Advanced LDV Instruments for Buried Landmine Detection

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ABSTRACT

Several experiments have demonstrated the potential of Laser Doppler Vibrometry, in conjunction with acoustic-to-seismic coupling or mechanical shakers, for the detection of buried landmines. For example, experiments conducted by The University Of Mississippi and MetroLaser, Inc. have shown the ability to scan a one square meter area in less than 20 seconds with a 16-beam multi-beam LDV (MB-LDV), and find the landmines under a variety of soil conditions. Some critical requirements for this technology are to reduce the measurement time, increase the spatial resolution, and reduce the size of the systems. In this paper, MetroLaser presents data from three optical systems that help achieve these requirements: 1) A Compact MB-LDV, 2) A two dimensional, or Matrix Laser Doppler Vibrometer (MX-LDV), and 3) A Whole-field Digital Vibrometer (WDV). The compact MB-LDV produces a 1-D array of beams, which may be scanned over the target surface with a scanning mirror. The size of the new, compact MB-LDV system has been reduced to approximately 17" x 11" x 9", thus enhancing its capability for field applications. The MX-LDV, to be developed in 2006, produces a 16x16 array of beams over a one meter area, allowing the ground velocity of the entire area to be measured in a single measurement. The WDV uses a camera-based interferometry system to take a snapshot of the ground vibration over a one meter square area with very high spatial resolution. Field tests for this system are scheduled for mid-2006.
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1. INTRODUCTION

Laser-acoustic methods of landmine detection have demonstrated excellent results in detecting buried landmines with a low false alarm rate[1,2,3]. These methods are based on the excitation of vibrations in the ground and a measurement of the ground vibration velocity. The presence of a buried landmine can be detected by studying the spatial distribution of the ground velocity spectra. Initially, these measurements were performed with a single point scanning LDV[1]. To expedite the data acquisition time, more recent experiments have used an array of single point LDVs[2] or a scanning multi-beam LDV[3]. Although each of these methods has successfully demonstrated the detection of buried landmines, there remains a need to further reduce the system measurement time. In addition, recent experiments have shown that many landmines exhibit a multi-mode vibration pattern[4]. A mapping of this vibration pattern would aid in the identification of the mine type, but would require spatial resolution on the order of a few millimeters.

In this paper, MetroLaser describes three instruments that will improve the performance of laser-acoustic landmine detection systems. The first is an enhancement to the multi-beam laser Doppler vibrometer (MB-LDV) described in Reference 3. This new, compact MB-LDV has a much smaller footprint, a shorter standoff distance, an increased number of beams, and additional signal processing options. The second instrument is a two-dimensional, or Matrix laser Doppler vibrometer (MX-LDV), which will produce a 16x16 array of beams over a one meter area. The third instrument, a Whole-Field Digital Vibrometer (WDV), will be the primary focus of this paper. The WDV uses a camera-based interferometry system to take a snapshot of the ground vibration over a one meter square area with very high spatial resolution.

2. COMPACT MB-LDV

A schematic for the design for the MB-LDV is shown in Figure 1. The MB-LDV divides the beam from a single laser into multiple beams with a Diffractive Optical Element, directs each beam onto the target, and then measures the target

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velocity at each beam location with an independent detector. Further details of the MB-LDV design can be found in a previous publication[5].

