Applications of Acoustic-to-Seismic Coupling for Landmine Detection

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Abstract-- **An acoustic landmine detection system has been developed using an advanced scanning laser Doppler vibrometer. Landmines buried in the subsurface induce distinct changes in the seismic vibration of the surface when acoustic sources insonify the ground. A laser Doppler vibrometer senses these acoustically-induced seismic motions of the ground surface in a non-contact, remote manner. Recent field-testing has demonstrated promising results both in downward- and forward-looking scenarios. This system exhibits significant advantages over conventional metal-detecting sensors due to its capability for detecting both metal and non-metal mines, particularly plastic mines. A further development of the current system using a continuously moving laser beam and a moving platform also indicates great potential for increasing detection speed. This paper describes the system configuration, the acoustic signals, data analysis, detection procedure, and recent field measurement results.**

***Index terms*—landmine detection, acoustic detection, acoustic-to-seismic coupling**

I. INTRODUCTION

Sound waves above the ground can penetrate into the ground surface due to poro-elastic nature of the soil or granular nature of road construction materials. The sound energy coupled into the ground causes seismic motion of the ground surface and subsurface, called acoustic-to-seismic (A/S) coupling. A review of the underlying physics can be found in reference [1]. Landmines buried in the subsurface will resonate [2] and induce distinct changes in the seismic motion due to scatter and reflection of the sound energy coupled into the ground.

The vibrational velocity on the ground surface is sensed using a laser Doppler vibrometer (LDV). The current landmine detection system employs a single-point interferometer. A laser beam is emitted from the LDV onto a vibrating surface of an object under test; the surface vibrational velocity causes a Doppler frequency shift of the laser light. The backscattered light from the measured object takes the opposite path back into the interferometer and is sensed by its photo-detector (see reference [1] and [3] for more details about a LDV). After FM-demodulation of the detector output, the signal is proportional to the surface velocity under test. The output of a LDV system is a voltage proportional to the instantaneous velocity of a particular spot on the object under test. In measuring a ground patch, the laser beam is steered in a raster-scanning or continuously-moving manner. During scanning, a sound source radiates pseudo-random noise typically covering the frequency range between 60 Hz and 400 Hz. This range was selected based on the results of experiments conducted in the frequency range between 40 Hz and 4 kHz. These experiments revealed the optimal frequency range lies between 80 Hz and 300 Hz for anti-tank landmines buried not deeper than 20 cm (8 inches). On the scanned patch, the sound pressure level can range between 90 dB (C) to 120 dB (C). The angle of sound incidence is not critical since the porous ground can be considered as locally reacting [1].

Sec. II discusses the raster-scan mode for both downward- and forward-looking detection. Sec. III discusses moving the laser beam continuously for scanning a ground patch. Sec III also includes preliminary experimental results using a single-beam LDV on a moving platform.

II. DOWNWARD- AND FORWARD-LOOKING CAPABILITY

A. Downward-Looking Landmine Detection

Fig. 1 shows a photo of the LDV-based A/S landmine detection system used in field measurements. The LDV head was mounted on a vehicular platform at a height of 3.5 m. The laser beam is focused downwards on the ground surface. Loudspeakers positioned on a platform in front of the vehicle radiate pseudo-random noise towards the road patch. The LDV scanning system predefined a grid of varying size on the ground source as shown in Fig. 2(a). In this example, a grid of 16 by 16 points covered a road patch of 1m by 1m. The laser beam stopped on each grid point. The LDV-based measurement system collected a number of periods of the A/S surface response to periodic pseudo-random noise excitation. The data analysis included fast Fourier-transforms with averaging in the frequency-domain. RMS values of velocity magnitude spectra within sub-frequency bands were then evaluated. The colored dots in Fig. 2(a) show representative results for a plastic anti-tank VS 2.2 landmine buried 7 cm deep in a U.S. Army test lane. Fig. 2(b) shows the scanning results in a color-coded 3D-presentation. Fig. 3 depicts two magnitude velocity spectra on top of and away from the mine, respectively. Two magnitude velocity spectra marked by A and B, relative to the background velocity spectra marked by C, and D (see Fig. 2(a)), exhibit strong amplification in the frequency range between 120 Hz and 170 Hz with a peak velocity around 55 um/s while the background velocity ranges between 3-8 um/s within this frequency range. The ratio between the velocity on the top of and away from a mine is referred to in this paper as (magnitude or amplitude) *gain*. Extensive field measurement results have shown that the A/S coupling gain of anti-tank landmines at the given acoustic excitation can range between two and several tens.

