Motion Parameter Estimation of Low Flying Aircraft using Acoustic Sensor

A. Saravanakumar, K. Senthilkumar

Division of Avionics, Department of Aerospace Engineering,

Madras Institute of Technology Campus, Anna University, Chennai-600044, India.

Saravanakumar_a@yahoo.com

ABSTRACT

Acoustics is emerging as a significant complementary modality to be explored and exploited in the development of Intelligence and surveillance systems that traditionally rely on technology rooted in electro-magnetic field phenomena. Acoustic sensors are appealing because they are passive, affordable, robust, and compact. Also, the propagation of sound energy is not limited to line of sight. An application of the current interest is the detection and localization of the sound sources on battlefield using Acoustic sensors in ground and on board unmanned aerial vehicle. The instantaneous frequency of the acoustic signal emitted by the target was received by Acoustic Sensor placed on the ground. The received instantaneous frequency varies due to the acoustical Doppler Effect under the condition that the target flies at a constant velocity and the trajectory is a straight line. Based on the instantaneous frequency model a Nelder-mead algorithm is used to estimate the motion parameters of the Low flying Aircraft.

1. INTRODUCTION

Unattended ground sensors are often deployed in remote areas for surveillance and early warning purposes. Sources of focal interest to land-based surveillance systems are ground vehicles and aircraft (jets, propeller-driven aircraft, and helicopters). Owing to the high levels of acoustic
energy radiated by the propulsion systems of aircraft and by the engines of vehicles, it is possible to detect these sources using passive acoustic sensors mounted close to the ground. The presence of an acoustic source can be detected automatically by comparing the received acoustic signal level with a preselected or adaptively controlled threshold. Data from acoustic sensors can also be processed for source classification, localization, and tracking. When an aircraft travels at constant velocity and altitude, its trajectory is completely specified by a set of flight parameters. The retardation effect, which arises when the speed of the source is comparable with the speed of sound propagation in the medium, enables the estimation of some or all of the aircraft flight parameters using passive acoustic methods. The estimation procedure finds its solution by applying Nelder-mead simplex algorithm, a non constrained optimization algorithm without derivatives. The approach resorted to here consists of an iterative process of optimization of the estimated instantaneous frequency using the algorithm, and updation of the optimizing parameters towards the end of each iteration. Acoustic parameter estimation of aircraft motion offers a reliable mode of aircraft parameter estimation, as it being passive, escapes detection and is unmaskable. It finds tremendous scope in border security and vigilance, to identify the enemy aircraft.

2. INSTANTANEOUS FREQUENCY ESTIMATION USING DOPPLER SHIFT

![Geometrical configuration for a Aircraft & Acoustic Sensor](image)
The figure (1) represents Geometrical configuration for a moving source and the acoustic sensor. Based on the geometry, the derived model as follows.

A signal emitted by an UAV at time $\delta$ arrives at the microphone at time $t$

$$t = \delta + \frac{R(\delta)}{c},$$  \hspace{1cm} (1)

Where $R(\delta)$ is the distance from the aircraft to the microphone at time $\delta$

$$R(\delta) = \left\{R_c^2 + v^2(t - \delta_c)^2\right\}^{1/2}$$  \hspace{1cm} (2)

The instantaneous frequency received at the microphone is given by

$$f(t) = f_0 \frac{d\delta}{dt}$$  \hspace{1cm} (3)

$$f(t) = \frac{f_0^2}{c^2 - v^2} \left[1 - \frac{v^2(t - \delta_c)}{(R_c^2(c^2 - 2) + v^2c^2 + (t - \delta_c)^2)^{1/2}}\right]$$  \hspace{1cm} (4)

where $f_0$ is the unshifted frequency, $c$ is the speed of sound, $v$ is the vehicle speed, $\delta_c$, and $R_c$ are the time and slant range respectively at closest point of approach (cpa). Equation (4) is the required model for the acoustic detection of vehicles based on Doppler effect. Parameters including $v$, $f_0$, $\delta_c$ and $R_c$ at the cpa can be obtained by using an Nelder-mead Simplex algorithm.