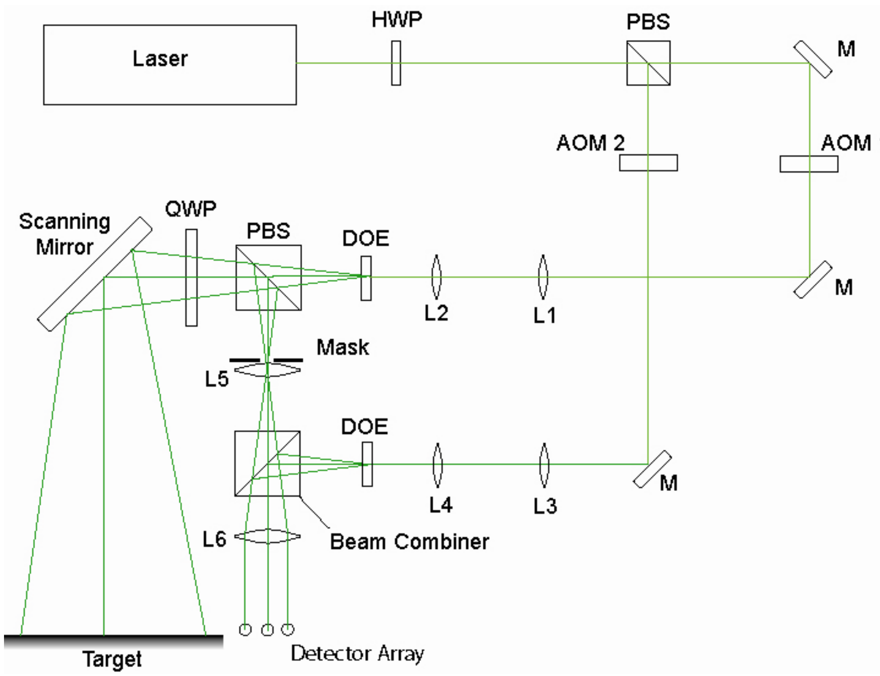


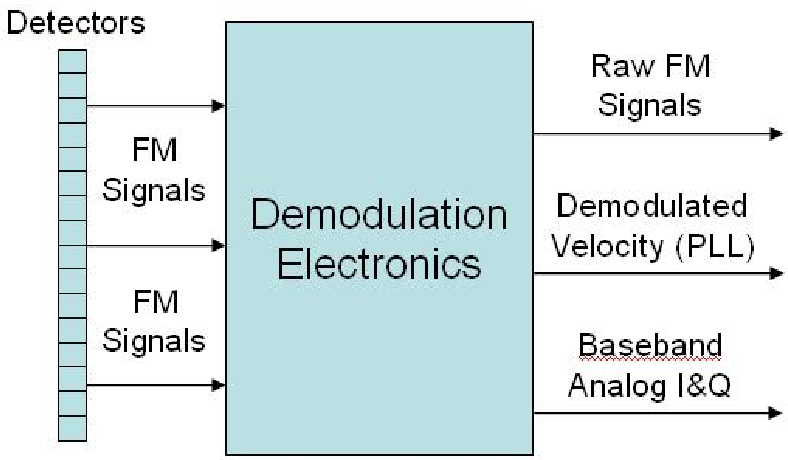
Figure 1. Schematic of the MB-LDV system.

The first version of the MB-LDV has been used in field tests for landmine detection for over two years, and has demonstrated great success in the detection of buried landmines. The system described in this paper incorporates several improvements over the first generation system. The primary difference is the size of the overall system; the initial system was 24” x 36” x 12”, while the size of the present system has been reduced to 11” x 17” x 9”, approximately one-sixth in total volume. A photograph of the first system is shown in Figure 2(a), while the new system is shown in Figure 2(b).

(a) (b)

Figure 2. (a) First MB-LDV mounted on a forklift. The dimensions of the optical head are 24”x 36”x 12”. (b) Compact MB-LDV, with dimensions of 11” x 17” x 9”.

In addition to the much smaller size, several other features have been added in the compact MB-LDV. One significant improvement is that the system can now accommodate up to 31 beams, which significantly improves the spatial resolution of the system. Also, the required stand-off distance to the ground has been reduced from 2.5 meters down to 1.5 meters. Another important development is that several types of output signals are now available. The first MB-LDV system utilized a Phase-Locked Loop (PLL) array for the velocity demodulation. The compact MB-LDV also includes the PLL array, but also incorporates baseband In-Phase and Quadrature (I&Q) outputs, as well as direct detector FM outputs. For moving laser beams, the I&Q and direct FM outputs have been shown to have better performance than the PLL array[6]. Field testing of the compact MB-LDV system is scheduled for Spring of 2006.



3. MATRIX LDV (MX-LDV)

Using the scanning MB-LDV system, the ground velocity over a one meter area can be accurately measured in approximately 10-20 seconds. One method to reduce the measurement time significantly is to expand the system from a 1-D array to a 2-D matrix. This allows the measurement to be made in a single shot, without the need for any scanning. MetroLaser, Inc. is currently developing a Matrix LDV system (MX-LDV) that produces 256 beams in a 16x16 beam pattern. In addition, by measuring all of the points in parallel, the relative phase of the ground vibration can also be studied. A photograph of the beam array on an aircraft panel is shown in Figure 3. System tests with the MX-LDV are scheduled for summer of 2006.