In general, three factors primarily influence the decision concerning whether or not a mine is present. The magnitude gain of velocity is used as the first major cue to detect mines. With consistent amplification of the magnitude of velocity over a relatively broad frequency band, the next major cue is a circular shape in the scanning image (as shown in Fig. 2 (a), (b)) that remains almost unchanged when stepping through the overall frequency range within a sub-band. Clutter enters and exits from the sub-band image. Lastly, the size of the spot of interest is exploited for a decision. Occasionally, the phase information is also used to animate scanning images to enhance identification of the circular-shaped target and to suppress anomalies [1],[3]. The blind-test results using the LDV-based A/S landmine detection system of the University of Mississippi, in the downward-looking mode, demonstrated a probability of detection (P_d) of 95% with a false alarm rate of $0.03/m^2$ [1].

B. Forward-Looking Landmine Detection

LDV-based A/S landmine detection can also be used in a forward-looking mode as shown in Fig. 4. This measurement setup achieved a stand-off distance of 8 m. Fig. 5 shows scanning results on the same anti-tank landmine using both downward- and forward-looking modes for comparison in a U. S. Army test lane.

The LDV system measures the velocity component along the direction of the laser beam. Extensive investigations on the LDV beam angle effects have been conducted in field environments [4]. Fig. 5 shows a group of experimental results obtained when changing the beam's grazing angle while keeping constant the sound pressure level on the patch and the distance between the LDV head and the scanning patch. With a decreasing grazing angle of the forward-looking laser beam, the magnitude gain on the ground surface near the top of the mine decreased, while the averaged background velocity changed insignificantly.

In general, the LDV-based A/S forward-looking landmine detection is subject to a number of challenges. With increased detection standoff distance, laser-power reflecting from the scanned patch is reduced and sound power is also reduced, resulting in a lower level of detection signals. With decreased grazing beam angle to the ground surface, the velocity component along the laser beam is also decreased. Laser light energy returning to the LDV is decreased once the beam is moved off of the normal incidence. Any platform movement/vibration also moves the laser beam on the spot of the ground where the beam is shining, resulting in lower and poorer detection signals.

Aware of all these challenges, the landmine detection team at the University of Mississippi conducted a blind test in the forward-looking mode at 45-degree beam angle and 6-m standoff distance. The P_d was 68% with a false alarm rate of $0.01/m^2$. This blind test result indicates that the LDV-based A/S landmine detection system retained its low false alarm rate in the forward-looking mode. The lower probability of detection (P_d) relative to the 95% P_d of the downward-looking mode was primarily due to challenges mentioned above resulting in reduced detection signals on the top of landmines.

In further field testing at grazing angles of 45 degrees, (a 5-meter sensor height and 5-meter look ahead distance), the data of the LDV-based A/S landmine detection system show very high P_d's for metal and plastic mines buried flush to 5- cm deep. Preliminary data show P_d's of greater than 95% for dirt and gravel roadways. The results are improved for plastic mines alone. The P_d decreases as the mine burial depth increases beyond 5 cm. Results show that, for mines buried between 10 and 15 cm, the P_d is 75% for the same roadways but with a continued low false alarm rate. Additionally for data at forward-looking angle of 22 degrees, (3-meter high sensor by 7-meter look ahead distance) the detection rate remains greater than 95% for mines buried flush to 5 cm but drops to 50% for mines buried between 10 and 15 cm. A continued low false alarm rate is maintained.

Because these methods of detection employ a "stop and stare" procedure for the LDV interrogating the surface velocity, this technology has been limited by slow scanning speeds. The next section will discuss potential possibilities of speeding up the scanning rate using the single-beam LDV system.

