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Geo-referenced flight path estimation based on spatio-temporal information extracted from aircraft take-off noise

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ABSTRACT

The closer proximity between airports and residential areas has created a growing attention regarding noise pollution. The noise abatement procedures established by the aeronautical authorities and the models for computing noise contours around airports are proof of that. There are also models for identifying aircraft taking off which have focused on the correlation between the aircraft position and the noise signal. However, this correlation has been made so far without spatial information. The present study proposes a method to estimate the geo-referenced flight path followed by an aircraft taking off, using the spatio-temporal information extracted from the noise signal and improved with a smoothing algorithm. A microphone array with twelve sensors is used in order to evaluate different sensor spacings and the spatial aliasing effect when working with take-off noise signals. The flight path estimation method assumes that the aircraft is following a ground track collinear to the runway and was compared against radar information and Automatic Dependent Surveillance-Broadcast (ADS-B) data. The average method accuracy was between 3 and 6 meters. The estimated flight path has a ground length of about two kilometers, including locations at least one kilometer apart from the measurement point.

1. Introduction

Aircraft noise has become a major issue at airports, which arises from growing air traffic, the airport expansion necessity and the closer proximity of residential areas (ICAO [12]). Many studies related with aircraft noise impact have been conducted to highlight the extent of the problem such as Clark, Head and Stansfeld [4], Givoni and Rietveld [10], Montazami, Wilson and Nicol [22].

Knowledge of aircraft type operating is a major requirement to estimate the acoustical impact of an airport on the community. It is a mandatory entry for both, models computing noise contours around airports such as ECAC [7], FAA [8], ICAO [11] and aircraft noise certification procedures. The flight path is also required as there are several elements that depend on the aircraft position with relation to the observer, such as lateral attenuation, that is determined by the airplane bank angle, the elevation angle and the lateral distance to the receiver (Plotkin, Hobbs and Bradley [28], SAE [31,32]). The current methods for computing noise contours around airports do not use the take-off noise signal, instead they use a default acoustic profile by aircraft type and expected operational conditions. Moreover, the vast majority of airport noise monitoring systems use the signal only to compute some statistical indicators such as the equivalent continuous noise level (DGAC [5], Jones and Pagdin [16], MASSPORT [21], TNO [38]).

Recently, a new computational model to identify aircraft class based on take-off noise signal segmentation in time was introduced by Sánchez-Pérez, Sánchez-Fernández, Suárez-Guerra and Carbajal-Hernández [36]. The model, that clearly improves the classification process over previous works such as Rojo, Sánchez, Felipe and Suárez [30], Sánchez-Fernández, Sánchez-Pérez, Carbajal-Hernández and Rojo-Ruiz [35], starts from the basis that aircraft noise is a non-stationary process that varies in frequency during a take-off and proposes a segmentation in time to attempt correlating the aircraft position with the noise signal. With the aim of obtaining this correlation accurately, the present study proposes a method to estimate the geo-referenced flight path followed by an aircraft taking off, by means of spatio-temporal information extracted from the noise signal measured with a microphone array

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Table 1
Relation between the sensor spacing and the maximum analyzable frequency, using sound speed of 343 m/s and sampling rate of 51 200 Hz.

Sensor spacing (cm)	Maximum detectable samples	Angular resolution (°)	Maximum analyzable frequency (Hz)
5	7.5	24.1	3420
10	14.9	12.1	1715
15	22.4	8.0	1143
20	29.9	6.0	858
30	44.8	4.0	572
35	52.2	3.4	490
40	59.7	3.0	429

and the fact that the aircraft ground track is collinear to the runway in the earliest stage of take-off.

This work is presented in six sections. Section 2 provides a detailed description of the measurement system, including the microphone array design. Section 3 introduces the spatio-temporal information extraction and improvement algorithm, also giving a profound evaluation of different sensor spacing. Section 4 presents the flight path estimation process and a detailed review of the spatial aliasing effect when working with take-off noise signals. Section 5 gives the method evaluation and the results discussion, followed by the conclusions drawn in Section 6.

2. Measurement system

Sound source localization by means of noise signal measurements requires using a microphone array, which allows signal direction-of-arrival (DOA) estimation. The key parameters of a microphone array are the microphone number, the array geometry and the sampling rate (Genescà, Romeu, Arcos and Martín [9], Kuo, Veltin and McLaughlin [19]).

2.1. Array specifications

The array geometry design involves selecting the adequate sensor spacing, which is directly related to angular resolution. As the distance between sensors increases, it is possible to detect lower angular changes and therefore a better angular resolution is achieved. However, the increase in distance leads to a decrease in the maximum frequency analyzable, which may result in information loss about the signal of interest. The latter restriction exists due to a common problem known as spatial aliasing.

