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Exploitation of Acoustic Signature of Low Flying Aircraft using Acoustic Vector Sensor

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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. 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. In this work a nonlinear least-square cepstrum and auto correlation methods are made to estimate the motion parameters of a low flying aircraft whose narrowband acoustic energy emissions were received by a ground-based Acoustic vector sensor. The data obtained from the sensor were processed and analyzed using digital signal processing approach. This passive technique is applied to real acoustic sensor data under the condition that the vehicle flies at a constant velocity and the trajectory is a straight line. The performances of both methods are evaluated and compared using actual acoustic data.

Keywords: Acoustic vector sensor, cepstrum, auto correlation

1. INTRODUCTION

The detection of signal sources especially at very low altitudes becomes very difficult by the use of Radio detecting and ranging. The solution for this problem can be obtained by making use of acoustic data. The acoustic signal emitted from the power plant of an aircraft is used for the flight path estimation by predicting its direction of arrival. This can be possible by utilizing the data collected by using acoustic vector sensor (AVS) and an array of scalar sensors. Acoustic sensors are appealing because they are passive, affordable, robust, and compact and the propagation of sound energy is not limited to line of sight. The low flying unmanned systems is a surveillance platform of choice in low intensity conflict scenario and it is important that maximum benefit be derived on situation awareness from its short and urgent missions[1]. Clearly, acoustics is its own nemesis because the aerial vehicle motor noise and flow noise can be significant factors when far field sources need to be listened to. Under these environments, an acoustic vector sensor (AVS) with its ability to directly measure particle velocity in three orthogonal directions together with the scalar pressure at a single point in air, offers a powerful option with its ability to determine bearing of a wideband source with simple algorithms[2]. The emergence of microflown, a particle velocity sensor in AVS configuration is a significant development in aero acoustics measurement technology. The microflown AVS sensor has been deemed ‘appropriate for the battlefield context’ by Hawkes and Nehorai[3]. The problem of detection and parameter estimation of low altitude flying aircraft using passive acoustical methods has been studied for years. The localization of acoustic source is usually done with sensor array in which the output of each sensor is a scalar corresponding to the acoustic pressure. Direction of acoustic source is found by correlating signal from each sensor and by calculating the delay among them[4,5]. It is a time consuming process and so we consider a different approach for solving this problem, using AVS. The main advantage of these vector sensors over traditional scalar sensors is that they make use of the more available acoustic information, hence they should outperform sensor array in their accuracy of localization. As the acoustic waves propagate through a medium, particles in the medium vibrate in the direction of wave. A vector sensor can measure this velocity. By multiplying the particle velocity and instantaneous pressure, intensity vector can be obtained[10]. As AVS consists of three mutually perpendicular vector sensors along with the microphone, by reading pressure signal from microphone and the particle velocity from three vector sensors intensity vectors in three directions was found. Using vector analysis the direction of initial point, CPA was calculated. Here is described a technique that utilizes the Lloyd’s mirror effect of the radiated sound to estimate the speed, altitude and elevation angle of a low-flying aircraft by using only a single sensor[6, 7]. The recorded sound of the Aircraft was used here for both spectrogram study and parameter estimation based on the assumption that aircraft following a straight line path.

2. ACOUSTIC FIELD TESTING

Development of an electric engines-based unmanned aerial vehicle system (both fixed wing and rotary wing), with capabilities to support a 1000 gm remote sensing payload, a system is focused with a view towards flexibility, to generate data for various types of sensors and is anticipating wide range of possible applications. In this work a 2 kg class fixed

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wing micro air vehicle is used as a test bed for acoustic field testing and analysis. The acoustic vector sensor is MEMS based vector sensor that integrates scalar acoustic pressure and three orthogonal particle velocity component measurements in a single package. The AVS is positioned at one meter height above the ground and data were captured for nearly 620 s by flying the MAV model around a 1000 m radius. The generated outputs were sampled at 20 kHz and the data were processed in overlapping blocks, each containing 8192 samples with 50 per cent overlap between two consecutive data blocks.

3. ACOUSTIC SIGNATURE ANALYSIS

The time frequency analysis of MAV Acoustic signature reveals clearly that the transit starting time of the vehicle is around 290th second (based on the harmonics pattern) which is also concluded by audio hearing. The Fig. 1 shows the sound pressure level in the direction of arrival of flight transit towards the sensor.