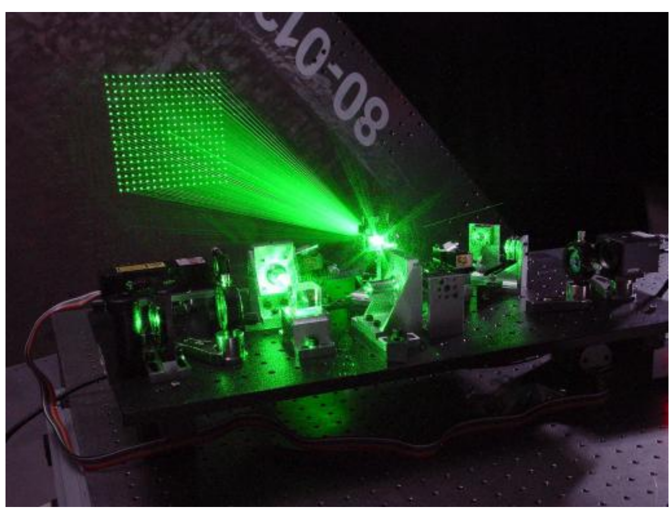


Figure 3. Beam pattern of the MX-LDV on an aircraft panel.

4. WHOLE-FIELD DIGITAL VIBROMETER (WDV)

The Whole-Field Digital Vibrometer (WDV) is a system to measure the ground vibration velocity over a large area in a single shot. The system is based on Electronic Speckle Pattern Interferometry (ESPI), which uses laser phase-shift interferometry and high resolution CCD cameras to provide high sensitivity along with high spatial resolution. Previously published work has used double-pulsed ESPI to demonstrate the required spatial and displacement resolution for buried landmine detection[7]. However, these previous experiments employed a double-pulsed ruby laser, which has a limited range of separation between the two pulses, and thus a limited range of displacement sensitivities and vibration frequencies. In this paper, we present a Whole-Field Digital Vibrometer (WDV) system that has arbitrary separation between the two laser pulses and instantaneous, phase shifting interferometry, which makes the system well suited to buried landmine detection.

Phase-shift interferometry is an established method for improving the accuracy and robustness of conventional laser interferometers. Phase-shift interferometers[8] typically have an element in the path of the reference wavefront that can introduce three or more known phase steps or shifts (for example, steps of 90, 180, and 270 degrees). By detecting the intensity pattern at each of the phase shifts, the overall phase distribution of the object wavefront can be calculated with higher precision. In addition, the direction of any 2π phase discontinuities can be unambiguously resolved.

The WDV interferometer uses a unique and patented instantaneous phase-shifting method. The patented[9] optical system works by dividing orthogonally-polarized reference and object beams into four identical copies, using a Holographic or Diffractive Optical Element (HOE, DOE), that are imaged contiguously onto a single CCD sensor array. Figure 4 shows the basic optical configuration used in the WDV to effect simultaneous phase-shift interferogram acquisition with a single sensor array. Each interferogram receives a different relative phase shift via a polarization quadrant mask that is placed on top of the detector array. By using a single detector array instead of four, the interferometer is compact and easy to align, is insensitive to motion of the detector array (because all pixels translate together), and has a simplified camera interface requirement. By using a fixed polarization mask to provide the phase shifts, the calibration is maintained even in harsh vibrational environments. Additional background material on phase-shift interferometry and ESPI systems can be found in Reference 10.

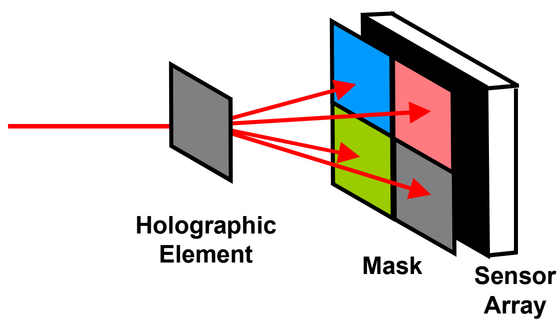


Figure 4. Basic optical configuration of the instantaneous spatial phase-shifting.

An overall schematic of the WDV system is shown in Figure 5. The system incorporates two independent green lasers than can each produce up to 150 mJ of energy in a 10 ns pulse. Each pulse is divided into an object beam and a reference beam. The object beam is expanded to illuminate the target, and then scattered light from the target is collected and imaged to a plane behind the Polarizing Beam Splitter Cube. The object and reference beam images are then directed through the HOE and Phase Mask, and produce four simultaneous phase-shifted specklegrams on the four megapixel CCD camera. From these four specklegrams, a phase map of the surface can be derived.

