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ACOUSTICS IN AIRCRAFT SENSING SYSTEMS

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1. INTRODUCTION

There is a requirement for modern weapon systems to be fully autonomous, relying on the intelligent processing of data gathered from a variety of on-board sensors to function with maximum effectiveness against appropriate targets without any manual intervention. A typical intelligent warhead fuze will progress through a logical sequence of phases during a target encounter, from initial detection and classification, to location and tracking of the target up to the closest point of approach. Depending on the particular requirements of the system, these functions can be performed by the most appropriate blend of technologies, such as electro-optics, radar or acoustics. The intended target can range from wheeled or tracked vehicles to fixed-wing and rotary-wing aircraft.

This paper describes some techniques that have been used by Ferranti to realise anti-aircraft weapon fuzes (so-called "Influence Fuzes") using acoustic systems. The functions are each described in more detail. The geometrical arrangements of acoustic sensors, and the associated signal processing techniques required to fulfil these functions, are also described. The detail contained in this paper is necessarily at a top level but the aim is to show the extent to which acoustic systems are being utilised in sensing systems.

Systems have been designed to act against either helicopters or fixed wing military aircraft. The application of a system is usually specific to a particular aircraft manoeuvre, and this has included low-level flight, landing, takeoff or taxiing.

2. SYSTEM REQUIREMENTS

There is a degree of commonality in the functioning of all autonomous weapon systems, although certain phases may be omitted depending on the particular system requirements. This section describes the individual phases of a notional generic influence fuze.

2.1 Detection

For most of its operational life a system will be in a dormant state, but must be alerted to the possible approach of a target sufficiently early for the subsequent phases to take place before the timely engagement of a target. In most systems the alert function is performed by the simple thresholding of an acoustic signal because of the low power requirements of deployment grade microphones. A low quiescent drain on the battery supply elongates the operational life of a stand alone system. Once alerted the system will become more power hungry, either because other transducers such as lasers or radars are switched on, or the acoustic processing is more intensive and possibly uses additional microphones. If the system is to perform in urban or vegetative areas or undulating terrain, the non line of sight capability of acoustic alerters is advantageous.

2.2 Recognition

After initial detection this phase attempts to verify the presence of a target suitable for the host weapon. This may be a broad classification between, say, aircraft and ground vehicles. More sophisticated schemes can determine the class of aircraft (eg fixed wing or rotary wing). Ultimately the specific aircraft type can be identified. The technique generally consists of matching aircraft specific spectral patterns in the received acoustic signal. To develop target recognition algorithms, a wide-ranging database of recorded acoustic signatures has been established at Ferranti from the attendance of numerous data collection exercises over a period in excess of fifteen years. However, algorithms that are robust against temporal and geographical variability in outdoor environments are a result not only of scrutinising recorded data, but of computer prediction of the effect of outdoor propagation on prospective identifiable features.

Increasingly the need to react only against enemy targets has led to the requirement for the Identification of Friend or Foe (IFF). In many cases this is achieved by the target responding automatically on reception of an interrogating electro-optic or radar signal by transmitting a predetermined identifying signal. The advent of acoustic target identification techniques has the attraction of performing a passive, and therefore non-cooperative, IFF. This overcomes the problems of active IFF that a valid target could pose as a friendly aircraft, or conversely that the response from a friendly aircraft may not be received.

2.3 Location

The finite effective range of weapon systems imposes a requirement to predict whether a target is going to pass through the "zone of authority". The eventual detonation trigger is often performed by power hungry electro-magnetic devices which will rapidly drain the battery supply if repeated false alarms are raised. Acoustic source location techniques are used, therefore, to track the target and cue the other sensors if the target is expected to pass within range. In general this is accomplished by measuring the propagation delay between spatially separated microphones. The application may require azimuth, elevation or full bearing tracking. High rates of change of bearing can be used as an indication of target proximity to overcome the fact that, unlike an active system, range cannot be determined directly.

Although multi-microphone systems are used for target tracking, considerable success has been achieved with a system that has only a single microphone sensor. For a particular application, it is capable of predicting from the acoustic signature alone when a target is within range and when the optimum point for detonation has been reached.

3. SIGNAL PROCESSING

The variety of functions performed by a typical influence fuze, together with the diversity of applications and operational requirements, dictates the use of a range of signal processing techniques. This section outlines the acoustic schemes that have been employed by Ferranti to realise influence fuzes for autonomous weapon systems.

3.1 Spectral Content

The spectral characteristics radiated forward of an aircraft can differ markedly from those to the rear[1,2]. During the passage of an aircraft past a microphone, the change over from one pattern to the other can be used to indicate the approach of an aircraft and when it is at the Closest Point of Approach (CPA). To accentuate the relative changes in level between selected parts of the spectrum, normalisation can be applied to account for the increase in level expected from decreasing range as an aircraft approaches. The process consists of subtracting the level in the specific narrow frequency bands from that in the overall audio spectrum. Figure 1 shows the effect expected for an acoustic source passing the microphone if the forward directivity lobe is dominated by high frequencies and the rear is dominated by low frequencies.