Another significant element is the sampling rate. If sound speed c remains the same, as well as the distance d between a microphone pair, but the sampling rate Fs is increased, more samples can be taken during the time interval that the sound wave takes to propagate from one microphone to another. Therefore a better angular resolution is achieved since more samples can be used to spatially map the position of the source. In this work, a sampling rate of 51 200 Hz was used, the highest allowed by the equipment used.

Table 1 depicts the abovementioned using sound speed $c = 343$ m/s. The maximum detectable samples m, refer to the highest number of samples that can be taken at a sampling rate Fs, during the time interval the sound wave takes to travel the distance d between a sensor pair. This quantity can be obtained as $m = (d/c)Fs$. The angular resolution is $180/m$ and the maximum analyzable frequency is $f = c/2d$, which is also a restriction due to the spatial aliasing.

2.1.1. Spatial aliasing

In array processing, if the signals coming from sources at different locations are not spatially sampled by the sensors array densely enough, i.e. the inter-element array spacing is too large, these will produce the same output and their positions cannot be uniquely determined based on the array signals received (Benesty, Chen and Huang [1], Liu and Weiss [20]).

For signals having the same angular frequency w and the corresponding wavelength λ, but different DOA θ_1 and θ_2 satisfying the condition $(\theta_1, \theta_2) \in [-\pi/2\ \pi/2]$, aliasing implies that the array response vectors for each signal $\boldsymbol{d}(\theta_i, w)$ are equal. Therefore, $\boldsymbol{d}(\theta_1, w) = \boldsymbol{d}(\theta_2, w)$, which leads to expression (1).

$$e^{-jw\tau_m(\theta_1)} = e^{-jw\tau_m(\theta_2)} \tag{1}$$

where τ_m is the propagation delay for the signal from sensor 0 to sensor m, which is a function of θ_i. For a uniformly spaced linear array with an inter-element spacing d, $\tau_m = m\tau_1 = m(d\sin\theta_i)/c$ and $w\tau_m = m(2\pi d \sin\theta_i)/\lambda$, where c is the sound speed. Consequently, the expression (1) changes to expression (2).

$$e^{-jm(2\pi d \sin\theta_1)/\lambda} = e^{-jm(2\pi d \sin\theta_2)/\lambda} \tag{2}$$

In order to avoid spatial aliasing, the condition $|2\pi(\sin\theta_i)d/\lambda|_{\theta_i=\theta_1,\theta_2} < \pi$ has to be satisfied. Then, $|d/\lambda(\sin\theta_i)| < 1/2$. Since $|\sin\theta_i| \leqslant 1$, this requires that the array distance d should be less than $\lambda/2$. According to the Nyquist sampling theorem, two samples are required for every period of the highest signal frequency Fourier component. In this case, two spatial samples are needed for every wavelength, making the element spacing $d \leqslant \lambda/2 = c/2f$, this result may be interpreted as a spatial sampling theorem (Benesty et al. [1], Chandran [3], Liu and Weiss [20]). It has been shown that a spacing that exceeds one-half wavelength produces ambiguity errors in DOA estimation algorithms. A detailed analysis of the spatial aliasing effect on take-off noise measures conducted in this study is presented in Section 4.1.

2.1.2. Array architecture approach

Based on sensor spacing limitations and their relationship to the angular resolution and maximum analyzable frequency, we state that twelve microphones arranged in a three-dimensional array is more than the minimum required to estimate the geo-referenced flight path of an aircraft taking off.

In order to verify the abovementioned, the following methodology was defined:

- Create a microphone array prototype, including the measurement system for sampling the signals in real time.
- Create a method to extract spatial information from the real time take-off noise measurements.
- Create a method to generate a geo-referenced flight path using the extracted spatial information.
- Evaluate microphone spacing with respect to the estimation accuracy.
- Evaluate the spatial aliasing effect on real time take-off noise measurement using different microphone spacing.

2.2. Architecture and operation

Several researches have shown that aircraft take-off noise relevant frequencies are below 3000 Hz, which are also used to identify between aircraft classes that include propeller-driven and jet aircrafts (Rojo et al. [30], Sánchez-Fernández et al. [35], Sánchez-Pérez et al. [36]). Bearing this in mind, a microphone array with three axes collinear with the x, y and z axes from the Cartesian coordinate system, was defined. Accordingly, four microphones were arranged for each axis, comprising distances from 5 to 40 cm and allowing analyzing frequencies up to 3430 Hz. Fig. 1(a) shows the arrangement for the x and z axes and Fig. 1(b) the arrangement for y axis.