximum value over time is retained. For the sake of convenience, this indicator will nonetheless be referred to by the standard.

2.3 Standard DIN45681

The DIN45681:2005-03 standard (9) follows the same principle as the annex C of standard ISO1996-2. It also aims to provide a dB adjustment to be applied to A-weighted sound level

[2] In the actual calculation of EPNL, instantaneous values of C are added to the instantaneous values of the Perceived Noise Level (PNL). The final EPNL value corresponds the maximum obtained value, after adding another correction factor to account for flyover duration.

measurements. However, there exist a few discrepancies:

- A-weighted spectral analysis in narrow bands. The frequency resolution is calculated so as to be in the range between 1.9 and 4 Hz with a number of FFT points equal to a power of 2, according to the sampling frequency of the signal. The obtained spectrum is then averaged over a duration of roughly 3 seconds.
- Procedure for automatic detection of tonal emergences (spectral emergence locally higher than 6 dB, and "clarity" higher than 70 %[3]).
- In each critical band where at least one tonal emergence was identified, calculation of the tonal emergence level L_T (energy summation if several distinct emergences were identified in this band) and the masking noise level of this critical band L_G.
- The emergence ΔL_k is calculated in the same manner as the Tonal Audibility of standard ISO1996-2 (i.e. by taking into account the masking index). Only the largest emergence over all critical bands is kept.
- The final emergence (called "Mean Difference") ΔL corresponds to the mean value of ΔL_k over time.

The dBA adjustment is derived from this Mean Difference, but is not considered here.

2.4 Aures' tonality

Aures (10) models tonality based on subjective evaluations of pure tones and narrowband noises by using four weighting functions for the effects of bandwidth, center frequency, prominence of the tone, and the loudness of the tone as compared to the total loudness, most of which were proposed by Terhardt et al. (11). Aures also proposes an algorithm for separating the tonal and noise parts in the sound, in signal windows of 80 ms.

For each i^th detected tone at the frequency f_i in Hz with a level L_i in dB SPL and a bandwidth Δz_i expressed on the Bark scale (i.e. as a fraction of the critical bandwidth), these functions are defined as follows:

- Bandwidth weighting w_1:

$$w_1(\Delta z_i) = \frac{0.13}{\Delta z_i + 0.13} \tag{2}$$

- Frequency weighting w_2:

$$w_2(f_i) = \left(\frac{1}{\sqrt{1 + 0.2(f_i/700 + 700/f_i)}}\right)^{0.29} \tag{3}$$

- Prominence weighting w_3:

$$w_3(\Delta L_i) = \left(1 - e^{-\frac{\Delta L_i}{15}}\right)^{0.29} \tag{4}$$

ΔL_i is the prominence in dB and is calculated as:

$$\Delta L_i = L_i - \log_{10}\left\{\left[\sum_{k\neq i}^{n} A_{Ek}(f_i)\right] + E_{Gr}(f_i) + E_{Hs}(f_i)\right\} \tag{5}$$

A_{E_k} is the is the secondary excitation at frequency f_i due to the k^{th} component, E_{Gr} is the masking intensity of the noise, and E_{Hs} is the intensity at the threshold of hearing.

Aures then combines these in the weighting w_T:

$$w_T = \sqrt{\sum_{i=1}^{n} [w_1'(\Delta z_i)\ w_2'(f_i)\ w_3'(\Delta L_i)]^2} \tag{6}$$

where $w_1' = w_1^{\frac{1}{0.29}}$, $w_2' = w_2^{\frac{1}{0.29}}$ and $w_3' = w_3^{\frac{1}{0.29}}$.

[3] Parameter related to the spectral width of the tone and to the spectral slopes of its edges.

The loudness weighting w_{Gr} accounts for the relative contribution of the tonal loudness to the overall loudness:

$$w_{Gr} = 1 - \frac{N_{Gr}}{N} \tag{7}$$

N_{Gr} and N are the loudnesses in sones of the noise and the whole sound, respectively.

Finally, Aures' Tonality T in tu (tonality unit) is:

$$T = c \cdot {w_T}^{0.29} \cdot {w_{Gr}}^{0.79} \tag{7}$$

where $c = 1.09$ is a constant chosen such that a 1-kHz pure tone with a level of 60 dB SPL would have a tonality of 1 tu.

2.5 Roughness

Given the typical fundamental frequency of the BSN component of flyover sounds (around 75 Hz for the takeoff sounds considered in the project), roughness was also considered as a potential indicator of the presence of this component.

