Acoustic Signature of an Unmanned Air Vehicle – Exploitation for Aircraft Localisation and Parameter Estimation

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ABSTRACT

Higher harmonics in the acoustic spectrogram of an unmanned air vehicle in-flight, as obtained from a ground-based microphone measurement, is shown to be useful for estimating the vehicle's altitude, speed and true engine revolutions per minute. Specifically, the Doppler-shifted frequency time histories derived from spectrogram contours are used in this estimation approach which is based on a least mean square error fit to an instantaneous frequency model proposed in the literature. Benefits of employing higher harmonics – rather than the fundamental only – in the computations are brought out. The results obtained are satisfactory. A possible system configuration for automatic detection and localisation of similar aircraft is briefly discussed here.

Keywords: Acoustic signature, unmanned air vehicle, exploitation for aircraft localisation, time-frequency distributions, target recognition, signal processing, acoustic spectrogram, ground-based stationary microphone

1. INTRODUCTION

There have been accelerated research efforts on the exploitation of mechanical waves in surveillance and target recognition tasks[1] with the surge in digital signal processing technology only fueling such efforts. The acoustic signal propagation characteristics of propeller aircraft and helicopters are of particular focus due to the fact that real-time computations on such signals could be conveniently carried out with modern digital signal processing hardware and advanced algorithms. Whereas, an array of microphone sensors could be deployed for quantitative analysis, signal from a single microphone is adequate for preliminary estimation requirements. Specifically, the Doppler effect in the acoustic spectrum of a propeller aircraft flying overhead as measured by a ground-based stationary microphone contains information about aircraft altitude, speed and actual revolutions per minute of the engine. Based on these parameters, a model for the time variation of the Doppler frequency has already been proposed[2]. The Doppler frequency is the instantaneous frequency of the acoustic signal and accordingly a two-stage solution approach is proposed to obtain aircraft information (i) computation of the instantaneous frequency of the signal, and (ii) estimation of aircraft parameters by least mean square error fit of the frequency estimate with that of the model. In this paper, a similar approach relevant to an unmanned air vehicle (UAV) in-flight has been studied. The UAV is powered by a pusher engine and the strong tonal features are exploited in the engine radiated sound in the analysis. Much research has gone into mathematical and algorithmic considerations towards the problem of estimating the instantaneous frequency of a signal. Standard short-time Fourier transform (STFT) and the

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more advanced algorithms Wigner-Ville distributions are the tools being actively employed for the purpose[3]. For the problem on hand, where the acoustic signal, as measured by a stationary observer, has a highly nonlinear FM structure, sophisticated signal processing methods that include the higher-order polynomial Wigner-Ville distributions are shown to be very useful[4]. In this paper, an application of STFT has been investigated to estimate instantaneous Doppler frequency and a numerical least mean square error fit approach for determining the UAV altitude, speed and actual revolutions per minute of the engine. In contrast to the work reported in literature, these parameters which are based on analysis of the higher harmonics in the sound spectrum are extracted.

2. THEORETICAL MODEL FOR DOPPLER FREQUENCY

The acoustic signal frequency spectrum is dominated by the propeller rate harmonics. A model for the apparent frequency[2,4] (Doppler frequency) $f_i(t)$ measured from a stationary microphone is given as:

$$f_i(t)=\frac{f_a c^2}{(c^2-\mu_a^2)}\left[1-\frac{\mu_a^2(t+h/c)}{\sqrt{\mu_a^2 c^2(t+h/c)^2-h^2(\mu_a^2-c^2)}}\right] \quad (1)$$

where

f_a = Source acoustic frequency

c = Speed of sound in the medium

μ_a = Velocity of the aircraft (assumed subsonic)

h = Altitude

It is seen that the instantaneous frequency depends on the moving source speed, altitude and frequency. The procedure is to compute the Doppler frequency time variation from the measured sound signal and to make a least mean square error fit with the above model.

3. INSTRUMENTATION, FIELD MEASUREMENTS & COMPUTATIONS

A general view of the UAV is given in Fig.1. The test point consisted in the UAV flying at a fixed altitude and engine settings are almost directly above the microphone location. The condenser microphone of a precision integrating sound level meter (B&K2230) positioned atop a stand was used for receiving the engine sound signal (Fig. 2). The random incidence setting was employed on the microphone. A digital recorder (Sony PC208Ax) was used to record and store the signals. A sampling

