HELICOPTER SOUND SIMULATOR FOR TRAINING DETECTION SYSTEMS

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ABSTRACT

The objective of this paper is to describe a simulation program for helicopter sound generation with realistic details. The underlined physical characteristics and theoretical prediction of helicopter noise are presented. Propeller noise (due to main rotor), non-axial inflow conditions of tail rotor, physical dimensions of blades, position and velocity vectors of observer and aircraft, atmospheric attenuation and distortion and ground effect make significant contributions to overall received sound signal characteristics. This simulator has been used to generate different flight conditions for training and testing of artificial neural network based helicopter detection system.

1. INTRODUCTION

One of the challenging air defense problems is the ability of low flying helicopters to penetrate the air defense systems, undetected by conventional radar. Sound signature produced by these low flying helicopters can be employed for their detection. For helicopter identification and classification problem, it is almost impossible to train the system using real sound samples under all possible flight conditions. Due to unavailability of these direct measurements, an alternative economical approach is to utilize a reliable simulator, which makes use of directly relevant data e.g., rotor angular velocities, number of blades etc. and empirical or theoretical prediction techniques. Previous efforts for helicopter detection (Cabell, Fuller and O'Brien 1992,1993: Meier 1993) relied on either simple model based on main and tail rotor blade passing frequencies and its harmonics or on very limited flight data.

The key parameters for predicting the helicopter acoustic signal are the number of blades, dimensions and tip velocities of main and tail rotor blades, engine noise and effect of atmospheric attenuation and ground reflection. Schematic of a single rotor Helicopter is shown in Fig.(1).

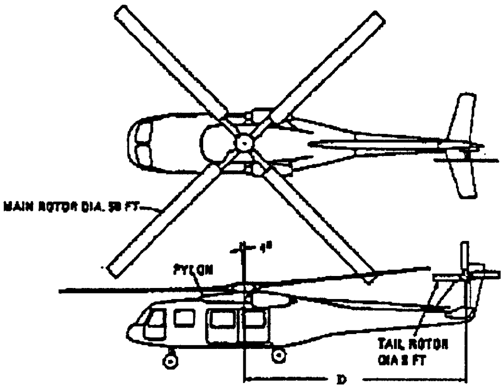

Fig.(1) Schematic of a Helicopter

The simulator used in this work consists of following four parts:

1. Helicopter data base which contains the key physical parameters of each helicopter of interest.
2. Sound production model.
3. Flight trip simulation which includes such variable parameters as speed, initial observation point, and 3D flight path with respect to the observer.
4. Disturbance model, which includes fading, Doppler shift due to wind gusts, and sound interferences., e.g., jet engine noise.

The quantitative prediction of all aspects of helicopter sound is extremely difficult. The acoustic signals of lifting-rotor (and tail rotor) are usually approximated to those associated with the propeller (Richards and Mead 1968). A significant additional phenomenon known as 'blade slap or thump' (Leverton 1971; Splettstoresser et al. 1984) is also an additional noise source. It occurs when one of the rotor passes through wake or tip vortex created by another blade. Helicopter rotor noise tend to grow in intensity, as tip speed and power increases. For a non-hovering helicopter, there will always be a substantial difference in relative tip speed between the blade on the "advancing" side and on the "retreating" side of rotor disc plane with respect to the flight direction (Wright 1969). High speed of the advancing blade produce the asymmetric noise output, often preferentially directed ahead of the helicopter(Wright 1969). The same effect occurs, albeit to a lesser degree, with the tail rotor.

At low blade speeds, the mean steady loading can be used to predict the fundamental rotor tone and low-order harmonics, using the propeller analogy. But at higher tip Mach numbers, thickness noise increases rapidly and propeller analogy breaks. Measurements may be further complicated by atmospheric attenuation and ground reflection effects. The observed sound is a function of main and tail rotors angular velocities and their number of blades, physical dimensions of blades, the aircraft position vector with respect to observer, the velocity vectors of the aircraft and the observer, atmospheric attenuation and disturbances, and the ground terrain. A typical section of the helicopter acoustic signal is shown in Fig.(2).