The roughness of a sound describes the sensation provoked by amplitude modulations at frequencies higher than 20 Hz. It reaches its maximum at 70 Hz. Usually roughness is associated to dissonance and tends to make the sound feel more aggressive and unpleasant. Zwicker and Fastl proposed a unit for describing roughness (8): the asper. One asper is the roughness of a sound of 1 kHz and 60 dB SPL, amplitude-modulated at a frequency of 70 Hz and a modulation depth of 100 %. The roughness model that was used here is that of Daniel and Weber (12). This model, after a first filter corresponding to the response of the outer and middle ear, applies a filter bank to the signal in order to separate it into the different Bark bands. A generalized modulation depth m_i^* is calculated in each critical band and the specific roughness r_i is calculated by the formula:

$$r_i = (g(z_i) \cdot m_i^* \cdot k_{i-2} \cdot k_i)^2 \tag{8}$$

g is the weighting function of the partial roughness given by Aures (10) (higher weight around the 11th and 12th Bark bands) and k_{i-2} and k_i are the correlations between, respectively, Bark bands $i-2$ and i, and Bark bands i and $i+2$.

Finally, the overall roughness is calculated through integration of the specific roughness over all Bark bands:

$$R = cal \cdot \sum_i r_i \tag{8}$$

cal is a calibration constant so that $R = 1$ asper for a pure tone at 1 kHz and 60 dB SPL, modulated at 100 % and 70 Hz.

This calculation is repeated in each successive 200-ms window of the signal, with an overlap of 50 %. The final roughness value is the median value over the whole signal duration.

3. Objectification of the unpleasantness by the indicators

In the framework of the PARASOFT project, a former study (3) aimed at the evaluation of the influence of the emergence level of tonal components on unpleasantness through a listening test. This section describes the part of the project dedicated to objectify the perceptual results of this study.

3.1 Experimental data

In the experiment conducted in (3), 30 participants rated, through a direct scaling method, the unpleasantness of 57 sounds of aircraft takeoff, obtained by synthesis (13). Each synthesized sound is composed of 3 components: a broadband noise (corresponding to different sources, jet, fan, airframe, etc.), an isolated tonal component (fan tone), and a harmonic series (buzz-saw noise), further referred to as BBN, BPF and BSN, respectively. Some of these syntheses corresponded to actual sounds recorded during the project, and the others included variations of the synthesis model, among which the emergence levels of each tonal component. Respectively 4 and 3 gain values in dB were applied to the BPF and BSN components of 3 initial syntheses (i.e. created with respect to recordings). Each of these 3 initial syntheses corresponded to a different aircraft model. Thus the sound dataset included 12 synthesized sounds for each of the 3 aircraft, corresponding to all possible combinations of gains of the 2 components. The gain values, referred to as ΔBPF and ΔBSN, were set to 0, -6, -12, and -18 dB for the BPF, and 0, -6, and -12 dB for the BSN, and the resulting sounds were all equalized in loudness.

Among the conclusions of the conducted experiment (3), it was shown that the gain variations had no effect on the unpleasantness ratings for 1 of the 3 aircraft. However, a significant effect of ΔBPF was revealed for another (further referred to as Aircraft A), and a significant effect of ΔBSN for the last one (further referred to as Aircraft B). A possible explanation is related to the fact that the initial syntheses, and thus the recordings on which they were based, had different relative levels of each component, that tended to favor the effect of one over the others. This hypothesis seems confirmed when comparing the evolution over time of the sound level of each component taken separately.

The 5 indicators detailed in section 2 were calculated over the 12 gain variations of these 2 aircraft. The following subsections address the link between tonality, roughness and unpleasantness for aircraft flyover sounds, and the efficiency of each indicator to predict the measured values of mean unpleasantness.

