A SYSTEM FOR AUTOMATIC CLASSIFICATION OF AIRCRAFT FLYOVERS USING ACOUSTIC DATA

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ABSTRACT
An overview of a system for the automatic classification of aircraft from flyover data is presented. The system is passive, utilising acoustic sensors to measure both broadband and narrowband energy. Aspects of the system architecture, sensor design and signal processing are covered. The processing is divided into three streams: broadband, narrowband and cepstrum. Each processing stream is capable of extracting flight parameter estimates from the acoustic data. Broadband estimation is based on the time-delay cross correlation of signals from multiple sensors. Narrowband estimation makes use of the spectrogram of the data to extract frequency lines produced by the aircraft and subject to the acoustical Doppler effect. Cepstrum processing tracks the primary harmonic in the cepstrogram due to multipath interference. A novel hidden Markov model tracking technique is applied to form tracks on the noisy spectrogram and cepstrogram data. Examples of real data processing and flight parameter estimates for classification are given.

1. INTRODUCTION
Conventional aircraft detection systems utilise microwave radar, which requires line of sight for detection and is suitable for high altitude aircraft. When aircraft are at low altitude target loss can occur due to obstacles such as hills being located between the radar and aircraft. To overcome this problem a complementary detection system based on remote location of acoustic sensors is a cost-effective solution. It also has the advantage of being a purely passive system and does not alert the aircraft to its presence.

An acoustic-based system can utilise the broadband and narrowband signals emitted during a flyover. Flight parameter estimates (FPE’s) can be calculated from tracking any of the narrowband Doppler frequency and, broadband time delays (between sensors or multipaths). The FPE’s can be compared to database values for classification of aircraft to various levels of complexity, for example, to differentiate propellers from jets or even to jet types. This paper presents some aspect of such a system.

2. AAD SYSTEM
The purpose of the Acoustic Aircraft Detection (AAD) system is to test the concept of detecting and classifying jet aircraft at remote locations using acoustic-based techniques. The system will be field deployed for an extensive period to gather acoustic and system performance data that may be used as a baseline for establishing the specifications for an operational aircraft detection/classification system. The present system consists of: (a) a base station; and (b) two remote sensor nodes. Figure 1 represents a breakdown diagram of the AAD system.

Figure 1: Acoustic Aircraft Detection System.
The base station will provide facilities for: (a) processing and analysing the incoming data from each node; (b) recording the incoming node data; (c) displaying the calculated aircraft parameters and classification; (d) plotting the aircraft tracks on a display; (e) controlling and monitoring the nodes via a communications link; (f) maintenance of an aircraft acoustic signature database; and (g) self test.

The signal processing will include the following functionality: (a) automatic and operator assisted detection, tracking, and classification of jet aircraft; (b) automatic discrimination of individual aircraft in multiple aircraft packages; (c) automatic discrimination against ground vehicles; and (d) discrimination between jet and non-jet aircraft.

This is to be achieved by the implementation of three different processing chains, as shown in Figure 4, namely: (a) narrowband; (b) broadband; (c) cepstrum.

3. SENSOR DESIGN

The AAD system requires a sensor subsystem, which works in an outdoor environment for an extended period of time. An important aspect of the operation of this subsystem is its ability to provide accurate data during a range of environmental conditions. One that is particularly pertinent is the ability to deal with the effects of the wind. It has been the practice in the past to use microphones with windscreen. However, even with a wind screen, when the wind blows over the sensor beyond a certain speed it generates turbulence, reducing the SNR of the system.

Rather than using a microphone and placing wind screens around the sensor, an alternative approach has been implemented. This approach uses a number of hydrophones instead of the microphone and wind screen. These hydrophones are potted so that the boundary layer is moved from the sensor and spatial averaging of the signals can result.

The basic construction of the sensor differs markedly from the microphone, as shown in Figure 2. In the case of the microphone the sensing element is very compliant in an effort to maximise the impedance matching to air. The hydrophone, on the other hand, is far less compliant and the element is mismatched to the air. This results in a reduced sensitivity to signals for individual elements which is easily compensated for by the addition of signals from all the elements in the array. Although space is not an issue, directionality is and the larger the array the lower the directionality cut off frequency. In viewing aircraft signatures there appear to be no significant narrowband lines above 3 kHz so the sensor should be close to omni-directional up to this frequency. This sets the size of the sensor.