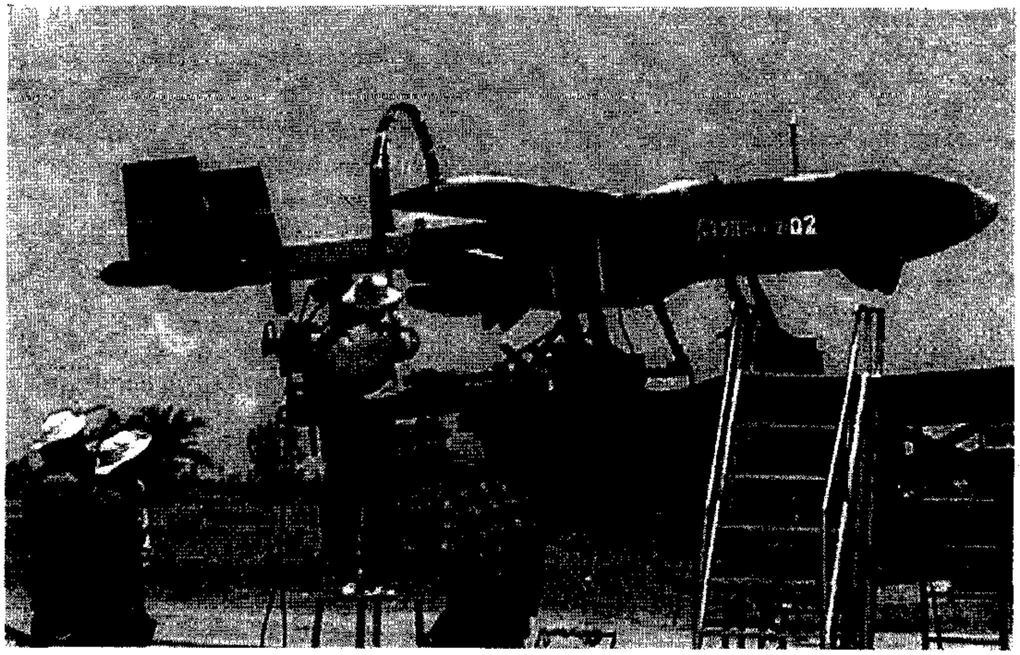

Figure 1. UAV on launcher

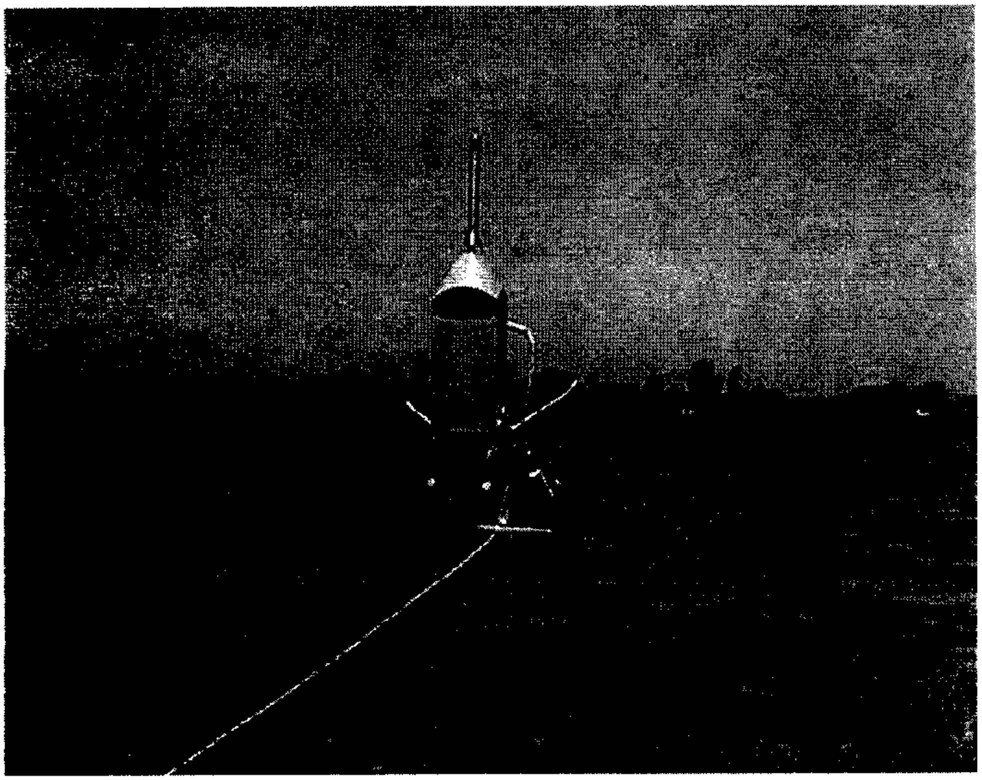

Figure 2. Sound level meter at test site

rate of 12 k samples/s was employed for spectrum processing the play-back signals. Contiguous blocks of 16384 pt windowed FFTs formed the basis for spectrogram computations[5] on MATLAB. For estimating the UAV speed and altitude, Eqn (1) was evaluated in a (velocity × altitude) grid of 81 cm × 346 cm on MATLAB. The search range for velocity was 20 m/s to 60 m/s in steps of 0.5 m/s and for altitude it was 50 m to 3500 m in steps of 10 m. The instantaneous frequencies of the model were computed at time instants corresponding to the observed frequencies derived from spectrogram of the measured sound signal for about 40 s in the approach and recede limbs of the time-frequency representation contours. The model velocity/altitude combination that was in agreement with the observations in the least mean square error fit sense is deemed the best estimate for the aircraft parameters.

4. RESULTS & DISCUSSION

To verify the tracking performance of the spectrogram frequency estimates, the analysis of the engine sound as the engine revolutions per minute was revved up and down in a ground integration run was done. The sound was captured as a .wav file using a multimedia mic of a PC located in the laboratory several tens of metres away from the site of engine run. Clearly, the contour representation is highly satisfactory and

