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Fluctuations by atmospheric turbulence in aircraft flyover auralisation

Dorothea Lincke[1], Reto Pieren[2]
Empa, Swiss Federal Laboratories for Materials Science and Technology
8600 Dübendorf, Switzerland

ABSTRACT

Long-term exposure to aircraft noise causes significant health issues among residents near airports. Therefore, noise impact assessments and noise control at the source are important aspects of the design of new aircraft. The design process of low-noise aircraft can be supported with auralisation of virtual flyovers. In order to render plausible aircraft auralisations, multiple propagation phenomena have to be considered, such as geometrical spreading, air absorption, Doppler effect, and reflections from the ground. Additionally, measurements of aircraft flyover show clear patterns of amplitude and phase fluctuations by atmospheric turbulence. Aircraft flyover auralisations should incorporate these clearly audible features of sound propagation in real-world conditions to be perceived as plausible. We present new approaches of time-variant filtering techniques to account for phase and amplitude fluctuations as a function of atmospherical conditions characterised by the von Kármán turbulence spectrum of wind and temperature fluctuations. Compared to earlier approaches, the proposed model is closer to the physical mechanisms. The application of the filters leads to a reduction of unnatural flanging and to a higher naturalness of level fluctuations. As the proposed method has shown to increase plausibility of aircraft flyover auralisation, its application in perception-based evaluation of future aircraft concepts is foreseen.

1. INTRODUCTION

Noise caused by civil aircraft can lead to annoyance, sleep disorders and cardiovascular diseases among residence near airports. Therefore, the design of low-noise aircraft has gained increasing attention in recent years, for example within in the European project ARTEM. A new concept for design processes of aircraft was introduced in [1] as "perception-influenced design". In this, the vehicle design is supported by auralisation. Auralisation is a method that allows data of non-existent situations to be made audible. Different designs can therefore be assessed before construction.

To provide plausible auralisation of aircraft, several propagation phenomena must be considered, such as geometrical spreading, air absorption, Doppler effect, and the ground effect. Ground effect is the interaction of the direct sound with the ground reflected sound. Additionally, meteorological effects caused by spatial fluctuations of temperature and wind should be considered in order to achieve convincing auralisations [2–5]. However, these effects have often been neglected in the past [6].

[1]dorothea.lincke@empa.ch

[2]reto.pieren@empa.ch

For aircraft auralisation, a simple approach to model coherence loss in ground effect has been proposed by Arntzen and Simons in 2014 [7]. The model is based on artificially attenuated ground reflected signals and artificially amplified direct signals. It is not based on physical processes and not extendable to situations with more than two propagation paths. We propose a new method, which is based on measurable meteorological parameters and a realistic turbulence characterisation by von Kármán turbulence spectra. A detailed description of the model was recently published in [8]. Further, we propose improvements to a model for turbulence-induced amplitude modulations in aircraft auralisation [3].

2. TURBULENCE INDUCED COHERENCE LOSS IN GROUND EFFECT

The coherence loss in ground effect can be described by the effect of the coherence factor C_{coh} on the total sound pressure of two interfering sound paths:

$$\left\langle p_{\mathrm{tot}}^2 \right\rangle = \frac{1}{r_{\mathrm{dir}}^2} + \frac{|Q|^2}{r_{\mathrm{gr}}^2} + C_{\mathrm{coh}} \frac{2\,|Q|}{r_{\mathrm{dir}} r_{\mathrm{gr}}} \cos\left(k\left(r_{\mathrm{gr}} - r_{\mathrm{dir}}\right) + \varphi\right) \tag{1}$$

with the spherical wave reflection factor Q with phase φ, the acoustic wave number k, and the propagation distances r_{dir}, r_{gr} of direct and of ground reflected sound, respectively. $C_{\mathrm{coh}} = 1$ represents full coherence with maximal constructive and destructive interference. In contrast, $C_{\mathrm{coh}} = 0$ results in a smooth frequency behaviour with incoherent summation of direct and ground reflected sound.

2.1. Von Kármán turbulence spectrum and parabolic equation method

In earlier studies turbulent fluctuations were considered based on Gaussian correlation functions of refractive index fluctuations [2, 9]. The theoretical foundation was laid by Daigle, Clifford, and Lataitis in [10] and [11]. Later it has been found that the Gaussian representation of turbulence spectra is insufficient for sound propagation in the atmosphere. An improved theoretical framework is presented in [12] and [13]. For a statistically isotropic random medium, the coherence factor is then expressed as [14]:

$$C_{\mathrm{coh}} = \exp\left\{-\pi^2 k^2 x_r \int_0^\infty \int_0^1 \Phi_{\mathrm{eff}}\left(0, \kappa\right)\left[1 - J_0\left(\eta \kappa h\right)\right] \kappa \, d\eta d\kappa\right\} \tag{2}$$

with k the acoustic wavenumber, x_r the propagation range, η is an integration variable, Φ_{eff} the effective turbulence spectrum, κ the turbulence wavenumber, J_0 the Bessel function, and h the maximum separation between the sound paths. For the von Kármán turbulence model, the effective turbulence spectrum Φ_{eff} is based on the turbulence scaling parameters friction velocity u_*, surface heat flux Q_H, on the Obukhov length L_o, and on the boundary layer height z_i.