Figure 2: The “underside” of a hydrophone array, with foam on the “top side”.

Figure3: Spectrum of hydrophone array data and microphone data.

Figure 3 shows a spectrum from the hydrophone array (top) and from a Sony microphone (bottom). The spectrograms are also presented to show a time history of the recording. It can be noted from the spectrogram that the wind gusts are increasing. This is evidenced in the overlays in the spectral plots, and it can be seen that the background levels increase by up to 20dB. In the area of interest, below 500Hz, a variation of up to 10dB occurs. It is noted that the spectrum of the hydrophone array is invariant over this time.

Increasing the size of the array does make it more susceptible to rain noise as this is a function of intensity. By placing a suitably constructed rain hat, which reduces
the speed of the drop without increasing additional acoustic noise, would ideally remove rain noise. This may be achieved substantially by bonding a closed cell foam onto the sensor. The thickness of the foam is a tradeoff between insertion loss and the allowable level of rain noise. Using a waterproof layer of closed cell foam 1.5 cm thick reduces the rain level at the sensor to an acceptable level for moderately heavy rain. Occasional spikes still occur when a drop still has sufficient energy to come into direct contact with the sensor.

4. SIGNAL PROCESSING

Figure 4 shows the three different signal processing chains used in the AAD system. Each chain is designed to extract particular characteristics of a received acoustic signal for a given measurement configuration. These characteristics are used to identify flight parameters and the latter are then utilised for classification of flyover aircraft.

![Diagram of signal processing chains](image)

**Figure 4:** The three signal processing chains in the AAD system

4.1 Broadband Processing

The broadband signal generated by a flyover aircraft can be assumed to be a distant source and the wavefront of the source tends to be planar when it reaches a set of ground sensors. In general the wavefront reaches each individual sensor at a different time. The time difference between two signals received by two spatial ground sensors (simply called time delay) depends on time, speed, height, slant range and bearing of the aircraft. This relationship has been utilised to estimate flight parameters [1] and to track flyover aircraft [2].

The time delay between the signals received by two sensors can be extracted by cross-correlating them. In order to enhance the SNR of the cross-correlation, a suitable band has to be chosen. In a measured signal, the lowest frequency band is dominated by environmental noise while the higher frequency band becomes non-coherent because of attenuation. After processing a large amount of field measurements, it was found that the frequency band from 50 Hz to 400 Hz could compromise the above two effects. After bandpass filtration, the spectrum of the signal is whitened to reduce the effect of dominant frequency components. Then time delay tracks are obtained by taking the maximum in each time slice of cross-correlation.

4.2 Narrowband Processing

A flyover aircraft may generate a constant frequency (narrowband) component which can be attributed to rotating machinery or to aerodynamic resonance. When the aircraft approaches a ground sensor the pitch of the received signal appears higher, and when the distance between the aircraft and the sensor is increasing the pitch appears lower. This phenomenon is the so-called acoustical Doppler effect. The Doppler frequency shows up as a function of time and flight parameters in the spectrogram of the received acoustic data. The Doppler model was presented in [3]. Typically the narrowband frequency lines generated by aircraft are accompanied by noise and interference. The false alarm level in the spectrogram data can be very high and therefore high performance tracking techniques, such as hidden Markov models (HMM), are required. Public domain work on HMM tracking techniques for sonar systems includes [4, 5]. Previous work by Thomson Marconi Sonar in this area has appeared in [6, 7].

The narrowband processing chain comprises the following steps: (1) generation of the spectrogram of the received acoustic signal; (2) normalisation of the data batch and local peak extraction; (3) automatic track formation using a multiple-model HMM frequency line tracker; (4) narrowband track validation and segmentation. These steps are now described.

The spectrogram of the data batch is formed by 1024-point short-time Fourier transform (STFT) using a Hanning window and taking the squared magnitude. Data blocks are overlapped by 50%. The spectrogram is then normalised by subtracting a cell-averaged version at each time slice. A low threshold is applied. Peak selection followed by parabolic interpolation generates a set of time frequency peaks for input to the tracker. This process is illustrated in Figure 5
The hidden Markov model tracker operates in batch mode. The Forward part of the Forward-Backward algorithm is applied to generate frequency-cell conditioned likelihoods for three different dynamical models. The models reflect (1) a stable frequency line; (2) an unstable frequency line with zero net drift; (3) a drifting frequency line. Peaks with a high likelihood are selected for track initiation and the corresponding model is used for tracking during the batch. Tracking is achieved using the Viterbi algorithm, which generates maximum a posteriori probability estimates of the frequency tracks on a discrete grid. Tracks are continued across overlapping batches of data. A score metric related to the integrated track SNR is used to perform automatic track maintenance. Frequency tracks surviving this process are then passed to the validation stage.