3.2 Sound Pressure Trends

For an acoustic source approaching a sensor position, the Sound Pressure Level can be expected to change with time as shown in Figure 2a. The first and second time derivative of the SPL are then as shown in Figure 2b and 2c. It can be seen that the zero-crossing points of the second derivative gives an indication of the approach of an acoustic source (X on Figure 2), and the zero-crossing point of the first derivative is an indication of CPA (Y). Other useful functions can also be realised, such as a reset of the fuze to its quiescent state if detonation does not occur, by detecting the second positive region of the second time derivative (Z).

The signal averaging time is a selected compromise to obtain a smooth temporal variation without an excessively long system reaction time. Exponential averaging techniques[3] are ideally suited for this highly dynamic situation because of the emphasis of the most recent data. Similarly, the periods over which the rates of change are determined should be chosen to represent the trends in sound pressure level (over a period of a few seconds) rather than react to small, short-term perturbations.

3.3 Propagation Time Measurement

This is determined by the delay in arrival time of a signal at spatially separated microphones. The time delay will be a function of the angle of incidence of an acoustic plane wave and can, therefore, be used for target location[4]. The situation for two microphones is shown in Figure 3. The angle of incidence is related to the azimuth and elevation angles by:

$$\cos\beta = \cos\theta \cos\phi \qquad \textit{where}\ \theta = \textit{Azimuth},\quad \phi = \textit{Elevation} \tag{1}$$

Unless the situation allows broad assumptions to be made about the position of the source, a measured time delay between two microphones will only indicate that the source is somewhere on the surface of a cone. If the target is ground-based then the problem reduces to a "front-back" ambiguity. Even this may be acceptable if the target is always to one side of the microphone pair. For anti-aircraft systems, however, there is usually no such limitation on either azimuth or elevation of a target and additional microphones have to be introduced to resolve the ambiguities, as described in Section 4.
Frequency domain cross-correlation[3] is generally used to determine time delays, although the nature of the acoustic emission from the target is not always ideally suited to this technique. There may be a dominant tone from the compressor of a jet-engined aircraft, or the regular series of impulses from a helicopter rotor may give a highly harmonic characteristic. The periodicity of such signatures will be evident as an undesirable peak in the cross-correlation function, often obscuring that due to the propagation delay. To reduce the effect an attempt can sometimes be made to filter out the part of the spectrum containing the feature, although reducing the bandwidth in this way broadens the peaks in the cross-correlation function. The resolution can be recovered by prewhitening[5] in which the cross-spectrum is artificially made as broad and uniform as possible by, for instance, normalisation using the power spectrum of one of the single microphones. The technique preserves the phase information of the cross-spectrum, and so the cross-correlation function, formed by the inverse FFT, has a peak that is narrower than before but in the same location. The required time delay peak can then be selected by intelligent post-processing.

3.4 Beamforming

Considering the two microphones in Figure 3, if the signal from microphone 2 was delayed by an amount $\tau = (d \cos\beta)/c$, the signals from a source at angle β would be in phase with each other. Summation of the two would amplify the source signal but would tend to cancel the uncorrelated noise. If the time delay is continuously adjusted, the receive direction can be electronically steered from 0 to 180°. This is the basis of the technique of beamforming[6], which is generally used with large-scale arrays of microphones (see Section 4). The increase in signal to noise ratio over that from a single microphone is of the order of 10log(N), where N is the number of microphones. Beamformers are, therefore, useful for the long-range detection of aircraft. Since the summed signal is available for processing, as for a single microphone, target recognition algorithms are applicable. The technique is also used to locate and track targets from a knowledge of the steering time delays in use when a target was detected.
The beamformer may be mounted on an armoured vehicle and adaptive processing is used

to reduce the level of background noise by cancellation[7]. The host vehicle's self-noise, which is monitored by a judiciously placed reference microphone or accelerometer, is subtracted from the beamformer sensor outputs by adaptation of the weights of digital filters, making the desired target signal more prominent. Alternatively, the beamformer weights can be adapted to sharpen the directivity of the beamformer in the receive direction, whilst steering nulls towards off-beam noise sources.

4. SENSOR CONFIGURATIONS

In this section the possible physical arrangements of microphones are discussed. The requisite signal processing techniques from the previous section are identified.

4.1 Single Microphone

Using rates of change of sound pressure level it is possible to design an influence fuze with a single microphone that can alert to an approaching aircraft and detonate in the region of CPA. The magnitude of the received signals is used to give an indication of the range to the target at CPA. There is considerable difference in sound output dependant on aircraft type and, without the benefit of aircraft identification on this particular system, the threshold can be designed to give various detonation profiles. For example, a low threshold would maximise the probability of triggering against small trainer aircraft within the lethal range of the warhead, but this is likely to detonate harmlessly against larger aircraft at a greater distance. Conversely, the likelihood of such a false trigger can be reduced with a corresponding reduction in the number of successful triggers against small aircraft. The optimum set of algorithm parameters is selected by modelling the effect of deploying weapon systems, fitted with influence fuzes employing a range of algorithm parameter sets, at a hypothetical airfield housing a uniform range of aircraft types. The preferred parameter set is then identified as that which maximises disruption to the operation of the airfield.

