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AMPLITUDE MODULATIONS IN AIRCRAFT FLYOVER MEASUREMENTS BY ATMOSPHERIC TURBULENCE IN CONVECTIVE ATMOSPHERIC BOUNDARY LAYERS

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ABSTRACT

Aircraft noise in the vicinity of airports is influenced by meteorological conditions. Turbulent fluctuations of temperature and wind velocity in the atmospheric boundary layer lead to amplitude modulations (AM) of aircraft noise at the ground. This study presents an analysis of turbulent AMs for a large number of aircraft flyovers measured around Zurich airport. Takeoffs of aircraft from the Airbus A320 family are considered. Acoustical measurements were supplemented by meteorological measurements. In addition, estimations of atmospheric boundary layer heights and of surface sensible heat flux were included in the analysis. The estimates are based on the hourly reanalysis dataset ERA5 provided by the Climate Data Store. Standard deviations of AMs showed approximately normal distributions with mean values of about 2 dB. The values exhibit a clear diurnal cycle following the development of the atmospheric boundary layer height. The analysis revealed strong correlations of the standard deviations and modulation spectra of the AMs with the atmospheric boundary layer, mean temperature, surface sensible heat flux, and wind speed. The presented study will provide useful information for plausible auralizations of aircraft flyovers considering different meteorological conditions.

Keywords: *aircraft noise, atmospheric turbulence, statistical analysis*

1. INTRODUCTION

Aircraft noise in the vicinity of airports is influenced by meteorological conditions. Turbulent fluctuations of temperature and wind velocity in the atmospheric boundary layer lead to amplitude modulations (AM) of aircraft noise at the ground. This publication presents a statistical analysis of turbulent AM based on a large dataset of acoustical and meteorological measurements conducted around Zurich airport.

The results will be a valuable basis for the synthesis of plausible aircraft auralizations considering meteorological conditions. Plausible auralizations are required for applications like perception-influenced aircraft design and noise impact studies in laboratories [1].

The here presented analysis targets standard deviations and modulation spectra of amplitude fluctuations of aircraft flying during conditions of convective atmospheric turbulence.

2. DATA ACQUISITION

2.1 Audio data

The measurements were conducted during the day in June and July 2014 in the vicinity of Zurich airport within the sonAIR measurement campaign [2]. The terrain of the measurement was mostly flat. A total number of 907 takeoffs from aircraft of the Airbus A320 family have been measured. The flight trajectory is recorded via radar data recording. The minimal distance between the trajectory of the aircraft and the microphone is on average $1270\,\mathrm{m}$ with a standard deviation of $128\,\mathrm{m}$.

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2.2 Meteorological data

Meteorological data was measured simultaneously on the ground at Zurich airport. Measured variables included temperature and wind speed. During the measurement campaign, the temperature ranged from 9 °C to 32 °C with a mean of 20.4 °C. The wind speed ranged from 0.2 m/s to 3.9 m/s with an average of 1.9 m/s.

In addition, estimations of atmospheric boundary layer heights and of surface sensible heat flux were included in the analysis. The estimates are based on the hourly reanalysis dataset ERA5 provided by the Climate Data Store [3]. The hourly data was interpolated to match the time of the flyover event.

The meteorological variables which are included as independent variables in the presented analysis are listed in table 1.

Table 1. Meteorological variables included in the analysis.

$T_{5\mathrm{cm}}$ (°C)	Temperature at $5\,\mathrm{cm}$ above ground
$T_{2\mathrm{m}}$ (°C)	Temperature at $2\,\mathrm{m}$ above ground
u (m/s)	Wind speed at $2\,\mathrm{m}$ above ground
Q_H (W/m^2)	Mean surface sensible heat flux
z_i (m)	Boundary layer height

3. AUDIO DATA PREPARATION

The audio recordings are pre-processed and converted into key values which can be used for statistical analysis.

3.1 Pre-processing

Based on the known trajectory, the sound pressure measurements are back-propagated by de-dopplerization and compensation for geometrical spreading. The resulting audio data is bandpass filtered from 200 to 1500 Hz. The sound pressure level time history $L_p(t)(\mathrm{dB})$ is determined using a $0.5\,\mathrm{s}$ Hann window. Next, the moving average is computed by convolution with a Hann window of $15\,\mathrm{s}$ length. The moving average is subtracted from the sound pressure level time history resulting in a time series of amplitude modulation. For further analysis only a time window of $20\,\mathrm{s}$ of the amplitude fluctuation time series is used. The time window is centered symmetrically around the moment of shortest distance between microphone and aircraft in the de-dopplerized measurement. Figure 1 shows an example AM time series.

