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Aircraft localization using a passive acoustic method. Experimental test

Sara R. Martín [a,*], Meritxell Genescà [b], Jordi Romeu [a], Arnau Clot [a]

[a] *Laboratory of Acoustics and Mechanical Engineering (LEAM), Universitat Politècnica de Catalunya, C/Colom 11, 08222 Terrassa, Spain*
[b] *Acoustics Research Centre, Department of Electronics and Telecommunications, Norwegian University of Science and Technology, Trondheim, Norway*

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ABSTRACT

A passive acoustic method for aircraft localization is experimentally tested in this paper. The method relies on the Doppler effect influencing the signals received by a mesh of microphones distributed over the acoustic area of interest. The relative Doppler stretch factors between the microphone signals are estimated using a one-dimensional version of the Ambiguity function. Then, a Genetic Algorithm is used to solve the non-linear system of equations that relates the aircraft's position and velocity to this relative stretch factors. This method is used in this study to locate a radio controlled airplane equipped with a Global Positioning System (GPS). Seven microphones are distributed in the airfield area. Although the localization errors are influenced by the uncertainty in the microphones position, the acoustic system succeeds at locating the airplane.

1. Introduction

The interest in passive acoustic aircraft localization systems arises when the performance of RADAR systems is reduced such as non-line-of-sight tracking or when electromagnetic radiation is present. Acoustic aircraft localization systems can also be a cheaper alternative in small airports and, in addition, the data from the acoustic sensors can also be processed for source classification or noise monitoring purposes.

Several acoustic methods have been developed to determine the motion parameters such as height and speed of both jet and propeller driven aircraft flying in a straight line at constant flight level and speed. The methods developed for propeller driven aircraft take advantage of the Doppler effect and require one single microphone [1–3] or a distributed array of microphones [4]. The methods developed for jet aircraft use the time differences between microphones in a microphone array [3,5], the interference between the direct and ground reflected sounds [6,7] or both [8].

Other techniques are used for the 3D localization of maneuvering aircraft without limitations on the trajectory. For a low altitude aircraft, the sound wavefronts can be considered spherical and the bearing and distance of the aircraft can be estimated with a planar microphone array [9]. At larger distances, the front waves become planar and only the bearing can be obtained with a microphone array. Under these circumstances, a possible approach is to use a distributed network of nodes – a node being in this context a single acoustic sensor or a set of several acoustic sensors – where every node provides an estimate of the aircraft bearing. The 3D position of the aircraft can be calculated afterwards by triangulation of the bearing estimates from, at least, two nodes. Such an approach has the benefit that only the bearing data has to be transmitted to a central processing unit, but the disadvantage is that the nodes are complex systems such as microphone arrays [10–13] or, more recently, acoustic vector sensors [14].

An alternative approach to passive acoustic 3D localization that uses a network of single microphones was initially described in [15,16]. The methods were based on the estimation of time delay between the signals at the different microphones, and therefore they only obtain the bearing of the aircraft.

In contrast, the method used in the present paper relies on both the time delay (retardation effect) and the time stretch (Doppler effect) [17,18] to obtain the source position and velocity. Seven microphones are distributed on the ground within the acoustic area of influence of the moving sound source. This acoustic method for aircraft localization is experimentally tested in this paper.

The rest of the paper is organized as follows. Section 2 describes the acoustic localization method, Section 3 presents the experimental setup and describes the parameters used in the implementation of the algorithm for the test, Section 4 shows the experimental results, Section 5 discusses different sources of errors, and finally Section 6 summarizes the main findings of this paper.

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* Corresponding author.
E-mail address: sara.martin@upc.edu (S.R. Martín).

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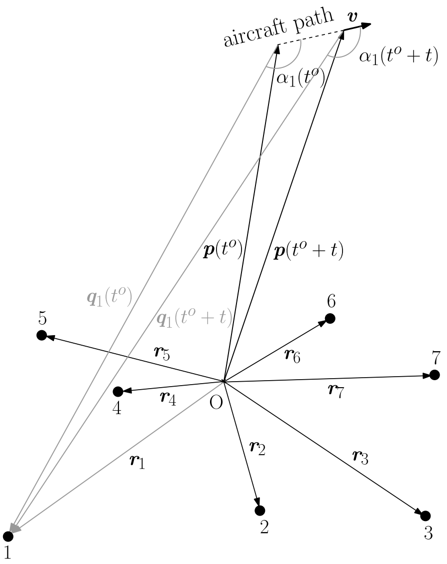

Fig. 1. Microphone set up and geometric variables relevant to the localization algorithm.

2. Localization algorithm

This section describes the localization algorithm and its implementation. Further details of the theoretical background can be found in [17] and [19].

The method requires at least seven microphones randomly distributed as showed in Fig. 1. Their positions $\boldsymbol{r}_n$ for $n \in \{1, .., 7\}$ with respect to an origin $O = [0, 0, 0]$ need to be known.

Let $s_e(t^o + t)$ be the signal emitted by the aircraft t seconds after a certain time t^o, this signal is received at the microphone n at the time $t^o + t'$, which accordingly to Fig. 1 is

$$t' = t + \frac{|\boldsymbol{q}_n(t^o + t)|}{c}, \tag{1}$$

where c is the sound speed in an isospeed medium and $|\boldsymbol{q}_n(t^o + t)| = |\boldsymbol{r}_n - \boldsymbol{p}(t^o + t)|$ is the position vector from the source to the receiver as shown in Fig. 1.

