Auralization of aircraft noise in an urban environment

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ABSTRACT

Aircraft noise is a major issue in urban areas and is one of the research topics within the FP7 SONORUS project. Current methods for determining the impact of aircraft noise on annoyance and sleep disturbance are based on energetic quantities disregarding the dynamic character of the sound. To obtain a more complete representation of annoyance, one should predict the audible aircraft sound and determine the impact of the aircraft sound on people.

A tool was developed to auralize aircraft noise. The propagation model includes, aside from the typically considered propagation effects like Doppler shift and ground reflection, also amplitude and phase modulations due to atmospheric turbulence. Depending on parameters that are used to describe the atmospheric turbulence, the amplitude modulations result in clearly audible modulations and vertical peaks in a spectrogram. The phase modulations cause additional decorrelation.

An inverse propagation model and an automated procedure to extract features to describe aircraft emission was developed. Validation of the features was done through listening tests where listeners were asked to rate both recordings and auralizations based on the extracted features and with the use of the propagation model.

Keywords: Auralization, Aircraft

1. INTRODUCTION

A tool is in development to investigate annoyance and sleep disturbance due to aircraft noise. A propagation model was developed that includes a novel method to take into account fluctuations due to atmospheric turbulence (1, 2). Furthermore, an automated procedure to analyze the emission of aircraft was developed (3).

Backpropagation is used to obtain the instantaneous sound pressure close to the receiver. The emission was analyzed on tones and noise, both as function of time. Recordings and other data obtained in the sonAIR project are used for this purpose (4). A preliminary listening test was conducted to check whether the chosen features were sufficient to generate the emission signal.

It should be emphasized that the tool was developed to investigate annoyance and sleep disturbance. Therefore, the auralizations should be rated the same as recordings with respect to these two effects. While it is desirable to create auralizations that are indistinguishable from recordings, this was not a design goal.

2. PROPAGATION MODEL

The propagation model takes into account geometrical spreading, Doppler shift, atmospheric attenuation and the ground reflection. Furthermore, a model was developed to include scintillations, that is, fluctuations due to atmospheric turbulence.

2.1 Geometrical spreading

Geometrical spreading causes a decrease in amplitude with distance and increase in propagation delay with distance due to the limited speed of sound. Far field is assumed in which case we obtain the sound pressure at

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the receiver p_{rcv} by scaling the magnitude of the sound pressure p_{src} at some other distance from the source r_{src}

$$p_{rcv} = p_{src} \frac{r_{src}}{r_{rcv}} \tag{1}$$

The propagation delay, which is relevant for the Doppler shift, is taken into account by resampling the discretized sound pressure signal. For a given sound travel time $\Delta t(t)$ from source to receiver. A Variable Delay Line (VDL) was created that uses Lanczos interpolation (3). The Lanczos kernel is given by

$$L(z) = \begin{cases} \mathrm{sinc}(z)\mathrm{sinc}(z/a), & \text{if } -a < z < a \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

where a is the size of the kernel. Consider now a signal with samples s_i for integer values of i where sample s_i corresponds to the sample at $t = i/f_s$. The value at retarded time t' is then given by

$$S(x) = \sum_{\lfloor x \rfloor - a + 1}^{\lfloor x \rfloor + a} s_i L(x - i) \tag{3}$$

where x is the sample at retarded time t'

$$x = -t' + i \tag{4}$$

2.2 Atmospheric attenuation

Atmospheric attenuation is accounted for by creating a filter of length n_{aa} with magnitude response calculated using ISO 9613-1:1993(5) and giving it linear-phase to make it causal. A single-sided spectrum is calculated as

$$H_{aa} = 10.0^{-d\alpha(f)/20} \tag{5}$$

where d is the source-receiver distance and $\alpha(f)$ the attenuation coefficient. The spectrum is real and even, and therefore the impulse response is real and even as well. After convolving the signal with the designed filter the first $n_{aa}/2$ samples were removed to account for the delay caused by the linear-phase.