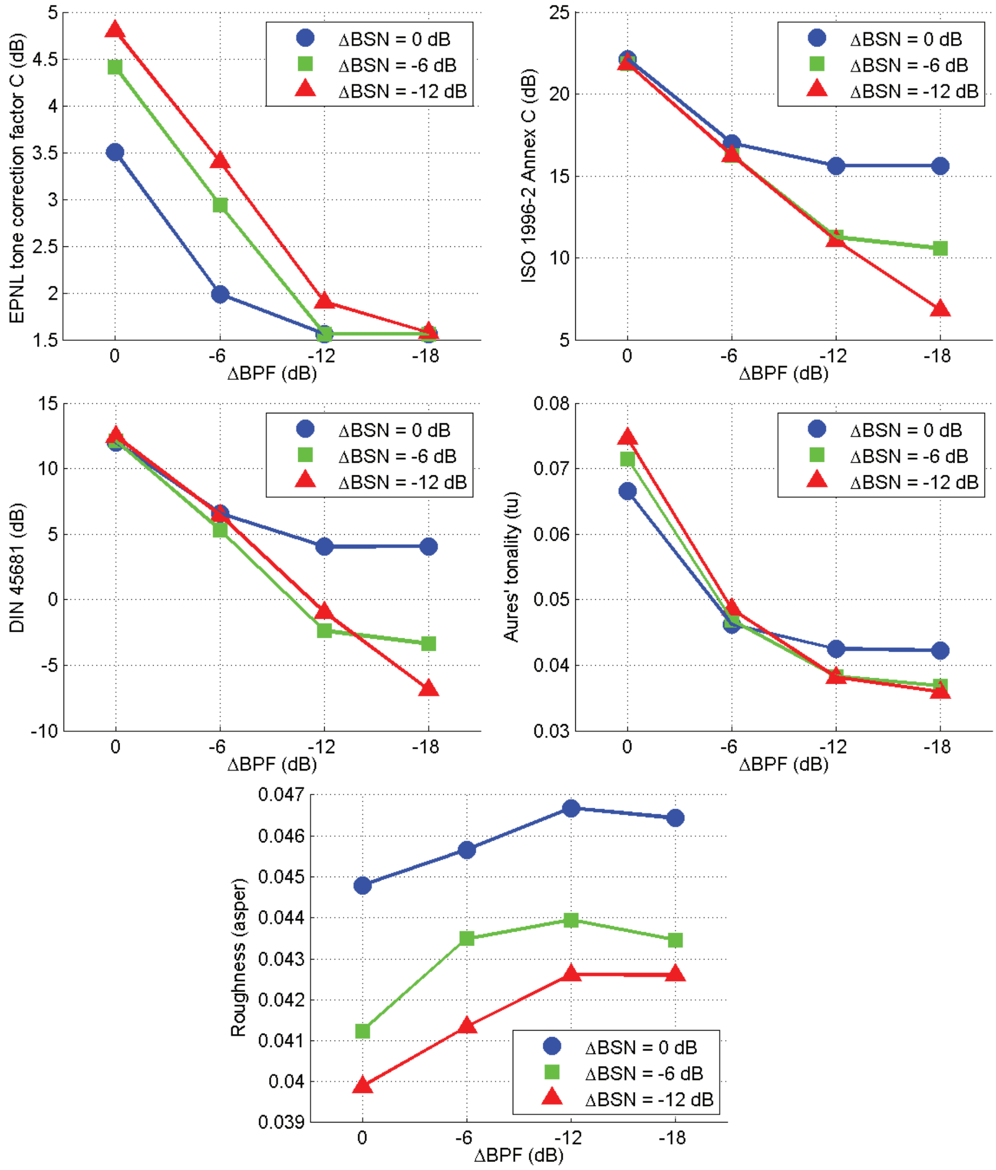

Figure 1 – Values of the 5 indicators for the 12 gain variations of BPF and BSN of aircraft A.

3.2 Aircraft A – Effect of BPF

Figure 1 displays the obtained values for the 5 indicators (EPNL tone correction factor, ISO1996-2 C, DIN45681, Aures' tonality and roughness) for each of 12 combinations of BPF and BSN gain values, for aircraft A. On each subfigure, indicators' values are on the Y-axis, ΔBPF levels are on the X-axis, and ΔBSN levels are on separate curves specified in the subfigure legend. The 4 tonality indicators manage to follow the variations of ΔBPF, as can be seen by the fact that the indicator values decrease with decreasing values of ΔBPF. However, these 4 indicators have different behavior with respect to ΔBSN variations.

First the tone correction factor is higher when ΔBSN is reduced. The logical explanation for this is that, at any level of ΔBSN, this component is not detected as an emergence, and, as a consequence, its presence tends to limit the level of emergence of the BPF with respect to the sum of the BBN and BSN components.

On the contrary, ISO and DIN standards manage to detect BSN emergence when ΔBPF is low enough, and give a moderate value of emergence. When the BPF component is at its initial level or only slightly reduced, ΔBSN has no effect on these 2 indicators.