Due to the high false alarm rate, many tracks are formed on false peak detections. The validation stage computes an estimate of the track frequency derivative by fixed interval Kalman smoothing. A series of statistical tests are then applied to the track. Validated tracks must first satisfy minimum duration, minimum SNR criteria. The track must also contain a monotonically decreasing frequency segment satisfying certain smoothness properties. Validated tracks are then segmented into non-overlapping portions likely to correspond to narrowband frequency lines. These validated track segments are the input to the flight parameter estimation stage.

**4.3 Cepstrum Processing**

A broadband signal emitted by an aircraft flyover arrives at an above ground sensor via a direct path and a ground-reflected path. Multipath propagation creates a destructive sound field at the sensor and this manifests itself as a set of Lloyds Mirror Rings (LMR) in the time-frequency domain (in the spectrogram) and as a family of rahmonics in the time-quefrency domain (in the cepstrogram). The spacing between any two adjacent rahmonics is the multipath time delay. This time delay can be used to estimate flight parameters (see companion paper [8]).

LMR’s are the troughs of a spectrogram and can very easily be buried, broadened or even shifted by background noise. The major rahmonic track consists of peaks of a cepstrogram. Extraction of a rahmonic track from a cepstrogram is much easier than the extraction of a LMR trough from a spectrogram. Previous experience shows that the flight parameters estimated from cepstrum tracks have smaller standard deviations than those from LMR’s.

The cepstrogram processing chain is similar to the spectrogram chain in section 4.2. For a given batch of acoustic data, the power cepstrogram is computed on 1024-point blocks with 50% overlap using a Hanning window for the STFT. The cepstrogram is a 2-D data set with dimensions of time and quefrency. The cepstrogram is first normalised by subtracting the local minimum SNR quefrency points in each time slice, computing the mean and variance and thresholding the normalised
statistics. Local peaks are identified and interpolation is performed based on SNR.

Ceprogram peaks are scaled in quefrency and SNR so that they more closely resemble the spectrogram data in resolution and dynamic range. The scaled peaks are input to the HMM tracker under a slightly different tuning regime to that used for spectrogram tracking. The output track set from the tracker may contain false tracks. Moreover, the main cepstrum track is often continued into the heavily cluttered region at low quefrency. It is necessary to validate the cepstrum tracks to minimise the false track rate and to determine which tracks contain valid cepstrum segments. The validation process includes a “hump”-detector based on a smoothed estimate of the quefrency derivative. Cepstrum humps correspond to changes in sign from positive to negative of the first derivative of quefrency. Cepstrum humps are then segmented since it is possible for one track to contain cepstrum humps from multiple aircraft. Flight parameter estimation is then performed on the validated cepstrum segments.

4.4 Flight Parameter Estimation

A NonLinear Least Squares (NLLS) procedure, the Levenburg-Marquardt method, is chosen to carry out Flight Parameter Estimation (FPE) from measured time delay tracks (broadband processing), Doppler frequency tracks (narrowband track) and cepstrum tracks. This method has been coded as a standard optimiser in Matlab® and can be directly used. Using this method requires error functions and their Jacobians to be constructed. The error functions can be formed by comparing measured tracks and their corresponding mathematical models and the Jacobians are the first derivatives of the error function with respect to the individual flight parameters. The mathematical models for the three processing chains tracks can be found in [1, 3, 8].

4.5 Examples

The following is an example of a single engine propeller flyover. Figure 6 shows a spectrogram of the flyover.

It is noted that the flyover contains both narrowband and broadband spectrum, the latter exhibiting LMR’s as the sensor is located above the ground. The narrowband lines automatically extracted by the HMM tracker are illustrated by the overlaid lines in Figure 7. Flight parameter estimates have been calculated for each discrete line and the results for the fourteen tracks are presented in Table 1.

