DETECTION OF GUNSHOTS USING MICROPHONE ARRAY MOUNTED ON A MOVING PLATFORM

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ABSTRACT

Detection of gunshots on a moving platform such as a vehicle is subjected to platform and flow-noise. Hence, detection of muzzle blast signal in the noise is extremely difficult. The received signal at a microphone consists of two parts: one due to direct path and other due to multipath. The signals due to multipath ride the noise and appear as fine fluctuations. In this paper we present a technique to detect the whereabouts of muzzle blast signal (due to direct path) buried in noise by first detecting the signals due to multipath. Once the muzzle blast is detected, the time difference of arrival (TDOA) at several pairs of microphones can be used to localize the origin of the gunshot.

***Index Terms*—** gunfire detection, time difference of arrival, platform noise, flow noise, localization.

1. INTRODUCTION

Gunfire detection is an active research area for the Army. There are several commercial systems, namely, Boomerang [1], Pilar [2], etc. are available. There are also soldier-worn gunshot localization systems [3, 4], where an individual soldier carries a miniature acoustic array on the shoulder or helmet to estimate direction of arrival (DOA) angles. Damarla et al. have developed a sniper localization system [5] using the time differences between the muzzle blast and shock-wave arrival times at distributed microphone sensors.

All the systems described above are stationary systems, where the acoustic arrays are placed at suitable locations, except for the soldier-worn systems. However, the Army has a need to detect and localize gunfire on a moving vehicle since they may be subject to gunfire when they are traveling or on patrol. Vehicle-mounted systems are subject to platform noise (due to body vibrations, engine, drive train, etc.) and flow noise (due to air flowing over the microphones). Quite often the combined platform and airflow noise prevail over the muzzle blast, making muzzle blast detection difficult. *The main contribution of this paper is a technique to detect the whereabouts of muzzle blast signal buried in platform and airflow noise.*

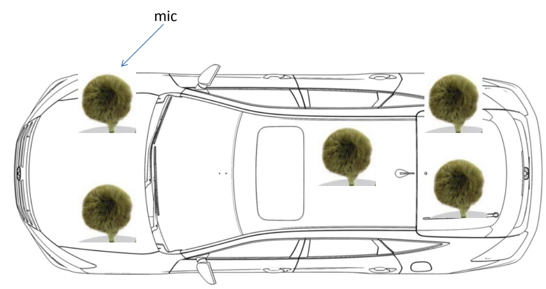

Fig. 1. Placement of microphones on a car for data collection

The organization of the paper is as follows. Section 2 describes data collection on a moving vehicle. Section 3 describes the techniques used to detect muzzle blast impulses (transient events) in the data collected on a moving vehicle. Section 4 presents localization of gunshots using time difference of arrival (TDOA). Section 5 concludes the paper.

2. DATA COLLECTION

In order to test the transient event detection on a moving platform, six microphones were mounted on the roof, back, and front hood of a car as shown in Figure 1. Two of the microphones are placed on either side of hood, two on the back, and two on the roof of the car. Each microphone is covered with a foam ball to reduce wind noise. In order to simulate the muzzle blast, we used a propane cannon which fired at regular intervals of ~ 18 sec. The car is driven at 40 – 50 kmph. The data are collected at 4000 samples/sec using a data acquisition system. All channels are time-synchronized so that the TDOAs can be measured accurately for localization of gunfire.

3. MUZZLE BLAST DETECTION

In order to localize the origin of a gunshot, one needs to detect time difference of arrival (TDOA) of muzzle blast at different microphones. The muzzle blast amplitude decreases with distance and its signal is often buried in the platform and flow noise. Figure 2 shows a typical transient signal collected on a moving vehicle. One of the pulses due to cannon firing occurred around the 3.5 sec mark on Figure 2(a) and three others occurred around the 20 sec, 37 sec and 54 sec mark. The former is clearly visible with high signal-to-noise ratio with a peak-to-peak amplitude of ~ 7.5 V. For this pulse, the distance between the cannon and the vehicle was around 60 m. As mentioned earlier the car was moving at about 40 – 50 kmph. The next cannon fire occurred around the 20 sec mark. The distance between the cannon and the vehicle for this event is $\sim$ 250 m. The signal-to-noise ratio is low. The expanded portion of the data around 20 sec and 54 sec are shown in Figure 2(b) and (c) respectively. We could identify the pulse due to cannon firing after careful inspection.