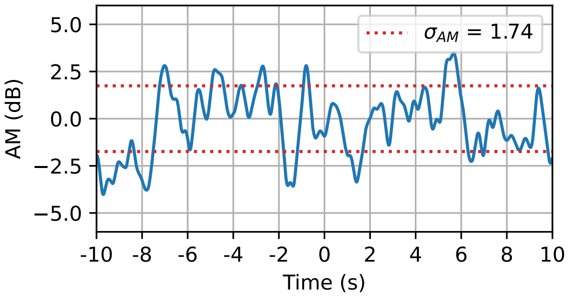

Figure 1. Time series of amplitude modulation for a single flyover measured 09:20 hrs. In this example, $T_{2\mathrm{m}} = 16.1\,°\mathrm{C}$, $u = 1.7\,\mathrm{m/s}$, $z_i = 1271\,\mathrm{m}$, $Q_H = 145\,\mathrm{W/m^2}$.

3.2 Dependent variables for statistical analysis

For the statistical analysis of the sound pressure measurement, key values are extracted from the AM to be used as independent variables. To characterize the strength of the AM, the standard deviation σ_{AM} is determined. Further, the modulation spectrum of the standard deviation is determined for the octave band filtered AM from $0.5\,\mathrm{Hz}$ to $4\,\mathrm{Hz}$. In the following, only values for the $1\,\mathrm{Hz}$ octave band are reported.

4. STATISTICAL ANALYSIS

4.1 Data distribution

Fig. 2 and Fig. 3 show histograms and quantile-quantile plots of the total standard deviation σ_{AM} and of the standard deviations of the octave band filtered AM $\sigma_{\mathrm{AM,1Hz}}$. In Fig. 2, the distribution of σ_{AM} probably shows a distortion for $\sigma_{\mathrm{AM}} \leq 1\,\mathrm{dB}$ because of undesired fluctuations in background noise. Therefore, very low values $\sigma_{\mathrm{AM}} \leq 0.5\,\mathrm{dB}$ are missing whereas values between $0.5\,\mathrm{dB}$ and $1\,\mathrm{dB}$ appear to be more frequent compared to an ideal normal distribution. Consequently, the quantile-quantile plot shows slight deviations from the ideal line.

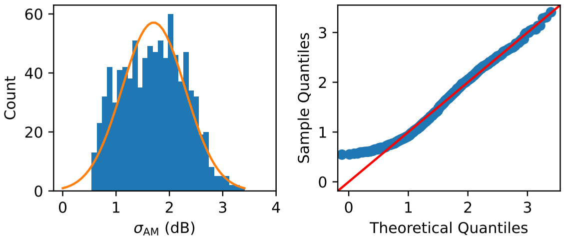

Figure 2. Histogram for standard deviation of AM. Solid line indicates theoretical values of an ideal normal distribution.

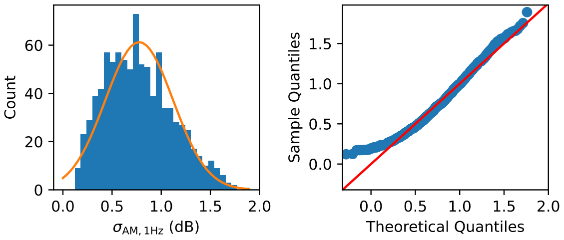

Figure 3. Histogram of 1 Hz octave band of the AM. Solid line indicates theoretical values of an ideal normal distribution.

4.2 Correlation analysis

The visual representation of the relation between σ_{AM}, the time of the day, and the boundary layer height z_i in Fig. 4 reveals a clear diurnal cycle connected to the height of the atmospheric boundary layer. Dark (purple) dots represent measurements during states of low boundary layer heights. Light (yellow) dots indicate large boundary layer heights.

Table 2 presents correlation coefficients for σ_{AM} and $\sigma_{\mathrm{AM,1Hz}}$ with the independent meteorological variables. The boundary layer height z_i is strongly correlated to σ_{AM}.

Table 2. Pearson correlation coefficients r rounded to the second decimal. All coefficients are significant with p-values $\ll 0.001$.

