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Future low-noise aircraft technologies and procedures – Perception-based evaluation using auralised flyovers

Reto PIEREN[1]; Lothar BERTSCH[2]; Demian LAUPER[1]; Beat SCHÄFFER[1]

[1] Empa, Swiss Federal Laboratories for Materials Science and Technology, 8600 Dübendorf, Switzerland.

[2] German Aerospace Center (DLR), 37073 Göttingen, Germany.

ABSTRACT

Residents living in the vicinity of airports are exposed to noise from departing and approaching aircraft. Noise may be reduced by introducing novel aircraft technologies and flight procedures. By means of auralisation and listening experiments, such possible future changes can be evaluated by considering human sound perception. In this study, flyovers of different aircraft types and flight procedures were auralised at multiple virtual observer locations, and subsequently evaluated in a psychoacoustic laboratory experiment with respect to short-term noise annoyance. An existing reference aircraft, a possible low-noise retrofitted version and a future low-noise design were simulated along standard and tailored approach procedures. Separate source signals were synthesised for engine broadband, fan tonal, airframe broadband, and cavity tonal noise. Further, smooth transitions between consecutive changes in configurational setting and operational condition were modelled to create realistic sounds. To enhance plausibility, the propagation simulation, amongst other effects, considered ground reflections and frequency-dependent amplitude modulation due to propagation through a turbulent atmosphere. The flyover sounds were spatially reproduced by a hemispherical loudspeaker array. The listening experiment revealed significant annoyance reductions for low-noise aircraft types and flight procedures, that maximal benefit is achieved by the combined optimisation of aircraft technology and procedure, and that distributed observers need to be considered.

Keywords: Simulation, Aircraft noise, Perception, Auralisation, Noise annoyance

1. INTRODUCTION

Residents living in the vicinity of airports are exposed to noise from departing and approaching aircraft. Aircraft noise may be reduced by introducing novel aircraft designs and flight procedures. By means of auralisation and listening experiments, such possible future changes can be evaluated by considering the human perception of sound. Using such information to steer the aircraft technology development process has recently been denoted as *perception-influenced design* (1).

In this study, flyovers of different aircraft types and different flight procedures are auralised, and subsequently evaluated in a psychoacoustic laboratory experiment. Within the presented study, the assessment focuses on approaching aircraft due to their increased complexity caused by the varying mixture of noise sources.

2. PERCEPTION-BASED EVALUATION PROCESS

Figure 1 illustrates the simulation process followed in this study. Starting with preselected Top Level Aircraft Requirements (TLAR), which contain e.g. mission range and number of passengers, air vehicles are designed on a physical feasible basis with the software framework PrADO (2). Approach and departure trajectories with underlying configurational settings, such as engine operation or high-lift usage, are simulated and optimised with the integrated FlipNA code (3). By auralisation, flyovers of the designed aircraft and procedures are artificially rendered audible in a virtual acoustic environment. This involves a sound source prediction, emission synthesis, propagation simulation and sound reproduction (see Section 3). Acoustic stimuli in the form of spatial sound fields of virtual

1 reto.pieren@empa.ch

flyovers allow a psychoacoustic evaluation in listening experiments. Resulting perception-based assessments are used to improve the simulation modules and ultimately also to optimise low-noise aircraft technologies.

The focus of this paper lies on the developed auralisation strategy for flyovers of jet aircraft (4). A comprehensive description of the concept is currently being prepared for publication elsewhere (5).

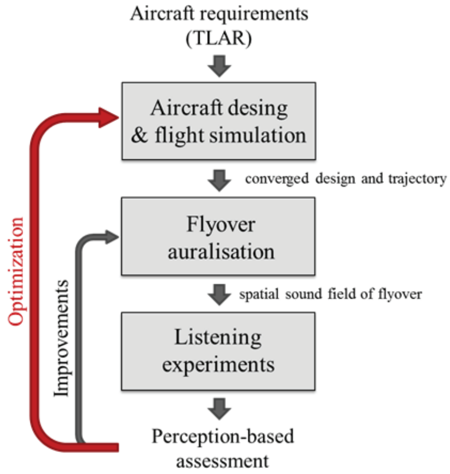

Figure 1 – Concept for perception-based evaluation of future low-noise aircraft designs and flight procedures (TLAR = Top Level Aircraft Requirements).

3. AURALISATION OF FLYOVERS OF JET AIRCRAFT

3.1 Emission synthesis

The simulation follows the source-path-receiver concept. Noise sources are predicted along the aircraft trajectory. In contrast to noise mapping applications, auralisation requires high time and frequency resolutions, and source descriptions with high temporal continuity (4).