III. CAPABILITY OF A MOVING BEAM AND PLATFORM

As with many detection techniques, an obstacle in acoustic detection methods is operational speed. Requirements for vehicle-mounted systems used in military mine detection demand speeds of up to 60 km/hr. While this may be a long-term goal in detection, intermediate steps seek methods to significantly increase the speed over the status quo. An array of multiple single-beam LDV devices can increase the scanning speed, but this is best employed after optimizing usage of the single-beam devices. This section discusses two methods for speeding up the operation speed using the current single-beam LDV-based detection system.

A. A Moving Beam on a Stationary Platform

The mirror-controlled motion of the single beam LDV system described in the previous section was modified in its scanning mode while the LDV-head was stationary on a vehicle. The laser beam was controlled to move continuously along a sweeping trace as shown in Fig. 6 while it measured the instantaneous velocity of the ground surface. The beam moved horizontally with a constant speed. When the laser beam arrived at the pre-defined edge of a scanning area, it stepped abruptly down. In this way the laser beam scanned a road area in a continuously-moving manner.

Fig. 7 illustrates moving-beam scanning results in a U.S. Army test lane. A plastic anti-tank landmine VS 2.2 was buried 2.5 cm deep in a gravel road. Two loudspeakers radiated four tones of equal amplitude at 110, 120, 130 and 140 Hz. The surface velocity response to the acoustic excitation was recorded while the laser beam was moving along the scanning trace as shown in Fig. 6. 16 horizontal lines were defined covering an area of 1 m by 1 m. Scanning results at three different moving speeds of 0.4 m/s, 0.8 m/s and 1.6 m/s are depicted in Fig. 7(b), (c) and (d) respectively. The corresponding scanning time to cover 1 square meter road patch was 40, 20 and 10 seconds long, respectively. Fig. 7(a) shows the stop-and-stare scanning result evaluated in a frequency range between 120 Hz and 130 Hz for comparison.

B. Forward-Moving Platform

In order to further investigate the moving detection capability, a single-beam LDV was mounted on a moving cart traveling at a constant speed while the surface velocity was recorded. Fig. 8 illustrates the measured results of this experiment [5]. Acoustic excitation was provided using a shaker attached on the ground near a VS 2.2 anti-tank mine buried 2.5 cm deep in a U. S. Army test lane. A single-tone at 190 Hz was driving the shaker. After appropriate post-processing of the recorded surface velocity, the figure shows the processed signals both in time and frequency domains. Amplified magnitude velocity could be detected when the LDV was moving across the top of the mine.

This section discussed experimental study on the moving detection capability of the laser Doppler vibrometer (LDV) based acoustic-to-seismic landmine detection. The preliminary field results shed light on continuously moving A/S landmine detection. While the stop-and-stare scanning using the current single-beam scanning LDV has been tested extensively in various field environments the moving beam detection is still the current and near-future focus of our research effort. Based on these results, the near term effort to increase scanning speed will rely on a moving LDV beam.

IV. SUMMARY AND CONCLUDING REMARKS

Acoustic-to-seismic (A/S) coupling has found successful applications in landmine detection leading to the development of the laser Doppler vibrometer (LDV) based A/S landmine detection system. Test results promise great success in the downward-looking deployment mode while showing strong possibilities for forward-looking detection.

Extensive field tests have shown that the stop-and-stare scanning mode can yield the most reliable detection measurements. However, its limited detection speed inspired further investigation on the moving beam and moving platform detection modes. While the preliminary experimental study on the moving platform reveals feasibility, systematic field tests on a moving LDV beam mounted on a stationary platform, even on the early stage, already substantiates a significant increase of the detection speed. These studies pave the way to the development of A/S moving landmine detection systems using multiple laser beams.

Acknowledgment

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Figure 1. Downward looking laser Doppler vibrometer (LDV) based acoustic-to-seismic coupling landmine detection system in a field environment. The LDV head is mounted on a vehicle 3.5 meters above the ground. The laser beam is focused downwards onto the ground surface. Two loudspeakers in front of the vehicle wheels radiate acoustic waves towards the road surface.