The spectrogram study shows that engine harmonics were clearly distributed up to 2000 Hz and the fringe pattern (narrow band energy) was caused by the phenomenon known as multi path propagation effect, i.e., the signal received by the sensor comes from both direct path and ground reflected path[8,9].

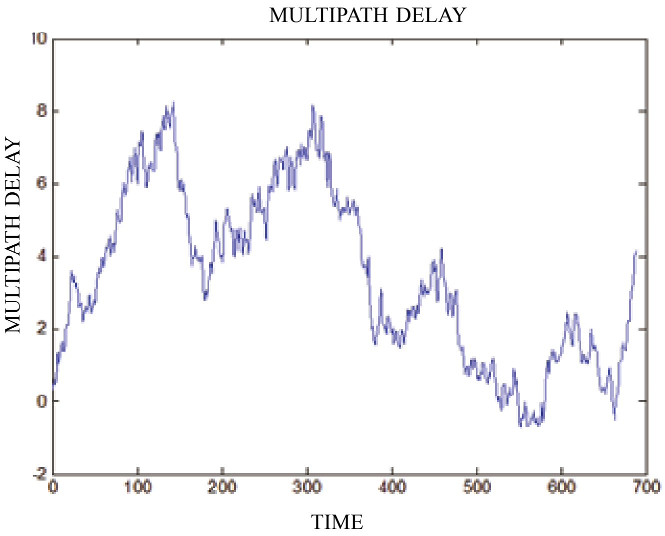

Figure 1. Sound pressure level during transit.

3.1 Multipath Propagation

The geometry of the multi path effect depicted in Fig. 2 shows an acoustic source (MAV) traveling in a speed v and altitude h_t over the ground[6]. An acoustic sensor is located at a height h_r above the ground. The source is at the closest point of approach (CPA) to the sensor at time t_c with the ground range at CPA being d_c. The delay time for the desired model is obtained as

$$D(t) \cong \frac{2(c_r^2 - v_r^2)/c_r^2}{\sqrt{\gamma^2(c_r^2 + v_r^2) + c_r^2 v_t^2 (t-\tau_c)^2 - v_r v_t (t-\tau_c)}} \tag{1}$$

where values of v_r,v_t,γ ,c_r are given by

$$v_t = v / h_r \tag{1a}$$

$$v_t = v / h_t \tag{1b}$$

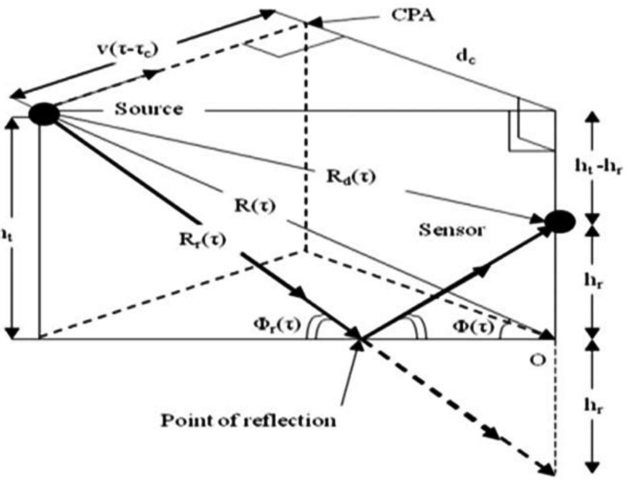

Figure 2. Diagram of source-sensor geometry.

$$\gamma = \sqrt{(1 + (d_c / h_t)^2} \tag{1c}$$

$$c_r = c / h_r \tag{1d}$$

Note that $D(t)$ is a function of $\{v_r, v_t, \tau_c, \gamma\}$or equivalently the flight parameters $\{v, h_t, \tau_c, d_c\}$.

3.2 Non-linear Least Squares Method

The main flight parameters such as $\{v_r, v_t, \tau_c, \gamma\}$ or equivalently $\{v, h_t, t_c, \gamma\}$ estimated using a non-linear least square method. That is by minimizing the sum of squared deviations of delay estimates from their predicted values. Defining the parameter vector as

$$z = [v_r, v_t, \tau_c, \gamma]^T \tag{2}$$

The estimate of z which is $\hat{z} = \left[\hat{v}_r\ \hat{v}_t\ \hat{\tau}_c\ \hat{\gamma}\right]^T$ is obtained by minimizing the cost function