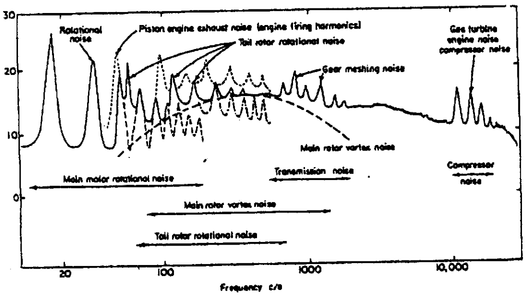

Fig.(2) Helicopter Noise – narrow band spectrum [Adapted from Richards and Mead 1968]

Helicopter sound is largely a tonal signature, a combination of tones from main rotor (3-40 Hz), the relatively higher tones due to tail rotor (25-110 Hz), broad band noise generated from the laminar flow and vortex wakes (200-600 Hz), noise emitted by engine drive train components (60-100 rotor angular speed), power turbine shaft (N2), and the gas generator/compressor turbine (N1) (900-2000 Hz), in addition to the effect of ground reflection and the atmospheric attenuation.

2. SOURCES OF HELICOPTER NOISE

The large number of separate sources contributing to helicopter noise can be summarized as:

1. Rotor noise, due to main and tail rotor, this consists of (a) rotational noise (b) vortex or broad band noise (c) discrete frequency noise known as 'blade slap'.
2. Noise emitted from engine drive train components, power turbine, shaft (N2) and gas generator/compressor noise.
3. Effect of ground reflection and atmospheric attenuation

2.1 Main Rotor Noise

The noise from rotating blades is of dipole order, and is generated by the fluctuating pressure distribution on the surface of the blade. Lighthill (Lighthill 1952) has shown that a fluctuating point source behaves like a dipole, giving a source strength proportional to the magnitude of the force resolved in the direction of the observer. Force fluctuations relative to the observer are the result of unsteady aerodynamics effects and blade rotation. So rotor noise increases rapidly with the tip speed.

In Fig.(2), the presence of a large number of peaks, suggests that a strong source of propeller noise arises from periodic excitation at the blades. Peaks are present at the fundamental and successive harmonics of the blade passage frequency. In addition to the discrete frequency component of the spectra, broad band noise is found in a region of 1-2 kHz.

Rotational Noise: According to Glegg (Glegg 1982) the sound pressure generated by a fluctuating point source is given by

$$p(R,\theta_0,\phi_0,t) = \frac{B}{8\pi r a}\sum_{m=-\infty}^{\infty}\sum_{n=-\infty}^{\infty}A_n\, e^{-imB\Omega(t-r/c_0)+i(mB+n)\phi_0} \times \left[mBM_s L_0 \cos\theta_0 - (mB+n)D_0\right] i^{mB+n+1} J_{mB+n}(mBM_s \sin\theta_0) \qquad (1)$$

where B is the number of blades, r is the distance between the source and the observer, *a* is the radius of the ring assumed by the source location on the blades, A_n is the magnitude of the rotor loading harmonics, Ω is the angular velocity of the rotor, m is the harmonic number, ϕ_0 is the point at which source strength variations are observed, M_s is the Mach number of the source, J(.) is the Bessel function, θ_0 is the angle between the source and the axis of rotation of the blades, L_0 and D_0 are the lift and drag components.

If we assume steady loading of the rotor blades then only terms with n=0 need to be considered, and the amplitude of each blade passing harmonic in the noise spectrum is approximated by (Glegg 1982).

$$p_{mB}(R,\theta_0,\phi_0) = \frac{mB^2\Omega}{4\pi R c_0}\left(L_0 \cos\theta_0 - \frac{D_0}{M_s}\right) J_{mB}(mBM_s \sin\theta_0) \tag{2}$$

where c_0 is the chord length

In our simulation, low speed (Mach number 0.6-0.66) is assumed. In this case we can approximate Bessel function by its asymptotic value given as (Glegg 1982)

$$J_{mB}(mBM_s \sin\theta_0) = \tilde{P}_{mB} \cong \frac{e^{mB}}{\sqrt{2\pi mB}}\left[\frac{M_s \sin\theta_0}{2}\right]^{mB} \tag{3}$$

Which gives the amplitude of the m^th^ harmonic at the observer as

$$P_{mB}(R,\theta_0,\phi_0) \cong \frac{B\Omega}{4\pi R c_0}\left(L_0 \cos\theta_0 - \frac{D_0}{M_s}\right)\tilde{P}_{mB} \tag{4}$$