3. ALGORITHM IMPLEMENTATION

Aircraft motion parameters like its velocity, frequency spectrum, time and altitude at closest point of approach to the microphone can be estimated by employing Nelder mead simplex method to Doppler shifted acoustic signals received from the aircraft at a ground based microphone. This offers a reliable way of tracking stealth mode low flying aircraft as acoustic
signals can never be totally masked. The reverberations produced at the microphone are Doppler shifted, and depend on the relative velocity between aircraft and microphone. As the microphone is stationary, we can obtain sound frequencies which are solely dependent on the velocity of aircraft. Estimates of \( v, f_0, \delta_c \) and \( R_c \) at the CPA can be obtained by using Nelder-Mead simplex method to minimize the mean square error given as

\[
\sum_{t=1}^{T} [F(t) - f(t)]^2
\]  

Here \( f(t) \) is the \( t^{th} \) measured frequency at discrete time \( t \) (\( t = 1, \ldots, T \)), obtained from the spectrogram plot of the acoustic signal obtained at the sensor. \( F(t) \) is the instantaneous frequency estimated based on the values of \( [v, f_0, R_c, \delta_c] \) obtained from the current iteration, using the equation 4. The algorithm is implemented in mat lab using a function called \texttt{fminsearch()} which makes use of Nelder mead Simplex estimation to optimize the objective function specified. \texttt{fminsearch()} finds the minimum of a scalar function of several variables, starting at an initial estimate. This is referred to as unconstrained nonlinear optimization.

4. RESULTS AND DISCUSSION

![Figure 2: Doppler Effect](image-url)
The data collected were sampled and the spectrogram study was carried out. This study shows that the possible detection of transients as well as harmonics pattern of vehicle due to Doppler effect which is shown in figure(2). The exact transit time of a vehicle over the sensor was 36.39 sec, found from the elevation and slant range studies which were shown in figure(3) & figure(4).

![Figure 3: Elevation plot for Vehicle transit](image1)

![Figure 4 : Range plot for Aircraft transit](image2)
The algorithm was employed to minimize the sum square error between measured instantaneous frequency and the estimated ones at discrete time instants, and the value of parameters that minimize the sum square error gave the desired parameter values. Since fminsearch function was given the error in frequency, the difference between the estimated and calculated frequency, as the objective function, and the value of parameters that converge this error value to zero will give the optimized parameter value. fminsearch(), being an unconstrained minimization algorithm, makes the final value of function converge to a negative value. This had to be avoided as negative value of frequency difference is undesirable. To alleviate this problem, the objective function was taken as the absolute value of frequency error, which when optimized using fminsearch algorithm converged to a zero error value.

![Figure 5: Plot of optimization of function value](image)
The figure (5) & figure (6) shows the screen shot of the mat lab implementation represent the minimization process and the optimum values for the parameters. For an explicit comparison we tabulated the experimental results in the Table.1

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Estimated values</th>
<th>Real values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aircraft velocity(m/s)</td>
<td>63.28</td>
<td>65</td>
</tr>
<tr>
<td>Slant Range at CPA(in meters)</td>
<td>53.93</td>
<td>60</td>
</tr>
<tr>
<td>Un shifted frequency(in Hz)</td>
<td>254.3917</td>
<td>Unavailable</td>
</tr>
<tr>
<td>Time at CPA(sec)</td>
<td>39.92</td>
<td>36</td>
</tr>
</tbody>
</table>

Table 1. Comparison of simulated and reference values

5. CONCLUSION

In this work parameter estimation of Low flying Aircraft based on its acoustic signature was done. The Nelder-mead algorithm was employed to estimate the desired parameters of aircraft
motion and it was implemented in Mat lab. The outputs were verified with real time data available and converged to these values with a reasonable level of accuracy.

References