The effect of ΔBSN on the values of Aures' tonality seems rather small. This effect is however inverted between the high and low values of ΔBPF: when ΔBPF is high, the BSN component seems to temper the values of tonality; when it is low, tonality values slightly increase with those of ΔBSN. This dual effect may be related to the fact that Aures' tonality takes into account the masking of tones by other tones.

Finally, roughness seems to be able to detect the variations of ΔBSN, but its relation to ΔBPF is the opposite of that of the other indicators, probably because of a masking effect by the BPF component at a high level.

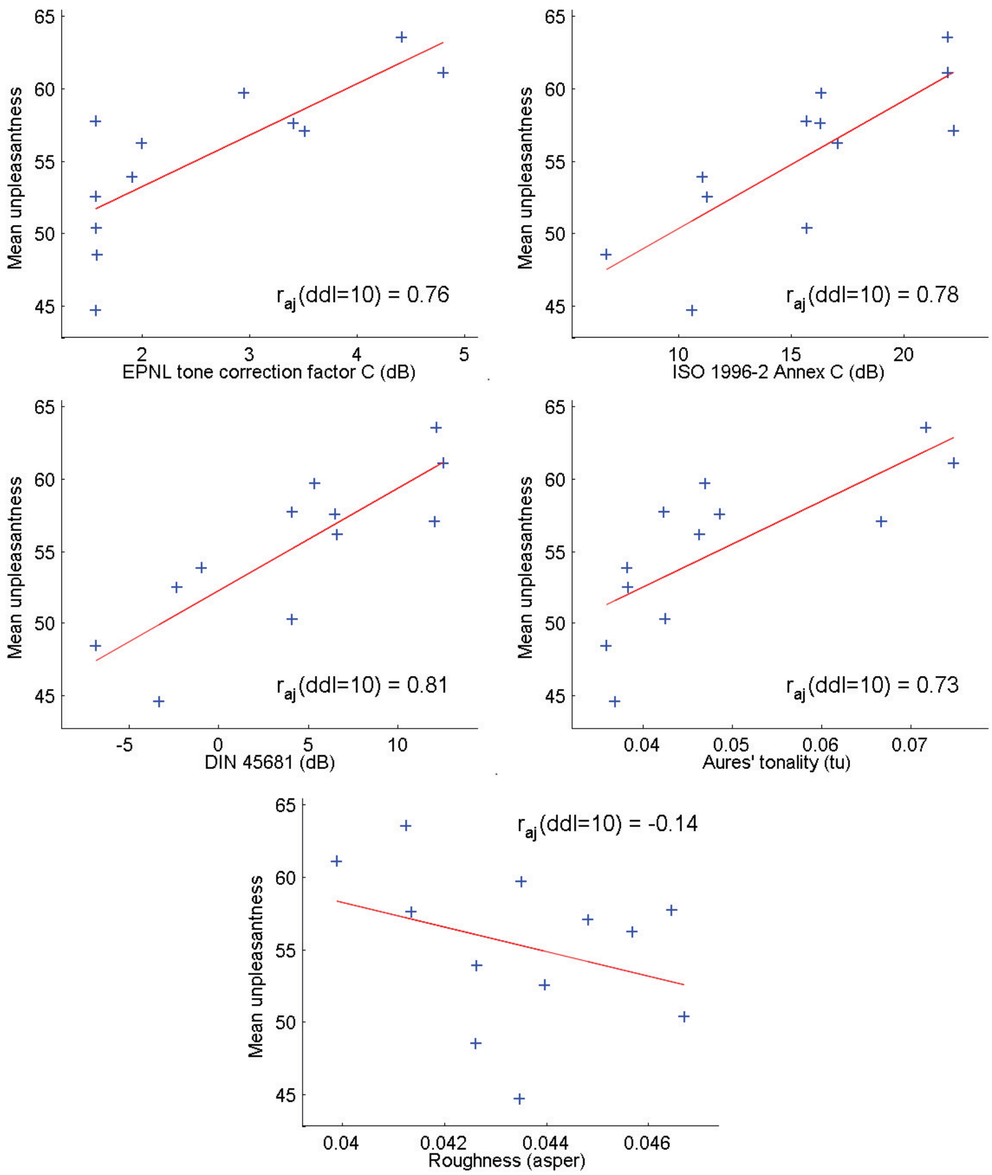

Figure 2 – Scatter plot between the mean unpleasantness values and each of the 5 indicators of aircraft A.

As a second analysis, the values of these indicators were compared to the mean ratings of unpleasantness through linear regression. Figure 2 displays the corresponding scatter plots, with the regression lines. The values of the adjusted Pearson product-moment correlation coefficient are also specified on this figure (“r_{aj}”, “dof” stands for “degrees of freedom”).