	T_{5cm}	T_{2m}	u	z_i	Q_H
σ_{AM}	0.61	0.44	0.44	0.70	0.54
$\sigma_{\mathrm{AM,1Hz}}$	0.48	0.32	0.36	0.52	0.46

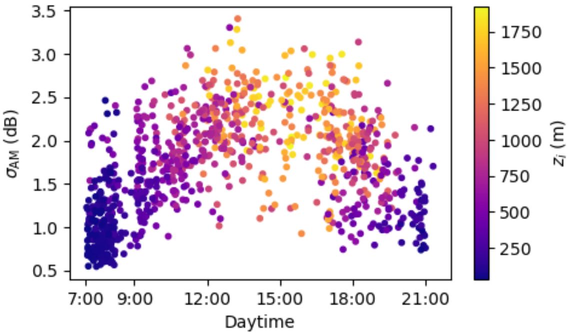

Figure 4. Relation between standard deviation of AM σ_{AM}, time of the day and estimated boundary layer height z_i.

4.3 Multiple linear regression

Due to high multicollinearity between the independent variables, it is not advisable to include more than two independent variables into the multiple linear regression analysis. Similarly, the combination of any variable with the boundary layer height z_i leads to high multicollinearity. Thus, only T_{5cm} and u are included, as they show a weak correlation ($r = 0.20$) and are easily accessible in field measurements.

4.3.1 Regression model for σ_{AM}

The fitted regression model for σ_{AM} is:

$$\sigma_{\mathrm{AM}} = 0.23 + 0.04 \cdot T_{\mathrm{5cm}} + 0.21 \cdot u. \tag{1}$$

The overall regression is statistically significant. The model explains $47\,\%$ of the variation in σ_{AM} ($R^2 = 0.472, F(2, 904) = 404.5, p \ll .001$). It was found that T_{5cm} and u significantly predicted $\sigma_{\mathrm{AM,1Hz}}$ ($T_{\mathrm{5cm}} : \beta = 0.54, p \ll .001$. $u : \beta = 0.31, p \ll .001$). The resulting regression plane is shown in Fig. 5.

4.3.2 Regression model for $\sigma_{AM,1Hz}$

The fitted regression model for $\sigma_{\mathrm{AM,1Hz}}$ is:

$$\sigma_{\mathrm{AM,1Hz}} = 0.09 + 0.02 \cdot T_{\mathrm{5cm}} + 0.10 \cdot u. \tag{2}$$

The overall regression is statistically significant. The model explains $30\,\%$ of the variation in $\sigma_{\mathrm{AM,1Hz}}$ ($R^2 =$

$0.303, F(2,904) = 196.2, p \ll .001)$. It was found that $T_{5\text{cm}}$ and u significantly predicted $\sigma_{\text{AM,1Hz}}$ ($T_{5\text{cm}} : \beta = 0.41, p \ll .001$. $u : \beta = 0.26, p \ll .001$).

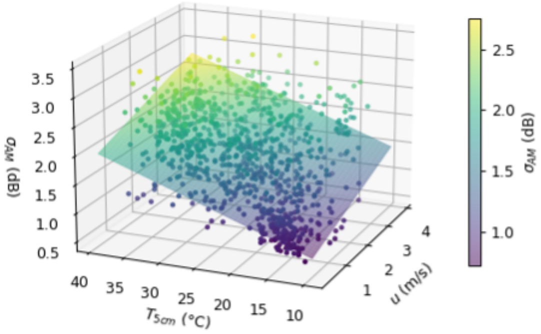

Figure 5. Visualization of multiple regression analysis for σ_{AM}

5. CONCLUSION

Field measurements of aircraft flyovers were statistically analyzed to establish a relationship between turbulent amplitude modulations in the acoustical and meteorological measurements of wind speed and temperature at one exemplary measurement location. The amplitude modulations were characterized by the total standard deviation of the level fluctuations σ_{AM} and by the standard deviation of the 1 Hz octave band $\sigma_{\text{AM,1Hz}}$. The aircraft flyover auralization in [4] used a value of $\sigma_{\text{AM}} = 3$ dB which seems to be a reasonable, but rather high representative value. The presented analysis reveals a large spread of σ_{AM} due to its dependence on the meteorological conditions. However, σ_{AM} exhibits a clear diurnal cycle and is highly correlated to the boundary layer height z_i.

The presented analysis is part of a larger analysis of long-term measurements including multiple measurement locations with varying source heights and varying meteorological conditions.

Future analysis will as well consider field measurements of turbulent scaling parameters captured with an ultrasonic anemometer.

The results of this study will improve the auralization of plausible aircraft flyovers by considering realistic meteorological conditions and the effect of atmospheric turbulence. Further, they allow to estimate level fluctuations in field measurements based on meteorological parameters, which can be easily determined or retrieved from the ERA5 dataset.

6. ACKNOWLEDGMENTS

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