Emissions of the major noise sources are calculated by the aircraft noise prediction tool PANAM (6). PANAM contains parametric calculation models for various componential noise sources of an aircraft. Engine and airframe noise sources are separately described as a function of aircraft design geometries and operational conditions. The componential noise sources are condensed into three contributions: (i) airframe broadband, (ii) engine broadband, and (iii) engine fan tones. Radiation angle-specific spectral sound emission levels are calculated in source time steps of 0.5 s. On that basis, source sound pressure signals for contributions (i) and (ii) are generated by subtractive synthesis where pink noise signals are spectrally shaped with a 1/3 octave band filter bank. The sound pressure source signal of the first five fan tones, $p_{\mathrm{em,fantones}}$, is generated using additive synthesis by five numerically controlled oscillators with amplitude and frequency controls (7):

$$p_{\mathrm{em,fantones}}[k] = \sqrt{2} p_0 \sum_{j=1}^{5} 10^{L_{\mathrm{em,fantone},j}[k]/20} \cos\left(\varphi_j + \frac{2\pi j}{f_s} \sum_{k'=0}^{k} f_{\mathrm{BPF}}[k'] \right) \quad (1)$$

with the signal sample indices k and k', the reference pressure p_0 = 20 µPa, the fan tone emission levels L_{em} in dB, a random initial phase angle φ in radians, the audio sampling rate f_s in Hz, and the fan blade passing frequency f_{BPF} in Hz.

Also relatively small structures at the airframe may lead to relevant narrowband aero-acoustic sources. One example is the wing cavity tones originating from fuel overpressure ports (FOPP) in the Airbus A320 family (8,9). The sound power of this double tone shows a strong speed dependency. For example, an airspeed increase from 80 to 100 m/s leads to a 10 dB increase in sound power. Initial attempts to synthesise cavity tones using additive synthesis failed, because listening comparisons to recordings revealed a very different hearing impression. In fact, cavity tones are generated by a Helmholtz resonator excited by a grazing airflow, featuring a random excitation pattern and a certain spectral bandwidth. Following this conception, in the developed synthesis model cavity tones are generated by subtractive synthesis with white noise as basic waveform and peak filters of the form (Laplace notation):

$$H_{\text{peak}}(s) = \frac{\omega_0^2}{s^2 + 2\zeta\omega_0 s + \omega_0^2} \tag{2}$$

with the Laplace variable *s,* the peak angular frequency ω_0 , and the damping ratio ζ used to set the bandwidth to about 2 Hz (see synthesis example in Figure 2). The synthesis parameters for the wing cavity tones are set based on field measurements (10,11).

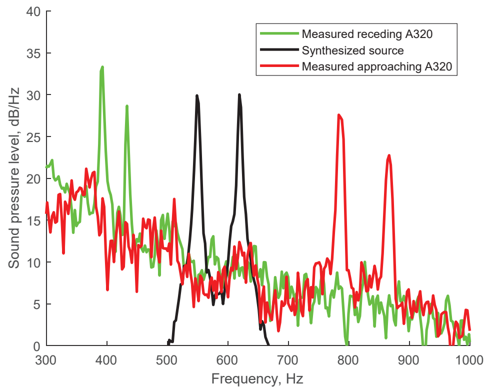

Figure 2 – Narrowband sound pressure spectra with distinct wing cavity tones as measured from an Airbus A320 at Mach 0.3 during approach. The Doppler effect shifts the two peaks from around 800 Hz (red) to 400 Hz (green) during the flyover event. Simulated data at Mach 0.3 by the developed synthesis model is shown in black (without Doppler effect).

3.2 Propagation filtering

The model conception behind the propagation simulation is that the most relevant propagation effects are independently described and modeled, similarly to current engineering propagation models. Time-variable propagation filters transform the source (emission) sound pressure signal into an observer sound pressure signal. The considered propagation effects are Doppler frequency shift, geometrical spreading, air absorption, ground effect and turbulence effect (7,12).

Attenuation due to atmospheric absorption is modelled for a stratified atmosphere described by the collection of height profiles for air temperature, relative humidity and static pressure. The effective atmospheric absorption coefficient is integrated along the propagation path using 20 vertical sampling points. From the atmospheric attenuation spectrum, an FIR filter with 1024 taps (at a sampling rate f_s = 48 kHz) is designed using the IFFT. The filter taps are updated every 200 ms.