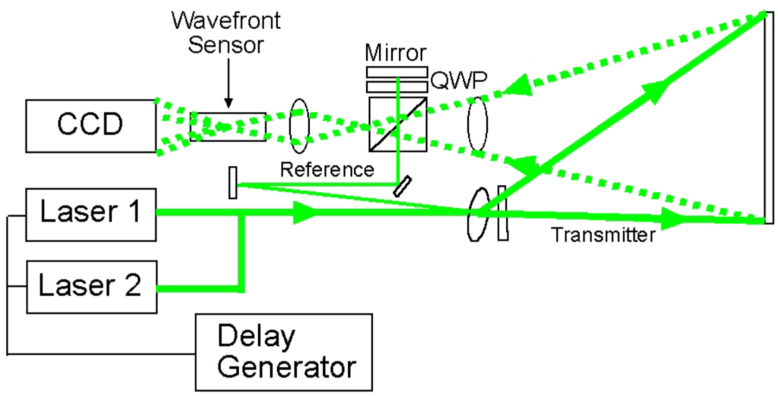


Figure 5. Schematic of the WDV system.

An overview of the system operation is shown in Figure 6. Here, a frequency of 400 Hz has been selected, and phase locations of 90 and 270 degrees have been selected. Based on this information, the computer generates a continuous tone at 400 Hz, which is used to drive the acoustic source. The computer then triggers the two lasers to fire; the first at the peak of the acoustic cycle (90 degrees), and the second at the valley of the acoustic cycle (270 degrees). The computer also triggers the CCD camera to acquire two frames, corresponding to the two laser pulses. When the two images are acquired, the computer will then compute the wrapped phase map, then the unwrapped phase map, and finally the overall surface displacement map. The computer can be used to automatically sweep frequencies over a specified range and to sweep different phase locations within the excitation.

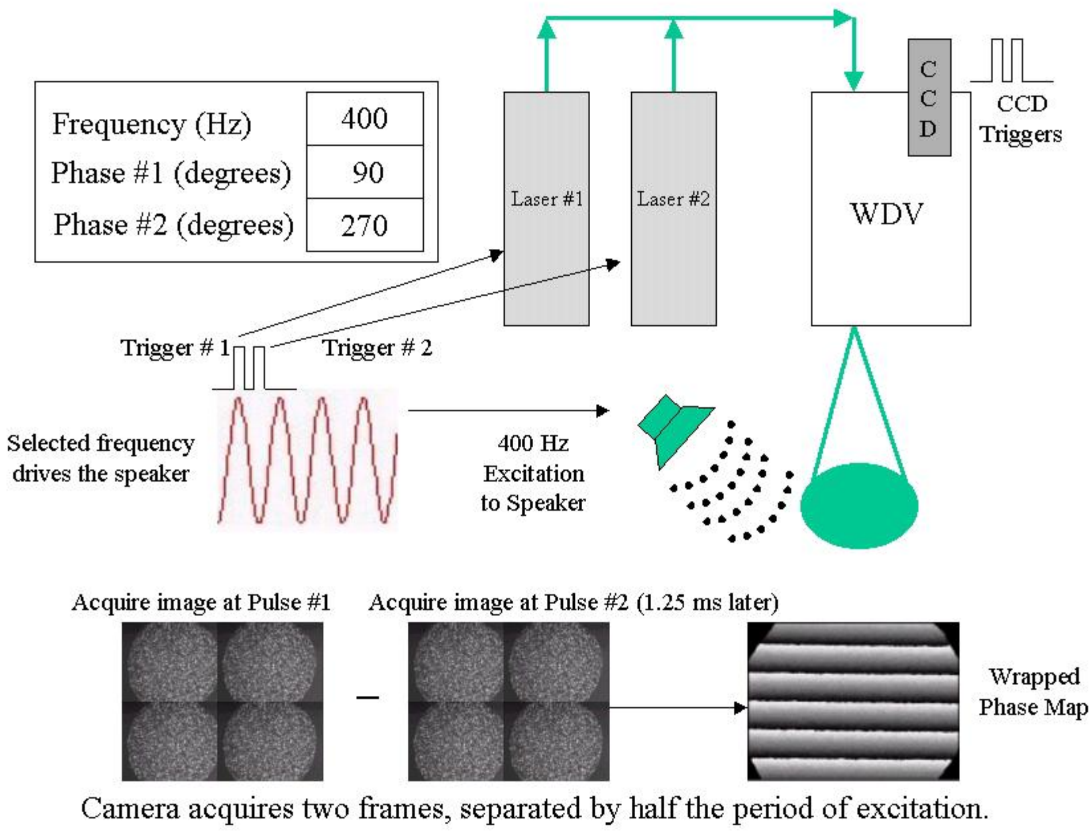


Figure 6. Overview of WDV system performance.