A second pass at track validation has also occurred resulting in the rejection of tracks 5, 7 and 10. Reviewing Times of closest Point of Approach (TCPA) show that those which occur at 32 ±0.5 seconds also result in agreement with velocity of 67 m/sec and average slant range of 521m. Thus tracks 1, 2, 4, 6, 8, 9, 11, 12 and 14 contain good data which can be used for classification. Five of these tracks are harmonically related to track 1. This is a strong indication of a propeller aircraft. So far, the data collected from jets do not exhibit multiple harmonic narrowband lines during a straight, level and constant velocity flyover.

The TCPA agrees with the time recorded from the narrowband data however the slant range (428 m) and velocity estimate are slightly underestimated. As can be seen there is a range of estimates from all the tracks. This can occur for a variety of reasons: for example, if a narrowband track only follows part of the Doppler curve.

<table>
<thead>
<tr>
<th>Track no</th>
<th>Rest freq (Hz)</th>
<th>Velocity (m/sec)</th>
<th>Range (m)</th>
<th>TCPA (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>17.8</td>
<td>67.1</td>
<td>523.0</td>
<td>31.8</td>
</tr>
<tr>
<td>2</td>
<td>312.6</td>
<td>67.2</td>
<td>525.8</td>
<td>32.0</td>
</tr>
<tr>
<td>3</td>
<td>473.3</td>
<td>54.5</td>
<td>483.3</td>
<td>30.6</td>
</tr>
<tr>
<td>4</td>
<td>463.1</td>
<td>72.3</td>
<td>645.4</td>
<td>32.2</td>
</tr>
<tr>
<td>5</td>
<td>INVAL</td>
<td>535.3</td>
<td>882.3</td>
<td>34.1</td>
</tr>
<tr>
<td>6</td>
<td>156.6</td>
<td>65.7</td>
<td>495.5</td>
<td>31.9</td>
</tr>
<tr>
<td>7</td>
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<td>330.0</td>
<td>248884</td>
<td>29.0</td>
</tr>
<tr>
<td>8</td>
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<td>67.0</td>
<td>519.7</td>
<td>31.8</td>
</tr>
<tr>
<td>9</td>
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<td>67.8</td>
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<td>13</td>
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<td>298.8</td>
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<tr>
<td>14</td>
<td>292.7</td>
<td>64.9</td>
<td>484.2</td>
<td>32.2</td>
</tr>
</tbody>
</table>
due to low SNR, as can be seen in Figure 6. Figure 7 also shows examples of tracks which have only followed part of the curve.

Figure 7 shows the cepstrogram derived from the spectrogram in Figure 6. Automatic tracking of the cepstrum line is also shown in Figure 7. The flight parameter estimates are given in the Table 2.

Table 2: Cepstrogram parameter estimates.

<table>
<thead>
<tr>
<th>Track no</th>
<th>Velocity (m/sec)</th>
<th>Height (m)</th>
<th>Horizontal Range (m)</th>
<th>CPA (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>56.3</td>
<td>356.6</td>
<td>238.4</td>
<td>32.0</td>
</tr>
</tbody>
</table>

In the case of the cepstrum data, the broadness of the track can allow a range of possible estimates to result. Rather than only accepting estimates which closely match it is important to allow a broader range of values to be acceptable. The cut-off for acceptable speed ranges between different processing techniques has been found empirically to be 10 m/sec for the classifier to have high confidence and 20 m/sec for a lower confidence level. These thresholds have been derived from over 300 flyovers.

CONCLUSIONS

An acoustic aircraft detection system has been developed which automatically classifies different aircraft types using both narrowband and broadband processing techniques. Aspects of the system architecture and sensor design were covered. The system incorporates parallel processing streams for broadband, cepstrogram and narrowband spectrogram data. The latter two chains use HMM tracking techniques for frequency and quefrency line extraction. Each of these processing chains provides estimates of the flight parameters. Performance evaluation on real data is being carried out and the results so far indicate that multiple FPE's for the same aircraft tend to be generated. While the sources of error in the tracking, validation, segmentation and parameter estimation stages are difficult to characterise statistically, it is clear that FPE results which show close agreement should be given high confidence and be retained for classification purposes. The system includes a database that compares the high confidence track data against the database values and assigns an aircraft type accordingly.

ACKNOWLEDGEMENT

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REFERENCES