This figure makes it possible to observe that, to the only exception of roughness, which is not correlated to unpleasantness, all indicators seem rather similar in terms of their ability to explain mean unpleasantness. One important result is that the EPNL tone correction factor is not significantly less correlated than other more “sophisticated” tonality indicators.

3.3 Aircraft B – Effect of BSN

Figure 3 shows the obtained values of the 5 indicators for each of the 12 combinations of ΔBPF and ΔBSN, for aircraft B. In each subfigure, the values of the indicator are on the Y-axis, the level of ΔBPF are on the X-axis, and the levels of ΔBSN are on distinct curves that are specified in the subfigure legend. The shapes of the curves on this figure are quite different from those of aircraft A. While the curves of aircraft A clearly tended to decrease with decreasing ΔBPF, this trend is less general for aircraft B curves. However, the effect of the BSN component is more distinct here, because the 3 curves in each subfigure are well separated from one another.

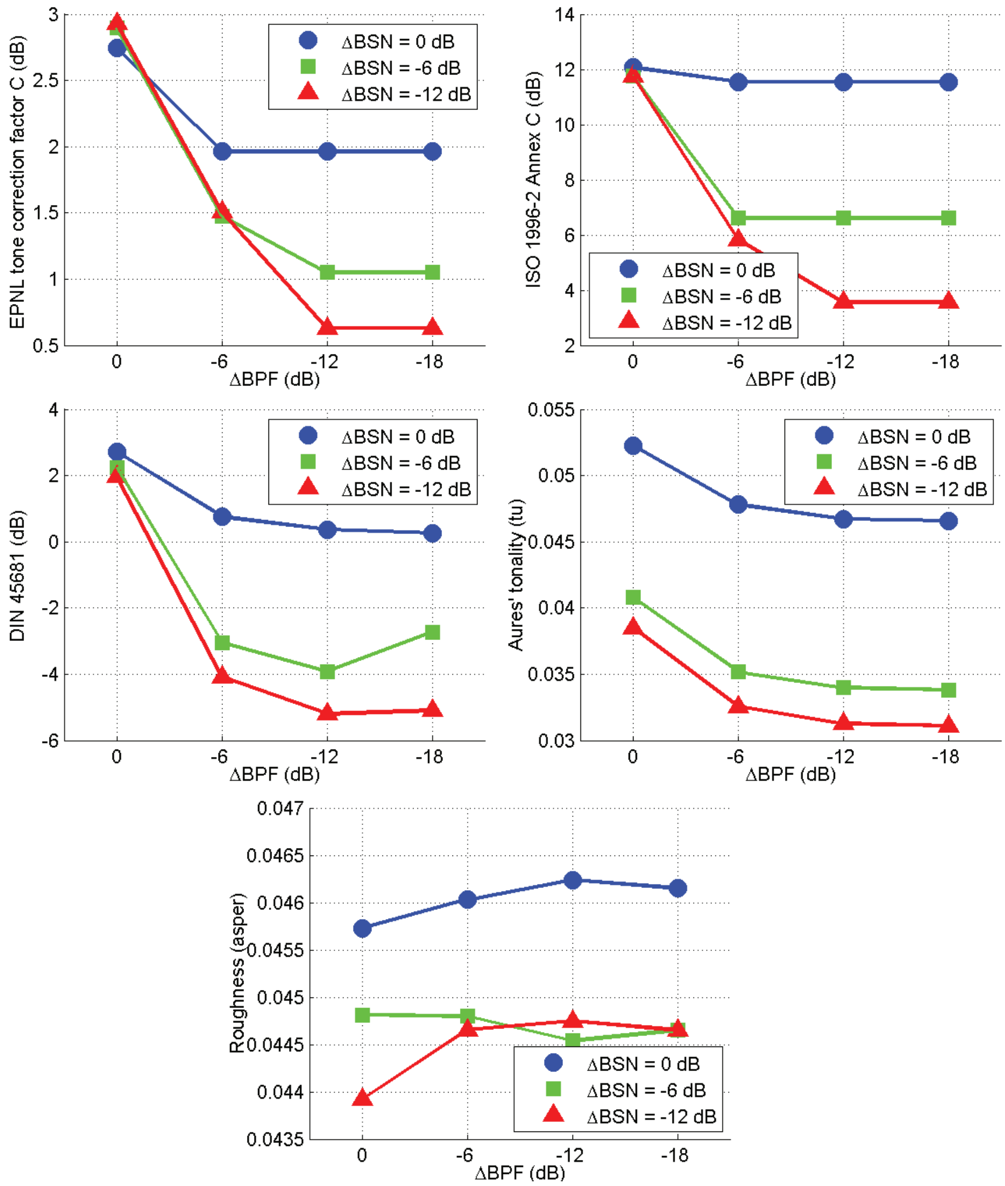

Figure 3 – Values of the 5 indicators for the 12 gain variations of BPF and BSN of aircraft B.