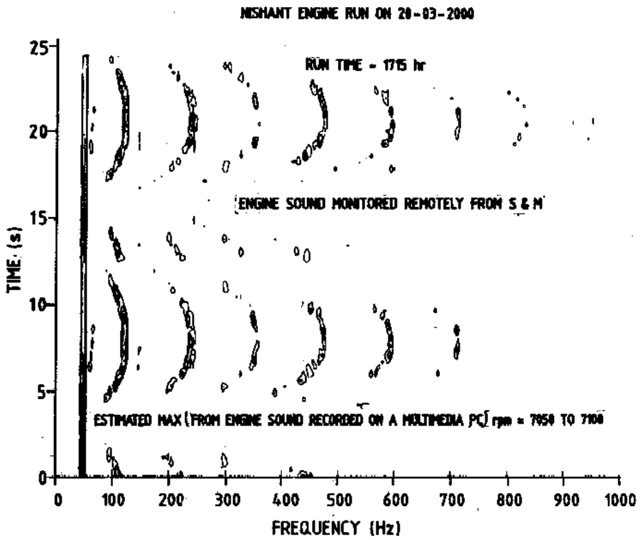

Figure 3. Spectrogram of engine sound in ground integration run.

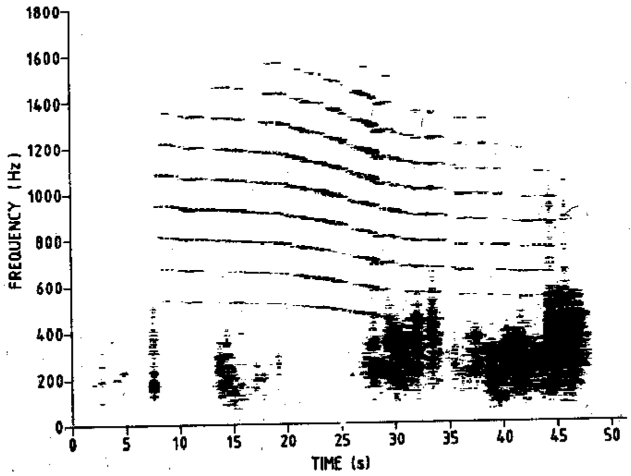

Figure 4. Overhead UAV cruise-acoustic spectrogram

the rich harmonic content is well brought out. The constant line about 50 Hz is the power line frequency. An accurate estimate of the maximum revolutions per minute achieved in this particular run could be made as also the revolutions per minute build-up rate from the spectrogram (Fig. 3).

The analysis of acoustic signal of the UAV flying directly over the stationary microphone is considered next. The spectrogram plot of the signal is shown in Fig. 4. The FFT block size used (16384 pt at 12000 pt/s) enables a frequency resolution of about 0.73 Hz. One hundred contour levels are plotted. The fundamental tone levels are seen overwhelmed by clutter, possibly by strong surface wind noise at the site of measurement and multi-path effects. However, higher harmonics are well identified. The task is to identify time of closest pass of the aircraft and to estimate instantaneous frequencies from the contours.