The appropriate choice of turbulence scaling parameters makes it possible to take into account different meteorological conditions. Figure 1 shows the frequency dependent coherence factor for different propagation ranges and friction velocities. The coherence factor changes dynamically during a fly-by because of its strong distance dependency. Therefore, the coherence factor becomes a function of frequency and time.

2.2. Coherence loss through signal decorrelation

As proposed in [8] the coherence loss is realised by applying a time-varying decorrelation filter. The filter is designed based on the coherence factor C_{coh} and on the approach described in [15]. The filter is energy-neutral and has the target frequency response

$$B(f) = e^{-j\beta(f)\phi(f)}, \text{ with } \phi \sim \; U\left(-\pi, \pi\right) \tag{3}$$

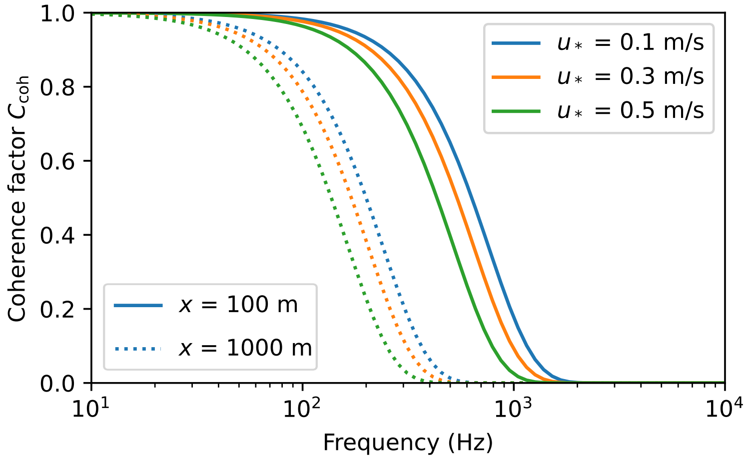

Figure 1: Coherence Factor C_{coh} for varying values of distance x and friction velocity u_*.

where ϕ is the uniformly distributed random phase. The scaling coefficient β can be directly related to the coherence factor using the approximation [8]:

$$\beta(f) \approx \beta_1(f) = (1 - C_{\mathrm{coh}})^{\frac{2}{3}} . \tag{4}$$

The decorrelation filter is implemented with an FIR filter. The FIR filter is designed in the frequency domain and then transformed using the inverse discrete Fourier transform (DFT) and the windowing method. For the FIR filter order N and using Equation 3 the filter frequency response $\check{B}$ is

$$\check{B}[n] = \begin{cases} B\left(f = n\frac{f_s}{N}\right), & \text{if } n < \frac{N}{2} \\ 1, & \text{if } n = \frac{N}{2} \\ B^*\left(f = (N-n)\frac{f_s}{N}\right), & n > \frac{N}{2} \end{cases} \tag{5}$$

$$= \begin{cases} e^{-j\beta\left(n\frac{f_s}{N}\right)\phi_n}, & \text{if } n < \frac{N}{2} \\ 1, & \text{if } n = \frac{N}{2} \\ e^{+j\beta((N-n)\frac{f_s}{N})\phi_{N-n}}, & n > \frac{N}{2} \end{cases} \tag{6}$$

leading to the FIR filter coefficients

$$b[m] = \frac{1}{N}\sum_{n=0}^{N-1} \check{B}[n] e^{j\frac{2\pi}{N}nm}, \quad m \in [0, N-1]. \tag{7}$$

Finally, b is zero-centered and windowed leading to a non-causal filter. We employed an audio sampling rate of $f_s = 48$ kHz and found $N = 2^{11}$ filter taps to be a suitable filter size. During an aircraft flyover auralisation, the filter coefficients are updated every 100 ms. A more detailed explanation can be found in the recently published paper [8].

2.3. Application to aircraft flyovers

Figure 2 shows the application of the filter to an auralisation in comparison to an aircraft flyover measurement. The first subfigure shows the baseline auralisation without application of the decorrelating filter. The second subfigure shows the auralisation after application of the new filter. The third shows the measurement of the recreated situation.