The EPNL tone correction factor is the indicator that best shows the effect of ΔBPF (decreasing shapes of the curves). This indicator is also able to detect the presence of the BSN component when

ΔBPF is low, but this ability totally disappears for the initial value of ΔBPF (0 dB). ISO and DIN standards have similar trends, although the effect of ΔBSN is more salient.

As for Aures' tonality, this indicator is the only one that distinguishes the 3 levels of ΔBSN at any ΔBPF level, including thus when ΔBPF is at its maximum value (0 dB). This means that Aures' tonality is able to detect harmonic series, even when an isolated tone stands out. This is probably related to the fact that it considers the entirety of the spectrum when calculating the level of tonal emergence, whereas the other tonality indicators only keep the maximum emergence.

Finally, it is interesting to note that roughness also manages to detect the variations of ΔBSN, even when ΔBPF is high. However, roughness values seem reduced by the presence of the BPF component.

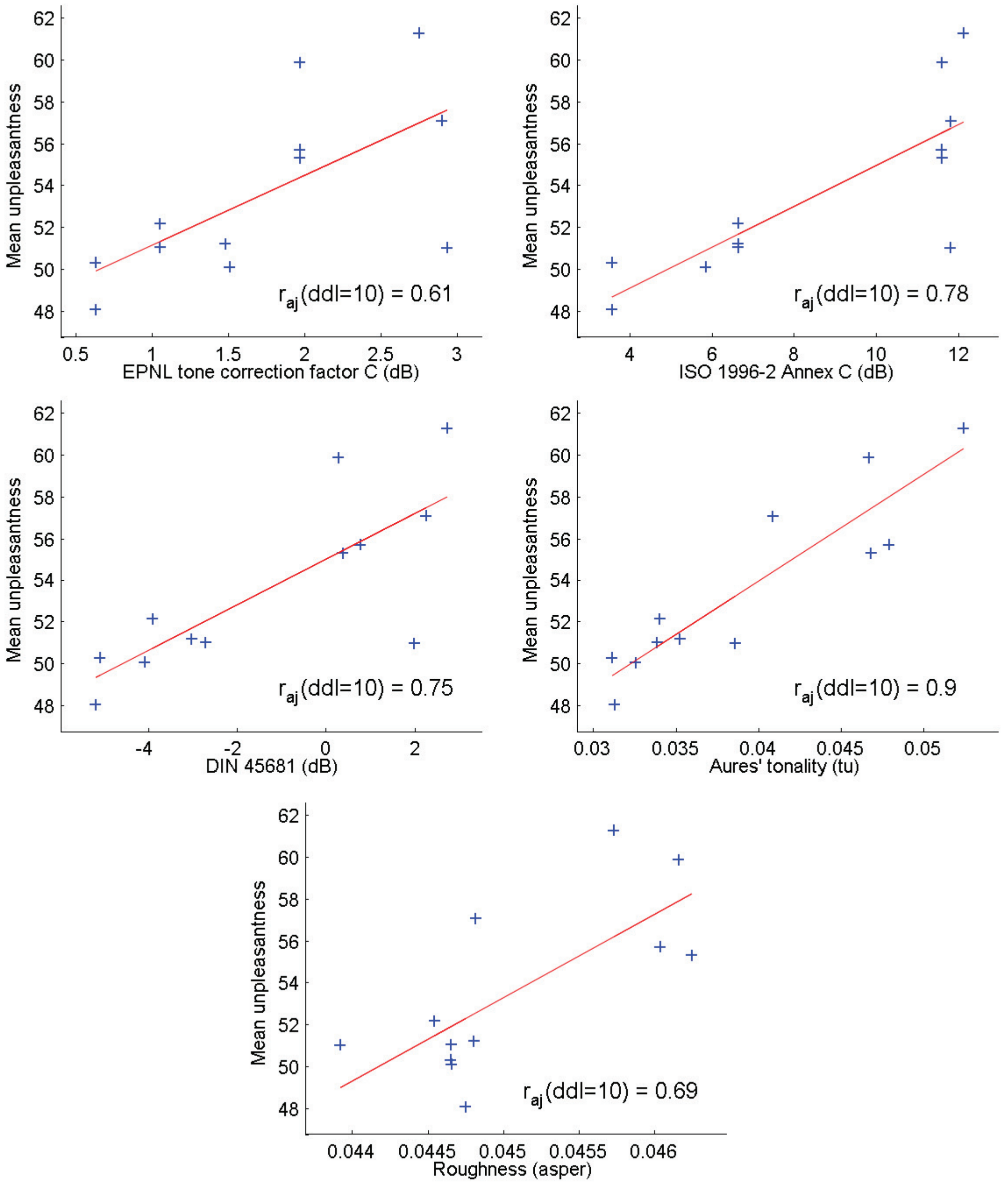

Figure 4 – Scatter plot between the mean unpleasantness values and each of the 5 indicators of aircraft B.

Linear regressions were also calculated between the values of these indicators and the mean ratings of unpleasantness. Figure 4 displays the corresponding scatter plots, regression lines, and adjusted Pearson product-moment correlation coefficients ("r_{aj}", "dof" stands for "degrees of freedom").

This figure firstly shows the limits of the tone correction factor of EPNL, whose correlation coefficient is clearly smaller than those of the other indicators, unlike for aircraft A. On the contrary, Aures' tonality gets a really interesting correlation coefficient for this aircraft. ISO and DIN standards have similar correlation coefficients that are also close to those obtained for aircraft A. Finally, roughness' correlation coefficient is moderate, and stands between those of the EPNL tone correction factor and the 2 standards. Nevertheless, roughness offers an interesting alternative for quantifying the perceptual effect of harmonic series such as the BSN.

3.4 Discussion