A zoomed look at the spectrogram is useful (Fig. 5). Broadly, the Doppler frequency variation is characterised by the three zones: (i) slow variation at a far-off range, up to 20 s (approaching limb), (ii) a steep middle region with rapid variation of frequency about the time of overhead flight, (20 s to 30 s), and (iii) again a flat region as the vehicle slant range increases (receding limb), beyond 30 s. The time origin for Eqn (1) is reckoned as the time at the middle of the steep limb. Also note, dips in the level about this time instant, at approximately 26 s. The interval between the harmonics (computed as the mean value between various harmonics shown) corresponding to this instant is the rest frequency of the engine, thus directly providing a measure of the actual de-dopplerised revolutions per minute. A graphical digitisation along the three dominant harmonics – 6^{th}, 8^{th} and 10^{th} – has been adopted to obtain instantaneous frequency estimates. These observed values are shown in Fig. 6 as discrete points. Also shown in Fig. 6 are the model curves for the Doppler time history that best fit the observations. The altitude and speed obtained as the mean of the three least mean square errorfit estimates (467 m and 40.8 m/s, respectively) match those

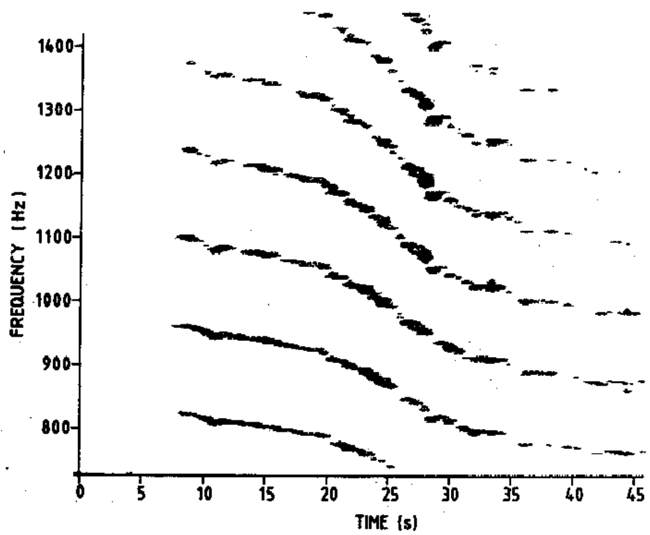

Figure 5. Zoom spectrogram

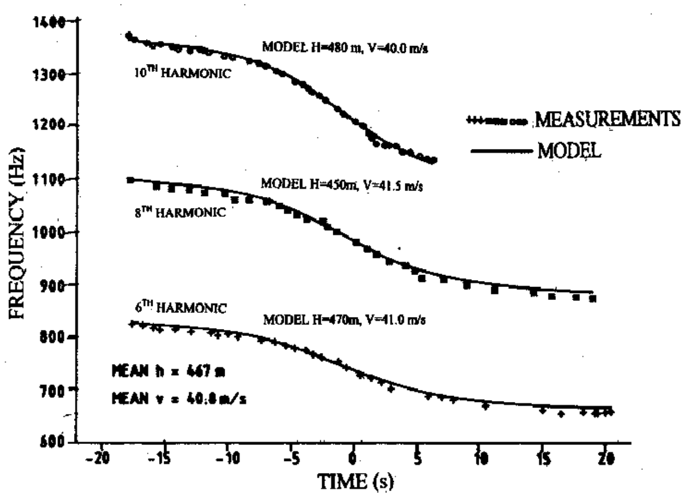

Figure 6. Model versus observations

from onboard sensors as recorded in the ground control station to within 10 per cent.

5. FURTHER WORK

The multimedia PC (possibly the notebook configuration) with its mic and audio recorder capability (.wav files) is expected to prove useful for field deployment. Alternatively, a PC-based computing environment (e.g. MATLAB) capable of driving a signal acquisition hardware and providing real-time digital signal processsing (spectrogram) capability in the audio range is a powerful platform for tasks related to automatic detection, parameter estimation and localisation of an airborne target. The configuration should also allow the use of more advanced algorithms – for instance, Wigner-Ville distributions – for the instantaneous frequency computation[3,4], and central to the present parameter estimation problem.

6. CONCLUSIONS

Acoustic spectrogram of signals measured using a ground-based stationary microphone, when the UAV passes directly overhead, is shown to be a powerful tool for obtaining estimates of the aircraft altitude, speed and engine revolutions per minute. Use of Dopplers of higher harmonics – rather than only the fundamental hitherto discussed in literature on the topic – is shown to be a significantly improved approach to the problem especially under the gusty clutter environment that is likely to overwhelm the fundamental and lower harmonics. Use of higher harmonics also provides powerful means to detect the engine rest frequency (revolutions per minute) and identification of the time of the closest approach of the target to the stationary microphone observer believed crucial for the success of the Doppler frequency model predictions. A possible system configuration for trial deployment is broadly identified.

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