5. WDV CALIBRATION RESULTS

Initial system tests were performed with a smaller field of view of approximately 6” in diameter. A small piezo-electric transducer was buried in a sandbox (see Figure 7). As described in Figure 6, the two laser pulses were timed to fire at the peak and valley of the excitation cycle. The PZT was excited at frequencies from 200 Hz to 500 Hz at a fixed drive voltage of 2.5 Volts. Since the PZT has a non-uniform response with frequency, the actual displacement at each frequency varies significantly, in a similar way to the resonant response of a buried landmine.

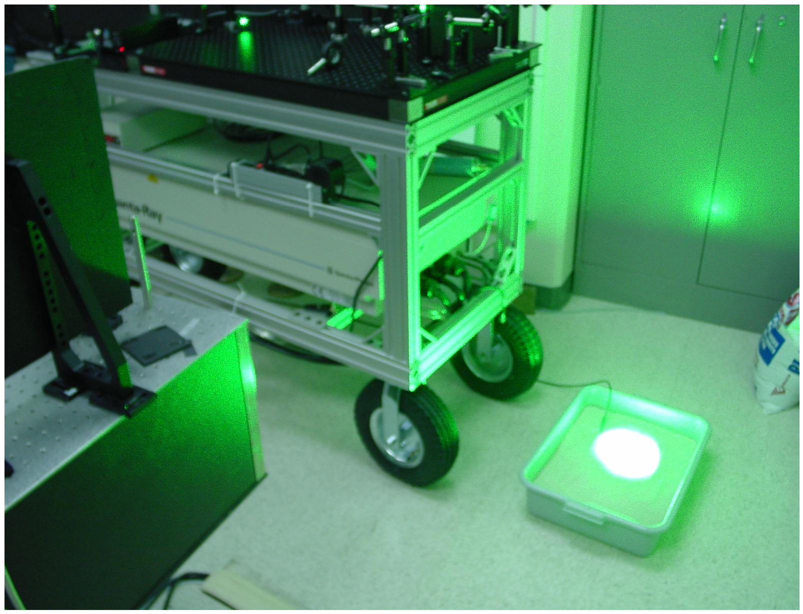
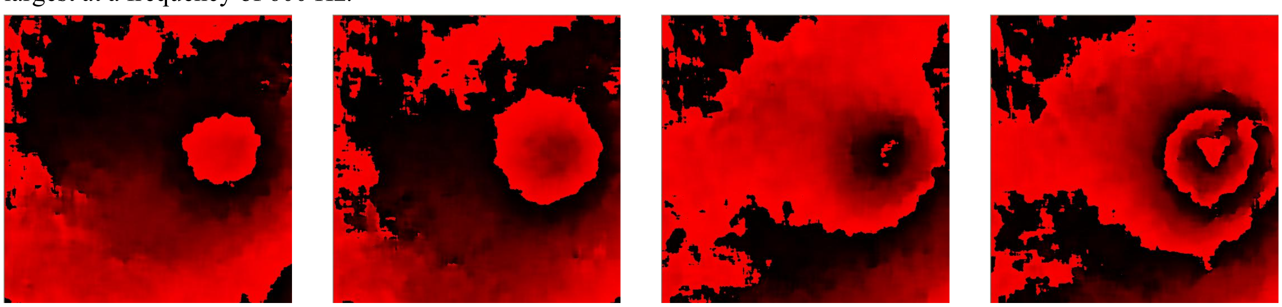


Figure 7. Photograph of the WDV measuring a 6” diameter region in a small sandbox.