The time varying harmonic component becomes

$$p_{mB}(R_0,\theta_0,\phi_0,t) = p_{mB}(R_0,\theta_0,\phi_0)e^{-i(mB)\Omega(t-R_0/c_0)+i(mB)\phi_0} \tag{5}$$

Broad Band Noise (Vortex Noise): The broad band noise is due to the shedding of vorticity at the airfoil trailing edge when the blade is operating in smooth airflow, induced due to local surface pressure fluctuations on the blade.The relationship for the intensity of overall sound pressure level *(O.A.S.P.L)* is defined by the following equation (Goddar and Stuckey 1967)

$$O.A.S.P.L. = 16.6\log T + 26.8\log V_T - 20\log\sec\phi + 2.8dB \tag{6}$$

where T is thrust per blade, V_T is tip velocity of the blades and ϕ is the angle between tip located dipole axis and observer.

Vortex shape is very well defined in terms of peak frequency 'f_p'. Peak frequency depends upon Strouhal number, S_t

$$f_p = S_t \frac{V_T}{c_0} \tag{7}$$

In our simulation, the lower cutoff frequency is taken as $f_L = {}^{f_p}\!/_{Q}$ and high cutoff frequency is $f_H = f_p Q$ with $f_{max} = f_p$ where Q is called quality or shape factor (Wright 1975). The vortex shedding is received modulated by the periodic blade passing waveform.

2.2 Forward Speed

The effect of the forward speed is to modify the length of the acoustic path between the source point and the observer. Expression(5) is valid for helicopters in hover state. For moving helicopter the distance can be substituted by $R_0 = t * v$, where v is the component of the helicopter velocity in the direction of the observer. Now Eq.(5) can be modified as:

$$p_{mB}(R_0,\theta_0,\phi_0,t) = p_{mB}(R_0,\theta_0,\phi_0)e^{-i(mB)\Omega(1-v/c_0)t+i(mB)\phi_0} \tag{8}$$

Above equation shows that the movement of helicopter induces a Doppler effect in the form of frequency shift in the observed spectrum. This change of m^th^ harmonic is given by $\Delta f_m = \frac{mB\Omega v}{2\pi c_0}$. The change in the orientation of the helicopter with respect to the observer causes a continuous fluctuation in the relative magnitude of each of the component of the received signal. These two effects result in jitters in the observed spectrum.

2.3 Tail Rotor Noise

The effect of the rear rotor is usually much less than that of the main rotor. Moreover, it is highly sensitive to the aircraft orientation with respect to the observer. Because of smaller diameter tail rotor runs at a much higher r.p.m. than the main rotor. As illustrated in Fig.(2), it produces a series of harmonics in a similar manner to the main rotor, but it has a higher fundamental frequency (40-120 Hz). The vortex noise from tail rotor is generally of lower level than the discrete or rotational tones (Richards and Mead 1968).

The effect of the rear rotor is assumed to be maximum when its axis is in the direction of its wake, resembling a cardioid directivity pattern. In case of dual rotor, the received sound is taken to be the addition of the sound disturbances produced by the two rotors separated by a distance *D* between the axis of rotation.

2.4 Engine Noise

Helicopter engine noise is due to exhaust gases and gas turbine. For piston engines the primary source of noise is the exhaust, which occurs in the range of 200-1000Hz (Richards and Mead 1968). The main source of noise on the turbine engine is the 'compressor whine' from the inlet. Additional gears are required to give a higher gear ratio in this type of engines which increase the transmission noise in turbine engines.

The noise emitted by engine drive train components, power turbine shaft (N2), and the gas generator/compressor turbine (N1) fall in the range of 900-2000 Hz. Due to lack of real data, the two vibration frequencies (N1and N2) of the engine

The figure below shows the spectrum of the simulated helicopter sound.

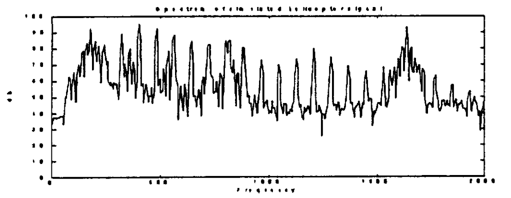

Fig.(7): Spectrums of simulated helicopter sound

5. HELICOPTER DETECTION

In this section we have applied Artificial Neural Networks (ANN) along with feature extraction techniques to detect the presence of helicopter. In designing such a detector three stages are involved: training, testing and implementation. The detection system basically consists of a front end feature extractor and a classifier as shown in the Fig.(8).