The landing was measured in August 2013 at height $h_r = 10$ m above flat, grassy ground. At shortest distance to the microphone, the aircraft travelled with a ground speed of 260 km/h at a height of h_s = 95 m above ground. At 2 m above ground, air temperature was 16.3°C, relative humidity 80% and wind speed u = 0.9 m/s. Air temperature 5 cm above ground was 18.9°C.

The auralisation procedure is based on [3]. The meteorological parameters have been retrieved from the ECMWF (European Centre for Medium-Range Weather Forecast) reanalysis data provided by Copernicus Climate Change Service (C3S) Climate Data Store (CDS) [16]. Following values were retrieved: Q_H = 150 W/m^2, u_* = 0.25 m/s, z_i = 1200 m.

The desired effect is visible especially for frequencies above 500 Hz and $t < 15$ s, as well as for $t > 25$ s. After the application of the coherence loss filter, distinct regular ground effect patterns are dissolved while they remain intact for lower frequencies and at instances with shorter propagation distances. The same behaviour is visible in the measurement. The model is able to adequately predict the coherence loss in ground effect using independent meteorological measurements. The synthesis is thus considerably improved by the proposed coherence loss simulation.

2.4. Perceptual evaluation

The model was perceptually evaluated by expert listeners under laboratory conditions in AuraLab at Empa. For this, two aircraft flyovers of an Airbus A320 were synthesised with and without coherence loss in ground effect. A two-alternative forced choice (2AFC) test was performed in which participants compared two synthesised sounds to the measured reference sound. The syntheses were the baseline auralisation without consideration of coherence loss and the auralisation including the proposed coherence loss simulation. The participants had the task to rate whether sample A or B sounds more similar to the measured reference. The order of presentation was randomized per participants. The expert listeners chose in 14 out of 16 trials ($\check{p}$ = 87.5%) the simulation with coherence loss. For participants without expertise in aircraft auralisation the results were less clear. Due to overall broadband and tonal differences to the reference, naive listeners were not able to discriminate A and B in all times. Clearer results are expected for syntheses of more turbulent situations, as the situations considered in the experiment included only low-turbulence situations.

3. AMPLITUDE MODULATION

3.1. Distance dependent modulation spectrum

To account for amplitude modulations by atmospheric turbulence in the auralisation of elevated sources, a semi-empirical approach was introduced in [17] and [3]. Amplitude modulation is modeled by a high shelf filter with a distance-dependent transition frequency and a random, time-dependent gain. The modulation spectrum is assumed to be constant. However, analyses of flyover data show a distance dependency of the modulation spectrum. Exemplarily, Figure 3 shows measured high frequency level fluctuations of a jet aircraft flyover under moderately turbulent conditions. Moreover, the semi-empirical approach does not take into account different meteorological conditions that can be characterised by the above parameters u_*, Q_H, z_i, and L_o. These parameters determine the variance of amplitude fluctuations. Theoretical descriptions can be found in [14] and [18]. Auralisations of aircraft flyovers will be improved by using a model of amplitude modulations considering these features. By this, the method will be based on physical mechanisms and be easier to generalise to different situations.

4. CONCLUSIONS

This contribution presents a simple approach to improve aircraft flyover auralisations by consideration of the turbulence-induced coherence loss in ground effect. The proposed model is based on a time-variant partial decorrelation filter. Atmospheric fluctuations are represented by the von Kármán turbulence spectrum, which is closer to the physical mechanisms compared to earlier approaches.