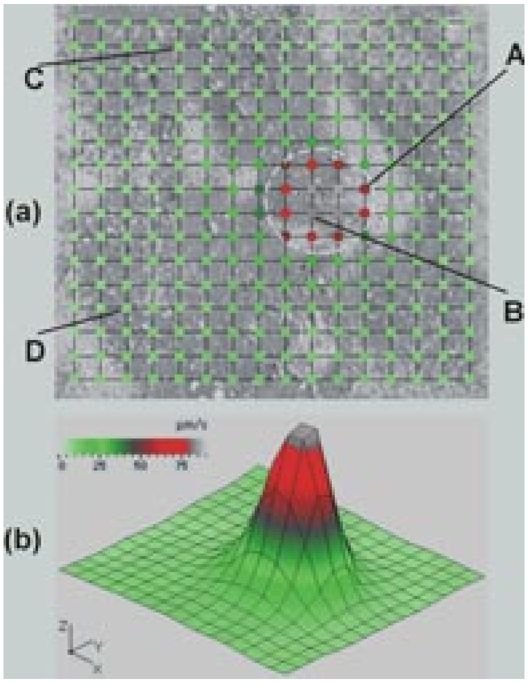

Figure 2. Stop-and-stare scanning results. A plastic VS 2.2 anti-tank landmine buried 7 cm deep in a U.S. Army test lane. (a) A grid of 16 by 16 points covering a road patch of 1m by 1m. The laser beam stops on each grid point on the ground surface to measure the surface velocity. A dot-line circle indicates the location of the target. The color scale is in (b). (b) Color-coded 3D presentation.

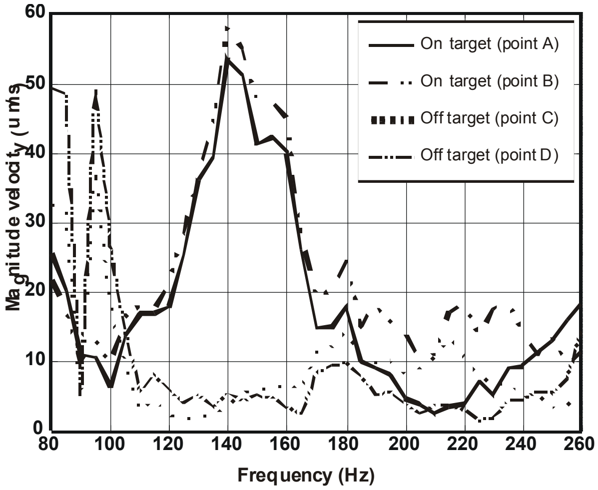

Figure 3. Magnitude spectra measured by laser beam of the LDV based A/S landmine system. The sound source radiates pseudo-random noise covering the frequency range between 80 Hz and 260Hz. Magnitude spectra were measured on individual grid points marked in Fig. 2(a).

Figure 4. Forward-looking laser Doppler vibrometer based acoustic-to-seismic coupling landmine detection system in field environment. The laser beam is focused forwards onto the middle of the road shown on the right side of the photo.

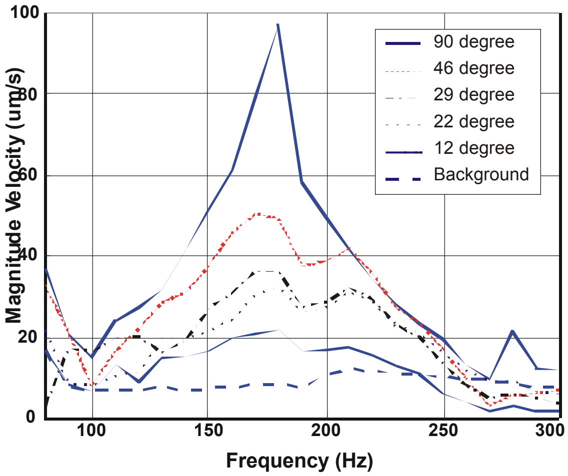

Figure 5. Beam angle effect in the forward-looking landmine detection mode. 90 degrees corresponds to the downward-looking scenario. As the beam (grazing) angle to the ground surface decreases, the magnitude velocity on top of a mine decreases as well, while the averaged background velocity changes insignificantly.