The results detailed here reveal interesting observations on how the tonal emergences of aircraft flyover sounds are taken into account by indicators. When the main component with respect to unpleasantness is an isolated tone (aircraft A), all tonality indicators seem quite efficient and are roughly equivalent. More specifically, the EPNL tone correction factor, including rather simple tone detection and emergence calculation methods, is not significantly worse, in terms of correlation, than more complex methods such as standards ISO1996-2 and DIN45681. Maybe one could just argue that the fit of the EPNL tone correction factor is not as good for the smallest emergences.

When the sound contains a harmonic series that appears to be more detrimental (aircraft B), the EPNL tone correction factor seems however quite insufficient to explain unpleasantness. Standards DIN45681 and ISO1996-2 are not much more efficient in this case. Only Aures' tonality appears to perform really well in predicting perceived unpleasantness. The explanation is most probably in the fact that it includes a tone emergence weighting (w_3) calculated over the whole spectrum, which then takes into account both the isolated tones and harmonic series covering a wide band of frequencies. On the contrary, the 3 other indicators only consider either the 1/3-octave band (EPNL tone correction factor) or the critical band (DIN45681 and ISO1996-2) around the main tonal emergence, which, in aircraft flyover sounds, is almost always the BPF tone. Therefore, these 3 indicators largely neglect the detrimental aspect of all harmonic partials of the BSN that are located outside of the considered band. Although each partial taken individually does not correspond to a large amount of energy with respect to the overall sound energy (and would probably not be saliently perceived alone), their combination can represent a non-negligible part that can easily stand out of the sound on a perceptual point of view.

The tone detection procedure can also have an influence, specifically in the case of the EPNL tone correction factor. In this case, emergences are located as a 1/3-octave band with a higher level than the adjacent bands (in a manner similar to the prominence ratio PR of ISO7779 standard). Yet a harmonic series such as the BSN would probably have similar levels in adjacent bands since the levels of consecutive partials are rarely strongly different.

Finally, roughness offers an interesting alternative for accounting for sound sources such as the BSN. However, its estimation seems rather disturbed by the presence of strong isolated tonal components such as the BPF tone. Therefore, roughness cannot by itself entirely explain the unpleasantness of the sounds considered here.