2.3 Ground reflection

The ground reflection was included by computing a second propagation path. For the ground reflected path the same emission was used as for the direct path. A filter was included to take into account the transfer funtion of the ground. For the ground reflection the plane wave reflection coefficient was used

$$R = \frac{Z \cos\theta - 1}{Z \cos\theta + 1} \tag{6}$$

with the impedance Z calculated with Delany and Bazley's 1-parameter model

$$Z = 1 + 9.08 \left(\frac{1000 f}{\sigma} \right)^{-0.75} - 11.9 j \left(\frac{1000 f}{\sigma} \right)^{-0.73} \tag{7}$$

which is a function of flow resistivity σ.

2.4 Atmospheric turbulence

A model was developed to take into account fluctuations due to atmospheric turbulence (1, 2). As the aircraft moves through the turbulent atmosphere the refractive-index fluctuations are sampled by the waves propagating from source to receiver. The model considers a line-of-sight situation and assumes a frozen atmosphere. A Gaussian applied turbulence spectrum and spherical wavefront was assumed (6, 7).

The autocorrelation of the Gaussian spectrum is given by (7)

$$C = \frac{\Phi(\rho/L)}{\rho/L} \tag{8}$$

and determines the shape of the log-amplitude χ and phase fluctuations S spectra. Because of the Wiener-Khinchin theorem we can take the type-1 Discrete Cosine Transform (DCT-1) to obtain the shape of the autospectra.

The autocorrelation is a function of ρ, the spatial separation between two receivers, perpendicular to the wave propagation direction, and L, the correlation length. Instead of two non-moving receivers we're considering a moving source that samples the refractive-index fluctuations, and we therefore perform a space-to-time conversion to obtain $C(\tau)$ and $\rho = v_{\perp}\tau$ where $v_{\perp}$ is the speed of the aircraft perpendicular to the wave propagation direction.

Gaussian white noise is shaped with this spectrum through a convolution to obtain log-amplitude and phase fluctuations. Time-variancy of the speed is taken into account not by updating the filter but instead resampling the sequence of fluctuations using a Variable Delay Line (VDL).

At this point the fluctuations have a variance of 1. The fluctuations are scaled by the square root of the desired variances (7)

$$\sigma_{\chi}^2 = \sigma_S^2 = \frac{\sqrt{\pi}}{2}\sigma_{\mu}^2 k^2 dL \tag{9}$$

which are a function of the variance of the refractive-index fluctuations σ_{μ}^2, wavenumber k, source-receiver distance d and correlation length L. This scaling can be time-variant.

The fluctuations are relatively slow, and therefore a filter is constructed to apply the log-amplitude fluctuations as this also allows to include the frequency-dependency of the fluctuations as shown in equation 9. This filter is obtained by taking the Inverse Discrete Fourier Transform (IDFT) of $\exp(\chi)$. From equation 9 it also follows that the phase-fluctuations have a linear-phase. Therefore, the phase fluctuations are converted to a propagation delay fluctuation and applied with a Variable Delay Line (VDL).

3. EMISSION SYNTHESIS AND BACKPROPAGATION

An automated procedure was developed to backpropagate from source to receiver and analyze the resulting time-domain signal to extract features that could be used either to develop an emission model or to directly resynthesize the emission.

3.1 Backpropagation

The ground reflection is ignored for now and atmospheric attenuation, Doppler shift and geometrical spreading were corrected for in that specific order and using the methods as described in the previous section (3).

At that point a time-domain signal is obtained that corresponds to the emission of the aircraft, assuming the aircraft is a point source. Since even a soft ground is relatively hard a -3 dB correction was applied to account for the ground reflection.

3.2 Feature extraction

We're interested in synthesizing the emission of the aircraft using spectral modelling synthesis, that is, by a superposition of sines and noise. Therefore, we would like to obtain the frequency, phase, and level of the tones, as well as the level of the noise, spectrally. A tone detection algorithm (in frequency domain) based on ISO 1996-2:2007 Annex C (8) was developed. This tone-seeking algorithm as described in the standard did not prove sufficient to detect all tones. If we however assume that all tones are harmonics, which is typically the case with our emission, then we can use this knowledge in combination with the tone seeking algorithm results to detect all tones, and more precise as well.