$$p(z) = \sum_{k=1}^{k} \left[\hat{D}(t_k - D(t_k, z))\right]^2 \tag{3}$$

where $\hat{D}(t_k)$ is the multipath delay at time t_k and $D(t_k, z)$ is the corresponding predicted value using Eqn. (1) the model for 1≤k≤K. Given the sensor height h_r, the speed, altitude and CPA ground range of the source is estimated as

$$\hat{v} = h_r \hat{V}_r \tag{4}$$

$$\hat{h}_t = \hat{v} / \hat{v}_t \tag{5}$$

$$\hat{d}_c = \left| \hat{h}_t \sqrt{(\hat{\gamma}^2 - 1)} \right| \tag{6}$$

The multipath delay at time t_k is estimated using cepstrum function method. The signal emitted by the MAV contains acoustic energy which arrives at the sensor via direct path and ground reflected path. The time difference between the two arrivals (multipath delay) causes their spectral components to interfere destructively with each other at certain frequencies[7]. This results in a pattern of interference fringes known as Lloyd's mirror effect (multipath propagation effect) in the time frequency distribution of the sensor output.

3.3 Cepstrum Method

The cepstrum of the data block is obtained by applying a FFT to the logarithm of its power spectrum. Quefrency is the independent variable of the cepstral graph. It is a measure of time, though not in the same sense as of the signal in time domain.

The data from sensor were processed in overlapping blocks, each containing 8192 samples, with 50 per cent overlap between two consecutive data blocks. Each data block was divided into three 50 per cent overlapping sections and their periodograms are calculated using fast Fourier transform (FFT). The three periodograms are then averaged to give the power spectrum of the data block. The cepstrum of the data block is obtained by applying a FFT to the logarithm of its power spectrum. Each peak in the cepstrum corresponds to a rahmonic and the position of the first rahmonic (peak) along the quefrency axis gives the multipath delay estimate. The estimated and the predicted delay time gives the error delay value which is minimized using a cost function.

The initial estimate of $\hat{z}_1 = \left[\hat{v}_r^o, \hat{v}_t^o, \hat{\tau}_c^o, \hat{\gamma}^o\right]^T$ is obtained using the following procedure.

Finding the time $\hat{t}_o^o$ at which $\hat{D}^{-1}(t) \equiv 1/\hat{D}(t)$ is the minimum (7)

$$\text{Computing } \hat{\gamma}^o = 2\hat{D}^{-1}(\hat{t}_o^o)/c_r \tag{8}$$

$$\text{Calculating } \hat{v}_r^o = -c_r \frac{\hat{D}_+^{-1} + \hat{D}_-^{-1}}{\hat{D}_+^{-1} - \hat{D}_-^{-1}} \tag{9}$$

$$\hat{v}_t^o = -(4/c_r)\frac{\hat{D}_+^{-1} + \hat{D}_-^{-1}}{\hat{D}_+^{-1} - \hat{D}_-^{-1}} \tag{10}$$

where $\hat{D}_-^{-1}$ and $\hat{D}_+^{-1}$ are the respective gradients of two straight lines that provide best fit to the first few and last few data points of $\hat{D}^{-1}(t)$.

$$\text{Calculating } \hat{\tau}_c^o = \hat{t}_o^o - \frac{\hat{\gamma}^o \hat{v}_r^o}{c_r \hat{v}_t^o} \tag{11}$$

The Fig. 3 shows the multipath delay of a vehicle transit using cepstrum method. From the graph, it can be found that the maximum multipath delay occurs at the 36th second and this could be used to find out the initial parameters using cepstrum method. The flight parameters are then estimated using the nonlinear least squares approach as explained earlier for the cepstrum method. The maximum delay value is obtained as 1.21 ms which is substituted in model and the values founded as altitude is 24 ft, CPA is 16 s and the speed is 28 m/s, respectively.

3.4 Autocorrelation

The data from the sensor is processed in overlapping blocks each containing 8192 samples with 50 per cent overlapping between two consecutive data blocks. The autocorrelation of each data block is implemented in the frequency domain using the fast Fourier transform (FFT). The location of the peak of the autocorrelation function in the positive time lag axis gives the multipath delay estimate. The multipath delay is calculated for every block and the maximum multipath delay can be obtained by plotting multipath delay for 200 s. The estimated and the predicted delay time gives the error delay value which is minimized using a cost function