4. Conclusion

The goal of this study was to address the question of how various indicators, mostly for tonality, are able to predict the unpleasantness of aircraft takeoff sounds with several tonal components that emerge at different levels. Results show that when an isolated tonal component (BPF) is prominent, all tonality indicators are roughly equivalent in their ability to explain unpleasantness ratings. However, when the sound includes a series of numerous harmonic partials with a low fundamental frequency (BSN), most tonality indicators show their limits. Indeed, they only consider the emergence level in one single spectral band where it reaches its maximum. The only exception is Aures' tonality, which is not limited to the maximum emergence. This indicator also takes into account different aspects of emergence (bandwidth, frequency, masking between tonal components, contribution to total loudness), all of which are not considered by the other indicators, and were not studied here. Several studies (14, 15, 16) addressed the influence of these parameters on perceived tonality and have confirmed the relevance of this indicator. However, even if Aures' tone detection procedure is not the most complex, the calculation of the final value of Aures' tonality includes a lot of different weightings and coefficients, whose physical meanings are not assured, and that can sometimes cloud the interpretation of the values of this indicator.

On a more general standpoint, the purpose of this work was to question the relevance of indicators of global unpleasantness that are commonly used for aircraft flyover sounds. If there is one thing that this study shows, it is that tonal components, whether isolated as the BPF tone or structured as a harmonic series such as the BSN, have to be considered. In the case of isolated tonal component, the EPNL seems relevant, and is to be preferred to sound level indicators such as the equivalent A-weighted sound level L_{Aeq}. However, in case of harmonic series such as the BSN, the EPNL could be upgraded, either by including a more refined tone detection procedure that would consider the tones in the entirety of the spectrum, or by adding a correction factor on the basis of roughness.

Furthermore, in the scope of the PARASOFT project, the considered unpleasantness factors for aircraft flyover sounds were not limited to tonal emergences. Indeed, another part of the project was dedicated to temporal factors of the flyover, namely the Doppler effect, the perceived duration, the "sudden" aspect of the flyover and the turbulence (4, 5). That part of the project also showed significant effect of perceived duration (already taken into account in the EPNL) and turbulence, which should be considered as well, when trying to efficiently predict the unpleasantness of such sounds.

ACKNOWLEDGEMENTS

PARASOFT is a collaborative project involving Université de Cergy-Pontoise, ONERA, INSA Lyon, and GENESIS, and was founded by FNRAE in the framework of the IROQUA program.

REFERENCES

1. Mediema HM, Vos H. Exposure-response relationships for transportation noise. J Acoust Soc Am. 1998;104(6):3432-3445.
2. International Civil Aircraft Organization, Annex 16, Chapter 3. 6th edition, 2011.
3. Brocolini L, Parizet E. Influence of tonal components on the unpleasantness of airplane noise at take-off. Proc Internoise 2015, San Francisco, USA 2015.
4. Paté A, Lavandier C, Minard A. Influence of temporal aspects of aircraft sound signature on perceived unpleasantness. Proc Internoise 2015, San Francisco, USA 2015.
5. Paté A, Lavandier C, Minard A, Legriffon I. Perceived unpleasantness of aircraft flyover noise: Influence of temporal parameters. Appl Acoust (submitted).
6. ISO1996-2:2007, Acoustics – Description, measurement and assessment of environmental noise - Part 2: Determination of environmental noise levels, 1987.
7. Pedersen TH, Sondergaard M, Andersen B. Objective method for assessing the audibility of tones in Noise Joint Nordic Method – Version 2. AV 1952/99 DELTA Acoustics and Vibration, 2000.
8. Zwicker E, Fastl H. Psychoacoustics: Facts and Models. Springer, 1990.
9. DIN45681:2005-03, Acoustics – Detection of tonal components of noise and determination of tone adjustment for the assessment of noise immisions, 2005.
10. Aures W. A model for calculating the sensory euphony of various sounds. Acustica. 1985;59:130-141.
11. Terhardt E, Stoll G, Steewann M. Algorithm for extraction of pitch and pitch salience from complex tonal sounds. J Acoust Soc Am. 1982;71(3):679-688.
12. Daniel P, Weber R. Psychoacoustical Roughness: Implementation of an Optimized Model. Acta Acust united Ac. 1997;83:113-123.
13. Minard A, Hourcade S, Lambourg C, Boussard P. Controllable sound simulations of aircraft flyovers. Proc Internoise 2015, San Francisco, USA 2015.
14. Parizet E, Fingerhuth S. Subjective evaluation of tonalness and relation between tonalness. Proc Internoise 2009, Ottawa, Canada 2009.
15. More SR. Aircraft noise characteristics and metrics. PhD thesis, Purdue University, 2010.
16. Hastings A, Lee KH, Davies P, Surprenant AM. Measurement of the attributes of complex tonal components commonly found in product sound. Noise Control Eng J. 2003;51(4):195-209.