Wave propagation through a turbulent atmosphere leads to distinctly audible amplitude modulations (AM). This effect was included to enhance plausibility of the hearing impression. The developed model considers that turbulence-induced AM is of random nature and depends on frequency and the propagation distance. Turbulence-induced AM is modeled by a high shelf filter with distance-dependent transition frequency and a random, time-dependent gain (12). A minimum phase first-order IIR filter is used here with the transfer function

$$H_{\text{turb}}^{t}(s) = \frac{\omega_c + 10^{G(t)/20} s}{\omega_c + s} \tag{3}$$

with the Laplace variable s, the high-frequency gain G in dB, and the angular transition frequency

$$\omega_c = 2\pi \frac{9000}{\sqrt{d(t)}} \tag{4}$$

where d is the source–receiver distance in meter. The gain G is created with a random process and is normally distributed with standard deviation σ and mean value $\mu = -0.115\sigma^2$, to ensure energy-neutrality of the turbulence effect.

3.3 Reproduction

To create a perceivable sound field, the (monophonic) sound pressure signal is distributed to a 3D loudspeaker array using directional information of sound incidence (time histories of azimuth and elevation angle). The 3D reproduction rendering is accomplished by dual-band amplitude panning where different normalisations are used for two frequency bands (13). The low frequency content is split off with a digital crossover (Linkwitz-Riley filters at 100 Hz) as subwoofer feed.

3.4 Application

A listening experiment with 32 subjects was performed in the listening test facility AuraLab at Empa in Switzerland. The sound reproduction system consisted of an upper-hemisphere layout with 15 satellite speakers (Neumann, KH 120 A) and two subwoofers (Neumann, KH 805) that were connected to a digital audio processor (Xilica, Neutrino A0816). The listening room features high structure- and airborne sound insulations, low background noise (below 7 dBA, GK0) and controlled room acoustics with a reverberation time of $T_{\mathrm{mid}} = 0.11$ s.

The subjects rated short-term noise annoyance of individual flyover events on the ICBEN 11-point numerical scale (14). Approaches of three civil tube-and-wing narrow-body aircraft with two flight procedures each and four observer locations were examined, making a total of 24 virtual flyovers.

No suspicious comments or remarks about plausibility were given by any of the subjects during or after the experiment, even though most had personal experience with aircraft noise. Furthermore, in a specific technical workshop, acousticians and aircraft noise experts rated the acoustic stimuli as “very plausible”.

Exemplary results of the listening experiment are shown in Figure 3. The novel aircraft design performs significantly better in terms of noise annoyance compared to the reference aircraft (similar to an existing A319-100). At distances closer than 15 km to the touch-down point, the tailored flight procedure leads to an additional improvement. However, this is not the case at larger distances, showing that distributed observer locations need to be considered for the assessment of low-noise aircraft technologies. Note that for this initial application example, only observer locations below the flight trajectory are assessed.

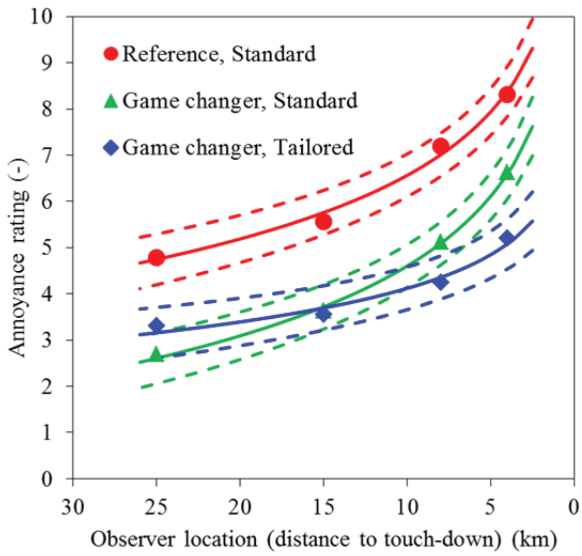

Figure 3 – Observed (symbols) mean short-term noise annoyance ratings for two aircraft types (Reference and Game changer) and two flight procedures (Standard and Tailored) at four observer locations. The curves show modelled data including confidence intervals.

4. CONCLUSIONS

In this study, a methodological approach for perception-based evaluation of future low-noise aircraft technologies was developed that involves, amongst others, enhanced auralisation models. Flyovers of different aircraft types with different approach procedures were successfully auralised at multiple virtual observer locations. Although the flyover sounds were fully synthetically generated, they were perceived as plausible. A listening experiment revealed significant reductions in short-term annoyance for low-noise aircraft types and flight procedures, that maximal benefit is achieved by the combined optimisation of aircraft technology and procedure, and that spatially distributed observers need to be considered to reliably assess low-noise aircraft noise technologies and procedures. Future work will furthermore include observer locations aside the flight ground track, departure procedures and different propulsion concepts, e.g., geared turbofan or propeller engines.

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