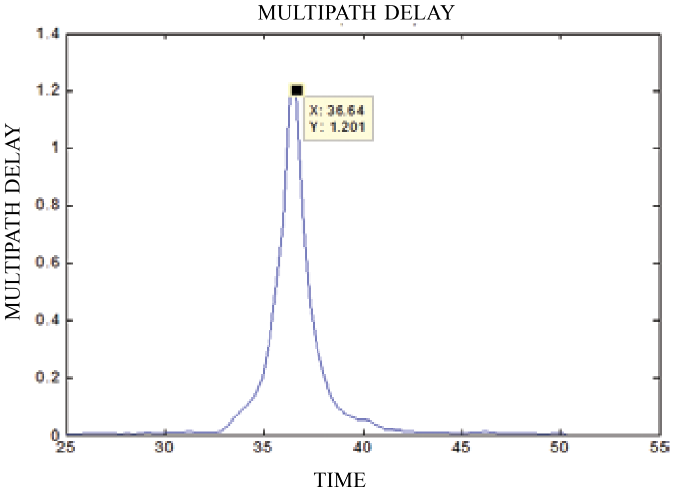

Figure 3. Maximum delay occurs during transit.

Figure 4 shows the Autocorrelation of a signal and the maximum multipath delay occurred found from the graph is 1.21 ms. By substituting the best fit points in the model the Altitude is 20 ft, CPA is 20 s and the speed of the vehicle is 22 m/s are obtained as results. The maximum elevation angle obtained during transit is around 89° which is shown in Fig. 5. For an explicit comparison we tabulated the experimental results in the Table 1.

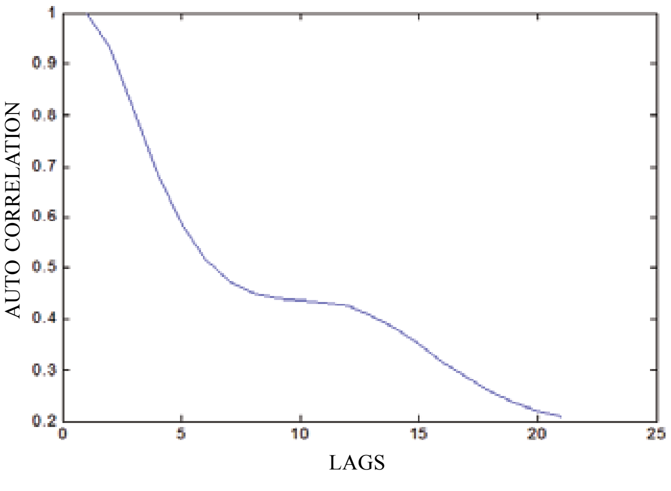

Figure 4. Auto correlation of a signal.

Table 1. Estimated and actual values

Parameters	Estimated by		Actual
	Autocorrelation	Cepstrum	
Speed (m/s)	22	28	30
Altitude (ft)	20	24	25
CPA (s)	20	16	15

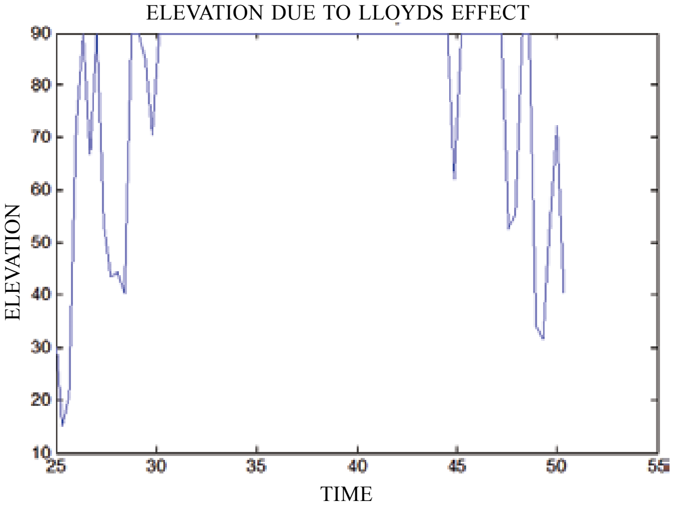

Figure 5. Elevation angle.

4. CONCLUSION

In this work, detailed spectrogram study was done in addition to the estimation of flight parameters using a single acoustic vector sensor based on the assumption that the aircraft following a straight line trajectory. Multipath propagation due to Lloyd's mirror effect was utilized not only to analyze the transit but also to estimate the various motion parameters like elevation angle, speed, CPA, and Altitude using cepstrum and autocorrelation least square methods. By making use of the intensity vectors, direction finding is possible, and which is in progress. The fringe patterns are more when the vehicle approaches the sensor and less when it leaves away from the sensor.

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