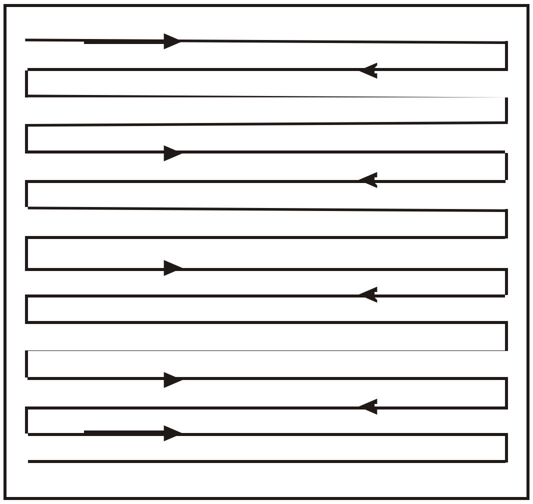

Figure 6. Moving beam scanning an area. The beam moves continuously across horizontal lines with a constant speed while stepping down when the beam arrives at the edge of the pre-defined area. The instantaneous velocity response on the ground surface is measured by the moving laser beam

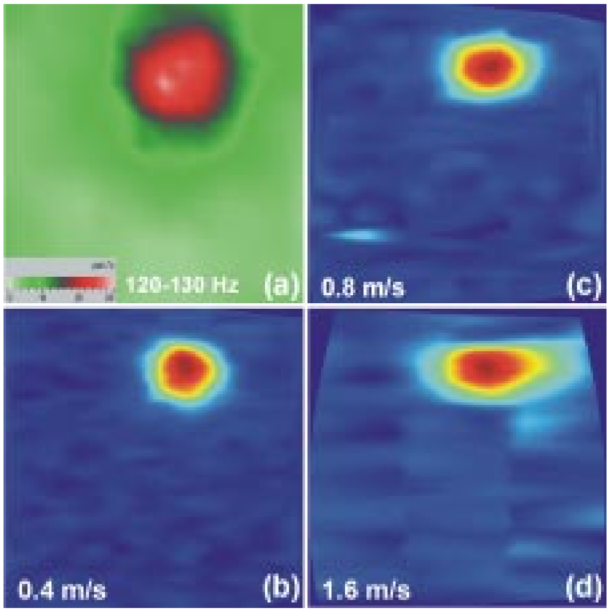

Figure 7. Scanning results using a moving laser beam over a buried VS 2.2 anti-tank mine buried (a) Stop-and-stare scanning results. (b) Scanning result at 0.4 m/s moving speed. (c) Scanning result at 0.8 m/s moving speed. (d) Scanning result at 1.6 m/s moving speed.

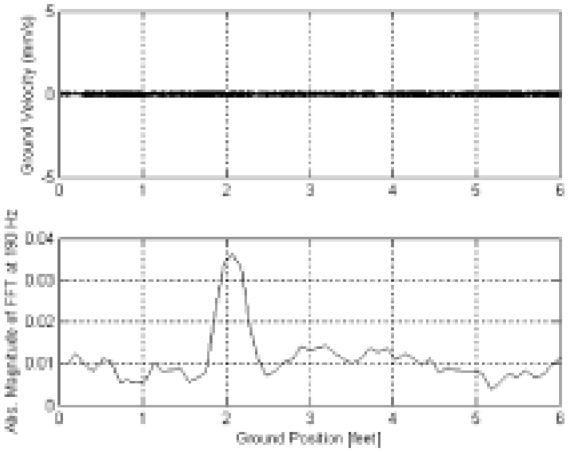

Figure 8. Field results achieved using a single-beam laser Doppler vibrometer mounted on a forward moving cart. Upper graph: surface vibration response in time-domain. Lower graph: RMS value of magnitude response evaluated in frequency domain.