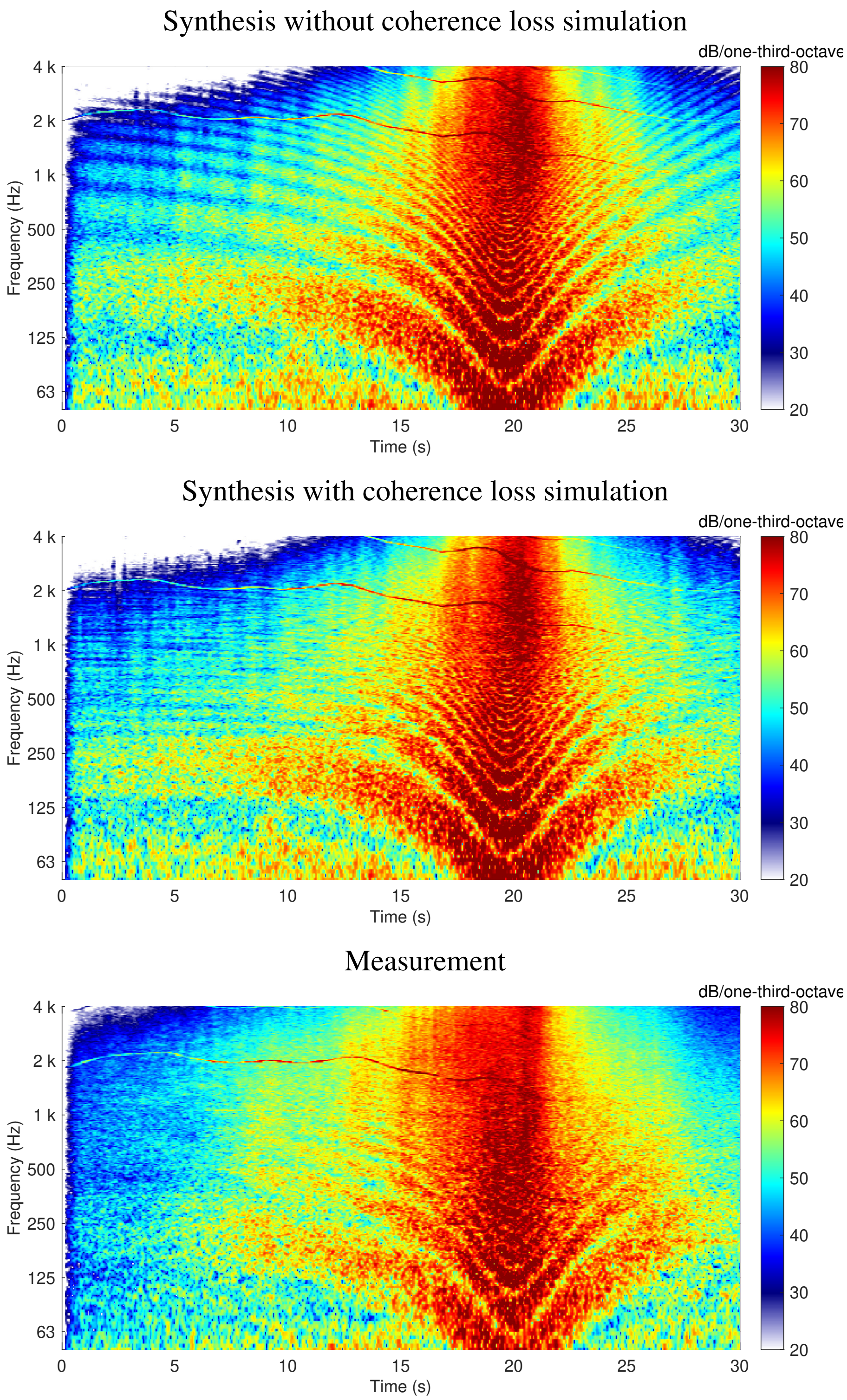

Figure 2: Sound pressure spectrograms of an Airbus A340 during landing. Microphone height h_r = 4 m over grassy flat ground. Aircraft at height h_s = 95 m above terrain and travelling with speed of 260 km/h at shortest propagation distance. The effect of the coherence loss simulation can be well observed for frequencies above 500 Hz and t < 15 s, as well as for t > 25 s.

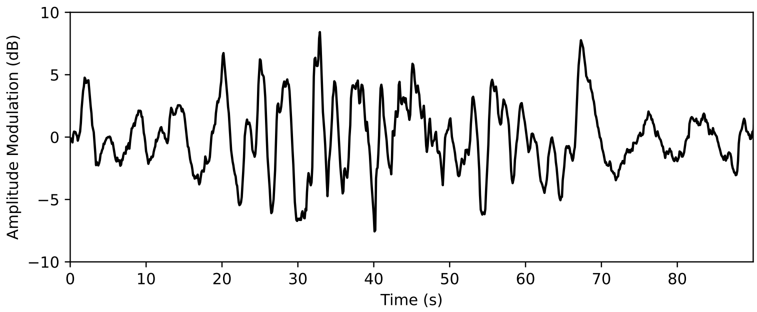

Figure 3: Sound level fluctuations in the frequency band 500-1500 Hz of an A321 aircraft flyover during landing. The measurement was taken in the morning under moderately turbulent conditions. The modulation frequency is higher at short propagation distance, i.e. around the instant of direct overflight at 42 s.

The application of the model and the perceptual evaluation revealed audible improvements. The reduction of unnatural flanging was audible for experts. However the effect of the filter was not apparent for naive listeners. This is likely due to the fact, that the included evaluation syntheses considered only situations with low atmospheric turbulence and that there were distinct spectral differences between the syntheses and the recording. Further validations will therefore be necessary with a larger variance in different atmospheric conditions.

The proposed model for coherence loss in ground effect will be used by the authors in auralisations of future aircraft concepts. The model will moreover be extended to consider distance-dependent amplitude modulations, which can be adapted to desired meteorological conditions.

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