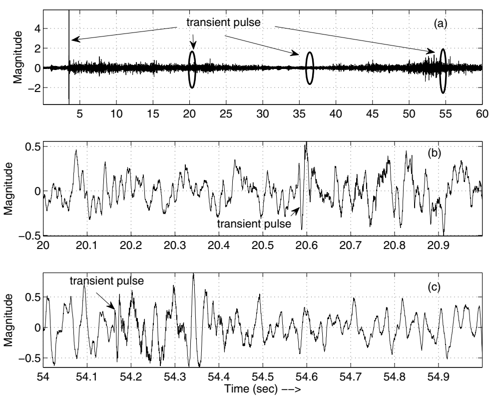

Fig. 2. (a) 60 sec of data with three impulses, (b) impulse at 20 sec mark (c) impulse at 54 sec mark

The noise and the signal due to muzzle blast captured on a moving vehicle is non-stationary. Traditionally, such non-stationary data is analyzed using time-frequency analysis techniques, such as, Wigner-Ville or wavelet transforms. The Wigner-Ville (WV) time-frequency analysis of signal $s(t)$ is given by

$$W_s(t,\omega) = \frac{1}{2\pi}\int s\left(t+\tau/2\right) s^*\left(t-\tau/2\right) e^{-j\omega\tau} d\tau \quad (1)$$

where '*' denotes the complex conjugate and τ is the time lag. Figure 3 shows the WV distribution of three seconds of signal starting from 53 sec mark shown in Figure 2(a). From Figure 3 it is hard to tell that the segment 54 – 55 sec is the one with an impulse corresponding to the muzzle blast as all three segments in the figure have similar properties. Prior to attempting to detect a transient pulse that is buried in noise, let us first model the signal $s(t)$ due to gunfire that is captured by a microphone.

$$s(t) = A_0 x(t) + \sum_{i=1}^{M} A_i x(t+\tau_i) + n(t) \quad (2)$$

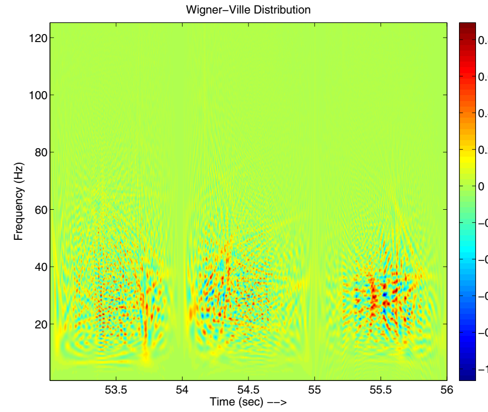

Fig. 3. WV distribution of data from mark 53 – 56 sec

where $x(t)$ is the muzzle blast signal, A_i and $x(t+\tau_i)$ are the amplitude and i^{th} multipath signal with time delay τ_i where $A_0 >> A_i$. The multipath signals arrive after the direct path signal and superimpose on the noise. This is seen in figures 2(b) and 2(c) (more clearly in Figure 5(a)) as additional fluctuations riding noise immediately after the occurrence of transient pulse. We use this feature to localize the occurrence of the transient event, that is, we try to find the time when the additional fluctuations in signal occur. Next, we show how empirical mode decomposition (EMD) of the signal can be used to detect these oscillations in the signal due to multipath.

Huang et al. [6] showed that a non-stationary signal can be decomposed into a sum of intrinsic mode functions (IMFs). The decomposition is based on the direct extraction of the energy associated with various intrinsic time scales. The IMFs have well-behaved Hilbert transforms, from which the instantaneous frequencies can be calculated. Hence, we can localize any event on the time as well as frequency axis.
Intrinsic mode functions [6]: An IMF is a function that satisfies two conditions: (1) in the whole data set, the number of extrema and the number of zero crossings must either equal or differ at most by one; and (2) at any point, the mean value of the envelope defined by the local maxima and the envelope defined by the local minima is zero. Figure 4 shows the decomposition of the signal in Figure 2(c) into its IMF components.