The fundamental frequency is given by

$$f_0 = \mathrm{gcd}\left(f_1, f_2, \ldots, f_n\right) \tag{10}$$

where gcd is the *greatest common divisor*. Implementations of the gcd attempt to find an exact solution. However, due to errors in the estimate of the tones and because some tones are not harmonics, an exact solution would not exist. Given an initial estimate of the fundamental frequency, one could define an error as the sum of the squared deviation between the target order of the harmonics and the actual (inaccurate) order

$$e = \sum_{i=0}^{n}\left(\frac{f_i}{f_0} - \mathrm{round}\left(\frac{f_i}{f_0}\right)\right)^2 \tag{11}$$

An estimate of the fundamental frequency is obtained by minimizing this error.

In the method in the standard each spectral line is assigned a label, e.g. tone or noise. The results obtained with the enhanced method were fed back in the method of the standard to get labels for each spectral line. Per tone the lines corresponding to that tone were integrated to obtain a level.

A value for the phase could not be obtained because the signal was too noisy. Initially a random phase was chosen for each harmonic, but according to the authors this made the tones less sharp than they were in comparison to the recordings. Because the harmonics are Buzz-Saw noise, a phase corresponding to a sawtooth signal was assumed. This however did make the tones sound slightly too sharp. The lines that were assigned noise were integrated into fractional octaves and the obtained levels were kept.

3.3 Emission synthesis

As mentioned before the emission was synthesized using spectral modelling synthesis. With the extracted features, which were obtained as function of time and at several receiver positions, it is possible to develop an emission model that takes into account directivity.

An important question to ask at this point is whether the extracted features are sufficient. Therefore, for a listening test auralizations of emission and immission were made based on recordings. For a specific event and receiver, the immission was backpropagated and features were extracted. These features were directly used to synthesize the emission again. This signal was propagated to the receiver. The assumption was made that the emission is identical for the emission angles corresponding to direct and reflected path.

4. LISTENING TESTS

A preliminary listening test was done to check whether the chosen features and the synthesis method were sufficient to describe the emission and to obtain additional feedback to improve the auralizations. This feedback was used to further improve the model. A final listening test is planned.

4.1 Preliminary listening test

For the preliminary listening tests auralizations were created as described before. Fluctuations due to turbulence were however not included. The listening test consisted of three parts.

In the first part participants were presented with individual stimuli and were asked 1) whether they believed the stimuli to be a real event, and 2) to rate on an 11-points scale how realistic the sound was to them. The stimuli consisted of a mixture of recordings and auralizations and each actual event was included twice, once as auralization, and once as recording.

In the second part participants were presented with the same stimuli, but now presented in pairs. Each pair consisted of a recording and an auralization corresponding to the same event. They were asked again two questions, 1) to choose which one they believed to be the recording, and 2) to rate on an 11-points scale how similar the two stimuli were.

The third part consisted of several open questions, and one of them was whether there were specific features they noticed they could use to discriminate between auralizations and recordings.

The listening test consisted of 11 participants, and the participants took the test simultaneously and using headphones. All stimuli were recordings and auralizations of an Airbus A320 taking off from Zurich Airport.

5. RESULTS

In the first part of the preliminary listening test 80% of the participants correctly identified recordings as such. Furthermore, 20% of the auralizations were identified as recordings. In the second part, the direct comparison, 85% was identified correctly. While at times the participants mistook auralizations for recordings and vice versa, it would seem there were differences they could use to identify whether a stimuli was a recording or an auralization.

The annoyance ratings for the auralizations were overall higher than those given for the recordings. In the similary ratings no trend was observed.

Participants mentioned they found some of the stimuli that they believed to be auralizations sound sharp or 'metallic'. The authors believe this is related to the initial phase of the harmonics which was now chosen to correspond to a sawtooth signal. It is expected that decorrelation due to atmospheric turbulence might reduce this effect.

6. CONCLUSION

A tool to create auralizations of aircraft was developed. A propagation model was developed that could also be used for backpropagation. Novel in the propagation model is a method to include fluctuations due to atmospheric turbulence.

The backpropagation model was used to backpropagate to the assumed point source, which, when combined with a custom feature-extraction algorithm was used in an automated way to extract features from the aircraft emission.

A preliminary listening test was conducted to test whether the synthesis method as well as the features proved sufficient to create plausible auralizations. From this listening test it would seem that there was noticeable difference between the auralizations and the recordings. A difference in annoyance ratings between auralizations and recordings were observed, with the auralizations being rated as more annoying. It is expected that including fluctuations due to atmospheric turbulence will improve the quality of the auralizations.

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