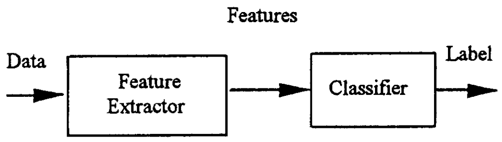

Fig.(8): Structure of a pattern recognition

A feature extractor normalizes the collected data, removes irrelevant information, enhances interclass similarities and transforms data to feature space. The audio signal is divided into small segments called frames and from these frames smooth spectral estimates are obtained. Line spectral pairs (LSP) which are an alternative of the direct form linear predictive coefficients can be used as features. LSP have both well-behaved dynamic range and filter stability preservation property. This motivates us to investigate its application in this detection problem.

The performance of the detection system can be improved by the use of ANN in combination with signal processing techniques to capture the full information contents of input data and exploit the information in an efficient manner. In ANN knowledge is acquired through learning process, which is preserved by interneuron connection strengths called synaptic weights. Highly popular backpropagation algorithm is applied for the training of the ANN classifier. The feature vectors describing the characteristics of the helicopter and non-helicopter sounds are applied as input to the ANN.

ANN classifier was trained using four different helicopters and a number of non-helicopter acoustic signals. Each 0.1 second acoustic frame was encoded into a 10 point LSP feature vector. 270 frames of training data, 200 helicopter sound frames and 70 non-helicopter sound frames were produced on keep-one-leave-three bases from the available acoustic signals. Due to limited number of LSP input features (10 in our case) and sensitivity of parameters with respect to spectral variations two hidden layers were employed to capture the spectral contents of the signal. Hidden layers contain 8 and 4 neurons respectively. The network was trained to SSE of 1.3, after which no change in SSE was observed. The helicopter signals were assigned a target of 0.9 and non-helicopter frames were assigned a target of 0.1.

The performance of the classifier on the test data is an indicative of real identification performance. Although, training and test data are drawn from same class of populations, since the classifier is optimized on the training data, it might over learn the training data missing more relevant discriminating characteristics. So classification error may increase on the test data if the class populations were undersampled or misrepresented in the training data. The results are shown in Table 1 below and are also plotted against the signal strength in Fig.(9).

Table 1: Correct detection using LSP's

% Detection	SNR				
of	Clean	18dB	12dB	9dB	3dB
Helicopter	100	99	83.5	69.5	34.5
Nonhelicopter	98.5	100	100	100	100
False Alarm	1.5	0	0	0	0
Miss	0	1	16.5	30.5	65.5

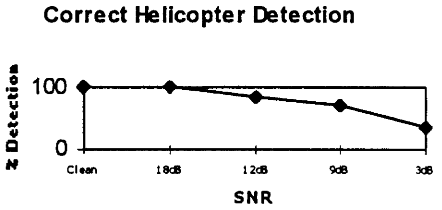

Fig.(9): LSP based detection with varying SNR

When the conditions were identical to those encountered in the training set, there was small drop in detection performance. This indicates that the training data has accounted for most of the variability in the test data. The performance of ANN classifier was also evaluated when the signal was embedded in the background noise. Data was generated from test frames corrupted by Gaussian noise with 18dB, 12dB, 9dB and 3dB signal-to-noise ratio (SNR). The performance of the recognition system was affected as the spectrum shape distorts and becomes more buried in the background noise. As the signal strength drops, relative to the background noise, the spectral peaks blend in the noise that distorts the spectral shape, until it becomes very different from its original shape. In response the feature values changes, affecting the performance quality. The degradation shown in the results illustrates the sensitivity of the ANN to these spectral changes.

6. CONCLUSION

In this paper we have described a helicopter sound simulator. The simulator accounts for acoustic disturbances generated by main and tail rotor, engine vibrations, vortex shedding and directivity effects. It also includes the Doppler's shift in the received spectrum caused by the maneuvering of the helicopters and the attenuation cased by air absorption, ground reflection and helicopter orientation. Later on this simulator was used in an helicopter detection study. Spectral estimates of the acoustic spectrum of helicopter and non-helicopter sounds were obtained in terms of LSP parameters. The performance of ANN based detection system was evaluated under different background noise levels.

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