The IMFs can be thought of as basis functions (not necessarily orthogonal) and their construction [6] is based on the physical time scales that characterize the oscillation of the phenomenon. In Figure 5(b) we plotted the first IMF signal generated by EMD of the signal in Figure 5(a). Figure 5(b) shows the change in signal level due to multipath after the transient pulse occurred. This change in level can be used to identify the approximate location of the transient pulse. This change in signal level persists for a fraction of second. Once the location of the change in signal levels is

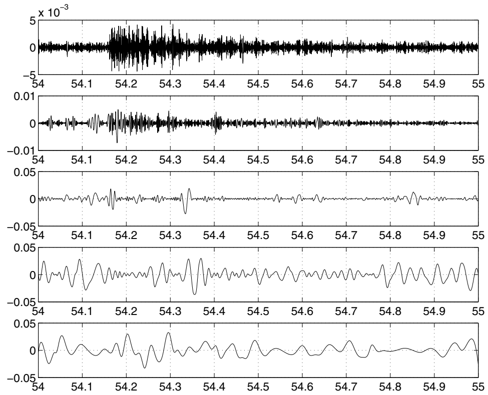

Fig. 4. IMF functions of signal at 54 sec mark

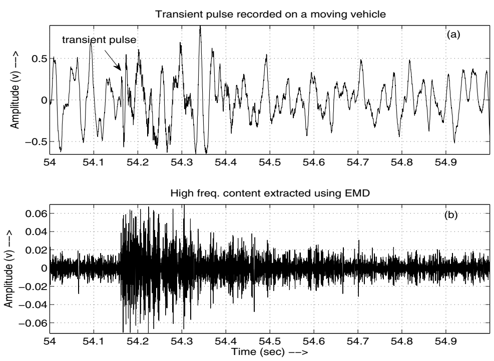

Fig. 5. (a) Signal with transient pulse and (b) first intrinsic mode function

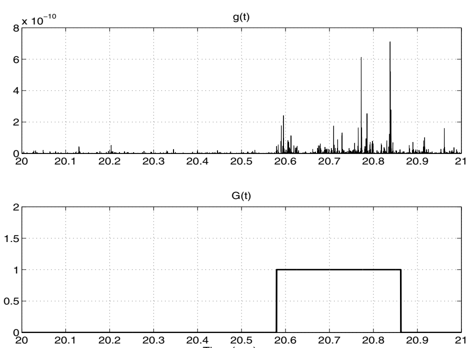

Fig. 6. Detection of the location of the transient pulse

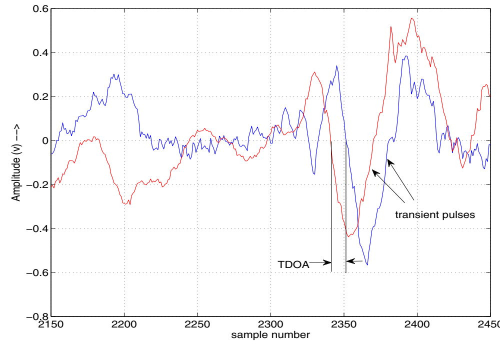

Fig. 7. TDOA between two microphones

detected, the transient pulses just precede these changes can be detected. The TDOAs can be estimated using generalized correlation methods [7]. The following algorithm is used in detecting the change in signal levels due to multipath.

Algorithm for detection of change in signal levels due to multipath:

1. Let s_i be the signal corresponding to the i^{th} microphone, $i \in \{1, \cdots, n\}$.
2. Let $e_i = \mathrm{emd}(s_i)$, where "emd" is the empirical mode decomposition of signal s_i and $e_i = \left[e_i^1, e_i^2, \cdots, e_i^k\right]^T$ is a matrix of 'k' intrinsic mode functions.
3. Compute $g(t) = \prod_{j=1}^{n} e_j^1(t)$
4. Set

$$G(t) = \begin{cases} 1, & \text{if } g(t+\tau) > \delta \text{ and } 0.1 \leq \tau \leq 0.3s \\ 0, & \text{otherwise} \end{cases}$$

where $\delta = m + 2 * \sigma$ is the threshold, m is the mean and σ the standard deviation of the absolute value $\|g\|$.

Figure 6 shows the output of the algorithm, showing beginning of the high frequency components that arise just after the transient pulse due to multipath, hence locates the vicinity of transient pulse. Figure 7 shows the TDOA between two microphones for the signals shown in Figure 5.