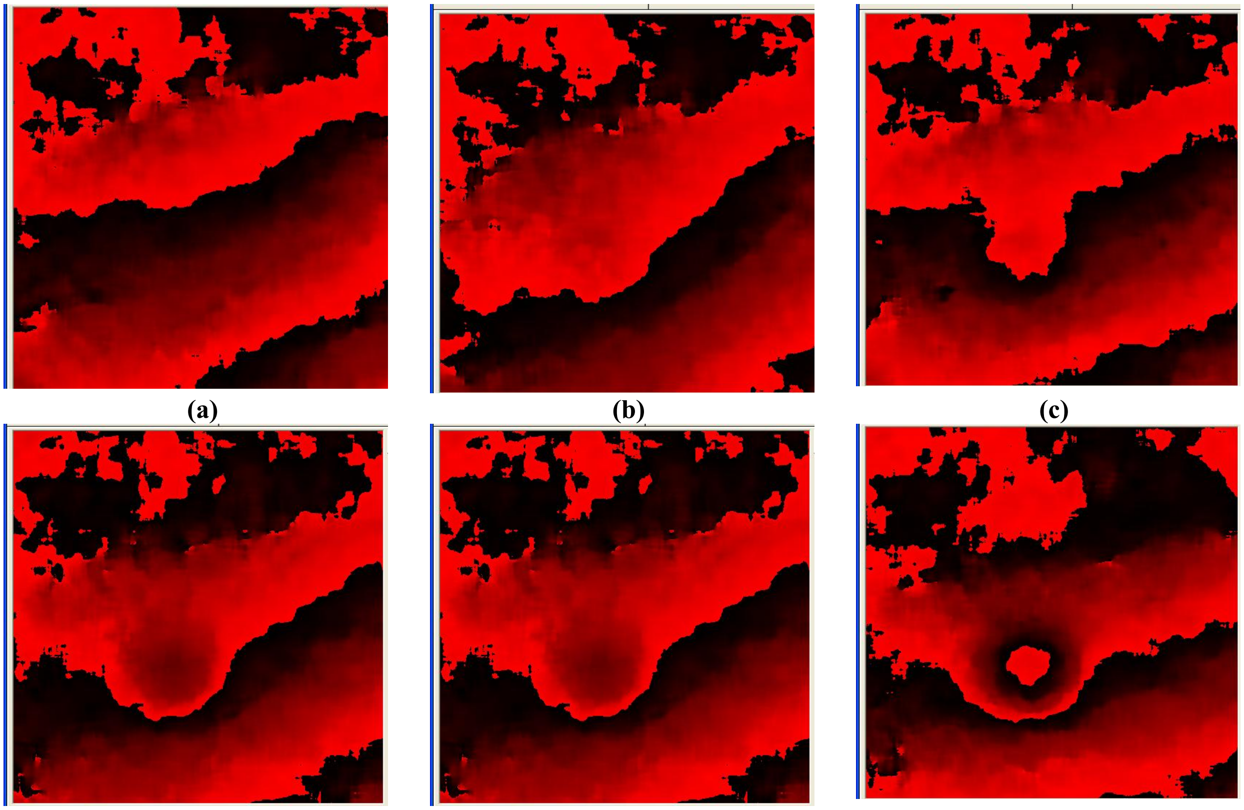
The measured displacement change between the two laser shots is shown in Figure 8, as the drive frequency to the PZT was varied. Each image shows the wrapped phase map, in which each transition from red to black corresponds to a displacement change of one-half the optical wavelength, or 0.266 microns. Figure 8(d) shows that the PZT response is largest at a frequency of 600 Hz.



(a) (b) (c) (d)

Figure 8. Unwrapped phase map at excitation frequencies of (a) 200 Hz, (b) 300 Hz, (c) 400 Hz, and (d) 500Hz.

In Figure 9, the amplitude of the PZT drive signal was varied while the frequency was kept fixed at a frequency of 300 Hz. The absolute displacement of the PZT was simultaneously calibrated with a laser Doppler vibrometer at each excitation voltage, and the displacement for Figure 9(b) was 62 nm, while for Figure 9(f), the displacement was 260 nm. These measurements show that the minimum displacement sensitivity of the WDV system is in the range of 50-100 nm.



(a) (b) (c)

(d) (e) (f)

Figure 9. Unwrapped phase map at an excitation frequency of 300 Hz and a drive voltage of (a) 0.0 Volts, (b) 0.2 Volts, (c) 0.4 Volts, (d) 0.6 Volts, (e) 0.8 Volts, (f) 1.0 Volts.