4.2 Microphone Clusters

These are geometrical arrangements of microphones used when target location and tracking is required. The ambiguities arising from a microphone pair can be resolved by adding one extra microphone, giving an equilateral triangle arrangement in a plane parallel to, or touching, the ground. If the angle between microphone pairs is α, applying equation 1 gives:

$$\begin{aligned} \cos\beta_1 &= \cos\theta \cos\phi \\ \cos\beta_2 &= \cos(\theta-\alpha)\cos\phi \end{aligned} \qquad (2)$$

For the equilateral triangle cluster there are three sets of microphone pairs, which can be used to provide three estimates of target bearing. More elaborate arrangements, such as regular tetrahedrons, can be used by adding a fourth microphone above the plane formed

by the triangular cluster. This can improve the resolution with which elevation angle can be determined.
Sometimes, where other sensor systems are being cued, it may only be necessary to know the elevation angle of the aircraft. A vertically stacked pair of microphones will be sufficient for this as the actual azimuth of the target is irrelevant.

4.3 Beamforming Arrays
These generally have a greater extent than the clusters and consist of more microphones. Horizontal linear arrays are common, but suffer from the same front-back ambiguity of the microphone pair. They are used for long-range detection of aircraft, and so the elevation angle can be assumed to be at, or close to, zero. A cruciform array is used in cases where the ambiguity must be resolved. Other arrangements, such as circular arrays, are possible, provided that the correct inter-element time delays can be applied to steer the receive direction.

5. CONCLUSIONS

The applicability of acoustic technology to influence fuzes for fully autonomous weapon systems has been shown. A wide variety of microphone arrangements and signal processing techniques allow acoustics to fulfil all the appropriate system functions. Acoustic technology can either be used alone, or in an alert and cueing function in multi-sensor systems.
It is worthwhile noting that as attempts are being made to make aircraft more stealthy in the electro-magnetic wavebands, the designers do not pay as much attention to the acoustic emissions.

6. REFERENCES

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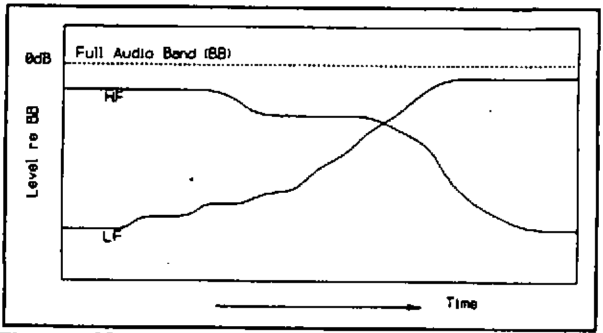

Figure 1 Normalised Band Levels for a Passing Aircraft

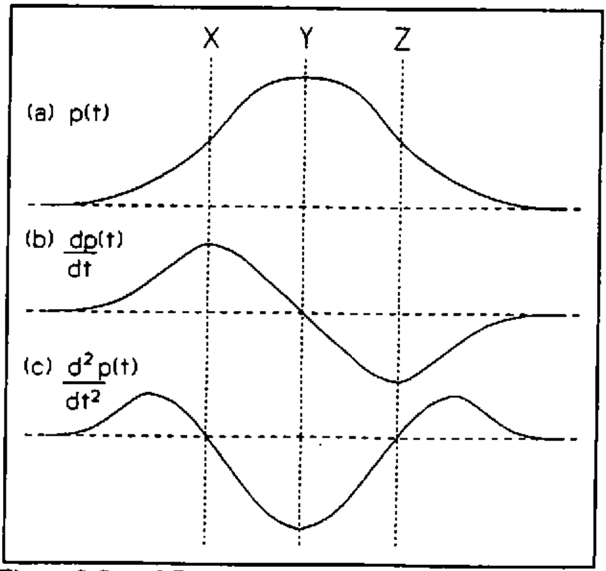

Figure 2 Sound Pressure vs Time for a Passing Aircraft

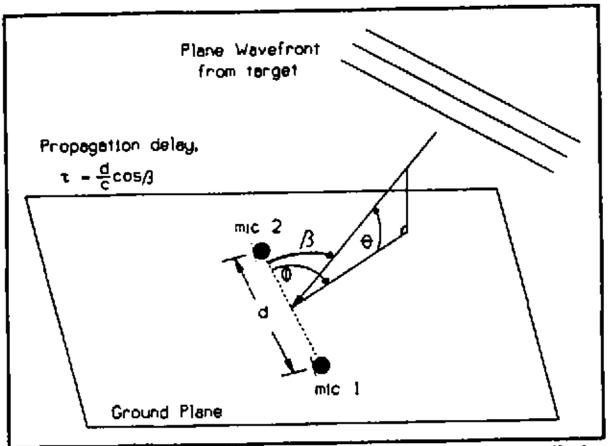

Figure 3 Acoustic Ray Incident on a Microphone Pair