In order to test the algorithm, several rounds of data are collected on two different days. A total of 50 shots (propane cannon bursts) were recorded and analyzed. Out of 50 shots 10 shots were not detected as the signal due to multipath was not present. Further investigation of the signal revealed that even the transient pulses due to propane cannon bursts could not be identified in the data for those 10 shots. The estimated distance for these 10 shots varied from 500 to 700 m and the amplitude of the transient pulse attenuated to a level that it is not perceptible. In all other 40 shots the transient pulses are detected.

For the sake of continuity we present the localization algorithm using TDOAs.

4. LOCALIZATION OF GUNFIRE USING TDOAS

Let the instant the gun's muzzle blast is emitted be t_0 and the time the signal arrived at the sensor S_i be t_i, then the distance the sound traveled is $r_i = (t_i - t_0)\, c$, where c is the propagation velocity of sound. Then the TDOA between two sensors, S_i and S_j, is given by

$$t_{ij} = (t_i - t_0) - (t_j - t_0) = (t_i - t_j) \tag{3}$$

and the difference in the distances is

$$r_{ij} = (t_i - t_0)\, c - (t_j - t_0)\, c = (t_i - t_j)\, c = r_i - r_j \tag{4}$$

The signal source must lie on the locus, which keeps the difference r_{ij} constant. This locus defines a hyperbola. If there are at least three sensors, the intersection of hyperbolas gives the location of the signal source. The following approach gives the procedure to find the point of intersection of the hyperbolas [8, 9]. Let $S = (x, y)$ denote the location of the sound source to be estimated; the locations of the sensors. $S_i = (x_i, y_i)$ are known. Without loss of generality, the location of S_1 is set at $(0, 0)$. Now, from equation 4

$$r_{i1} = r_i - r_1$$

or $\quad r_{i1} + r_1 = r_i = \sqrt{(x_i - x)^2 + (y_i - y)^2}$

or

$$(r_{i1} + r_1)^2 = K_i - 2x_i x - 2y_i y + r_1^2 \tag{5}$$

where $K_i = x_i^2 + y_i^2$ and $r_1^2 = x^2 + y^2$. Equation 5 can be rewritten as

$$x_i x - y_i y = -r_{i1} r_1 + \frac{1}{2}\left(K_i - r_{i1}^2\right). \tag{6}$$

Explicitly writing for all sensors, the above equation becomes

$$\begin{bmatrix} x_2 & y_2 \\ x_3 & y_3 \\ \vdots & \vdots \\ x_n & y_n \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} = r_1 \begin{bmatrix} -r_{21} \\ -r_{31} \\ \vdots \\ -r_{n1} \end{bmatrix} + \frac{1}{2} \begin{bmatrix} K_2 - r_{21}^2 \\ K_3 - r_{31}^2 \\ \vdots \\ K_n - r_{n1}^2 \end{bmatrix} \tag{7}$$

This is in the form of a linear equation

$$HX = r_1 G + D. \tag{8}$$

The least-squares solution in terms of r_1 yields

$$\hat{X} = \left(H^T H\right)^{-1} H^T \left(r_1 G + D\right). \tag{9}$$

Substituting this intermediate result into $r_1^2 = x^2 + y^2$, leads to a quadratic equation in r_1. Solving for r_1 and substituting the positive root back into equation 9 yields the final solution for X. This method is called the spherical interpolation.

5. CONCLUSION

Data collected on a moving vehicle using microphones for localization of gunfire are subject to platform and flow noise. These noise are predominant compared to the muzzle blast signal impinging on the microphones. The muzzle blast signal decreases with distance and is hard to detect in the presence of platform and flow noise. Searching for a muzzle blast signal in the presence of platform and flow noise is like finding a needle in a haystack. In this paper, we showed a technique to find the vicinity where the muzzle blast signal occurs. It is showed that direct signal due to muzzle blast is followed by multipath signals that appear as fluctuations riding noise. We showed empirical mode decomposition (EMD) of the signal allows us to detect these fluctuations riding noise. Since the actual muzzle blast signal precedes the high frequency signal, it is easy to detect the muzzle blast after detecting the fluctuations riding noise.

6. REFERENCES

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