If t is so small that, during the interval $[t^o; t^o + t]$, the distance traveled by the aircraft is much smaller than the distance between the aircraft and the receiver and also the aircraft velocity $\boldsymbol{v}$ can be considered a constant, then the relationship between the received and the emitted signal is [18]

$$y_n(t^o + t') = \rho_n \cdot s_e(t^o + [t' - \frac{|\boldsymbol{q}_n(t^o)|}{c}] \cdot [\frac{c}{c - |\boldsymbol{v}|\cos(\alpha_n(t^o))}]), \tag{2}$$

where y_n corresponds to the acoustic signal received by the n-th microphone, ρ_n represents the amplitude attenuation factor due to the sound propagation and α_n is the angle between the aircraft velocity $\boldsymbol{v}$ and the pathlength vector $\boldsymbol{q}_n$ pointing from the aircraft to the receiver n.

The term $\frac{|\boldsymbol{q}_n(t^o)|}{c}$ in Eq. (2) is the time that the signal takes to propagate from the initial position of the source to the receiver, and the term $\frac{c}{c - |\boldsymbol{v}|\cos(\alpha_n(t^o))}$ is the Doppler effect due to the movement of the source called further on absolute Doppler stretch δf_n. Therefore, the received signal y_n at a microphone n is the emitted signal s_e shifted in time by the propagation time $\frac{|\boldsymbol{q}_n(t^o)|}{c}$ and also stretched – i.e. expanded or contracted – in time by the Doppler effect term $\frac{c}{c - |\boldsymbol{v}|\cos(\alpha_n(t^o))}$. By recursion, it can be easily shown that the signals received at two different microphones are time shifted and time stretched to each other disregarding the amplitude.

The underlying idea of this localization method is that, since the Doppler stretch term is related to the speed and position of the aircraft, if the value of the Doppler stretch could be estimated by comparing the signals of the different microphones, the aircraft could be localized.

The method is iterative, and for each iteration $k \in \mathbb{N}^*$ the initial position $\boldsymbol{p}(t^o)$ of the aircraft at a time t^o needs to be known from the previous iteration. To initialize the method it is necessary that the real position of the aircraft is known at an arbitrary time. Let $\boldsymbol{p}^{\text{initial}}$ at $t^{\text{initial}} = 0$ s be a known value such that

$$t^o = (k-1)\frac{\Delta t}{2}$$
$$\boldsymbol{p}(t^o) = \begin{cases} \boldsymbol{p}^{\text{initial}} & \text{if } k = 1, \\ \boldsymbol{p}^{k-1} & \text{if } k \neq 1. \end{cases} \tag{3}$$

where Δt is the time interval between two successive position estimates, and $\boldsymbol{p}^{k-1}$ is the position estimate obtained in the previous iteration.

The following steps are repeated in each iteration.

Step 1: Signals synchronization

This step consists in selecting the signal portion $x_n(t')$ of every receiver signal $y_n(t^o + t')$ originated when the source was at position $\boldsymbol{p}(t^o)$ and lasting for Δt. The signal originated at $\boldsymbol{p}(t^o)$ reaches the receiver n after a time period $\frac{|\boldsymbol{q}_n(t^o)|}{c} = \frac{|\boldsymbol{r}_n - \boldsymbol{p}(t_o)|}{c}$. Therefore the set of synchronized signal portions $x_n(t')$ are obtained as

$$x_n(t') = y_n(t^o + (t' + \frac{|\boldsymbol{q}_n(t^o)|}{c})) \text{ with } t' \in [0; \Delta t]. \tag{4}$$

Combining Eq. (2) into Eq. (4) it comes out that the relation between the synchronized signal portions and the emitted signal is

$$x_n(t') = \rho_n \cdot s_e(t^o + [\frac{c}{c - |\boldsymbol{v}|\cos(\alpha_n(t^o))}]t'). \tag{5}$$

Eq. (5) shows that the set of synchronized signal portions are time stretched and attenuated versions of each other.

Step 2: Computation of the relative Doppler Effect

This step consists of the calculation of the relative Doppler stretch δf_{mn} between each pair of synchronized signal portions received at microphones m and n. Since

$$\delta f_{mn} = \frac{c - |\boldsymbol{v}| \cdot \cos(\alpha_n(t^o))}{c - |\boldsymbol{v}| \cdot \cos(\alpha_m(t^o))}, \tag{6}$$

the search domain can be limited to

$$\frac{c - |v_{max}|}{c + |v_{max}|} \leq \delta f \leq \frac{c + |v_{max}|}{c - |v_{max}|}, \tag{7}$$

where $|v_{max}|$ is the maximum possible speed reached by the aircraft.

To obtain the value of δf_{mn}, first the discrete Fourier transform $X_n(f)$ of $x_n(t')$ is calculated for all the receivers. Note that both t' and f are discrete variables since $x_n(t')$ is a digital signal. Second, the following discrete 1-dimensional version of the ambiguity function is calculated over a set of attempted relative Doppler stretches δf

$$\chi(\delta f) = \frac{\sqrt{\delta f}}{L+1}\sum_{l=0}^{L} |X_n(l \cdot \Delta f)| \cdot |X_m(\delta f \cdot l \cdot \Delta f))| \tag{8}$$