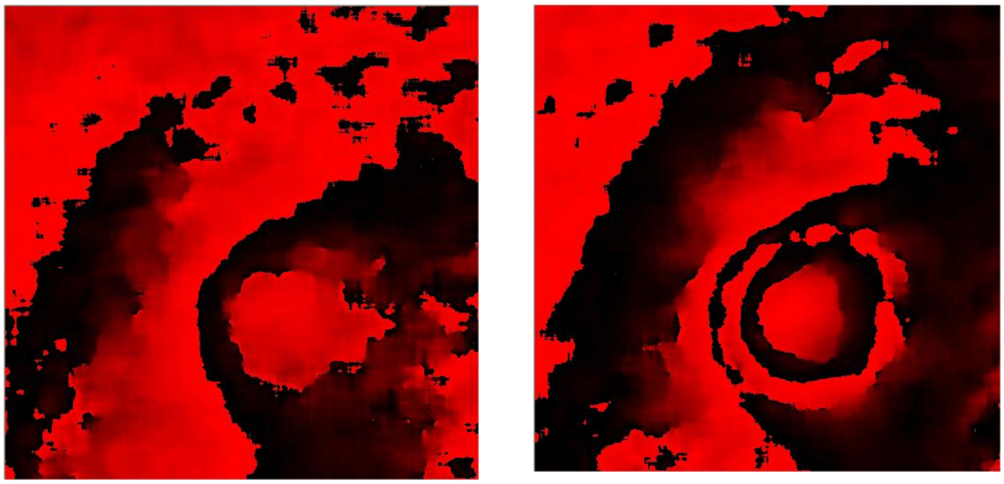
6. WDV OUTDOOR MEASUREMENTS

The WDV system has recently been tested in outdoor field conditions. A photograph of the system, mounted on a wheeled cart, is shown in Figure 10(a). The system illuminates an area on the ground of approximately one-half meter in diameter, as shown in Figure 10(b) (note that some parts of the beam saturate the image on the camera). The system was tested by burying a mine simulant (22 cm in diameter) a few centimeters below the surface, and exciting the ground with a loudspeaker. The frequency of the acoustic excitation was varied from 60 Hz up to 300 Hz.

(a) (b)

Figure 10. (a) Photograph of the WDV system. (b) Photograph of the ground illuminated by the green laser beam (note that some parts of the beam saturate the image on the camera).

The WDV system automatically can sweep the excitation frequency and record the target displacement image at each frequency. In the tests with the buried mine simulant, the mine was easy to observe at the appropriate resonant frequency, as shown in Figure 11.



(a) (b)

Figure 11. Wrapped phase map above a buried mine simulant near the resonant frequency of 80Hz. (a) Small amplitude excitation. (b) Large amplitude excitation.

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REFERENCES

[1] Xiang, N. and Sabatier, J.M., "Landmine detection measurements using acoustic-to-seismic coupling," Proceedings of the SPIE, vol. 4038, p.645 (2000).

[2] Sabatier, J.M., Xiang, N., Kelly, S., Bradley, M.R., Duncan, M., Burgett, R.D., Melton, J., Lal, A.K., Aranchuk, V., and Hess, C.F., "Mobile Mounted Laser Doppler Vibrometer Array for Acoustic Landmine Detection," Proceedings of the SPIE, vol. 5089, p. 591 (2003).

[3] Aranchuk, V.A., Lal, A.K., Zhang, H., Hess, C.F., and Sabatier, J.M., "Acoustic Sensor for Landmine Detection using a Continuously Scanning Multibeam LDV," Proceedings of the SPIE, vol. 5415, p. 61 (2004).

[4] Sabatier, J.M., Burgett, R., and Aranchuk, V.A., "High Frequency A/S Coupling for AP Buried Landmine Detection using Laser Doppler Vibrometers," Proceedings of the SPIE, vol. 5415, p.35 (2004).

[5] Original MB-LDV paper.

[6] Aranchuk, V.A. et al, "Speckle noise in a continuously scanning multi-beam laser Doppler vibrometer for acoustic landmine detection," Proceedings of the SPIE, vol. 6217 (2006).

[7] Sabatier, J.M., Aranchuk, V., and Alberts, W.C., "Rapid High Spatial Resolution Imaging of Buried Landmines using ESPI," Proceedings of the SPIE, vol. 5415, p. 14 (2004).

[8] Smythe, R. and Moore, A. J., "Instantaneous phase-measuring interferometry", Optical Engineering, 23, 4, 361-364, (1984).

[9] U.S. Patent Number 6,552,808.

[10] Lal, A.K. et al., "Whole-Field Digital Vibrometer System for Buried Landmine Detection," Proceedings of the SPIE, vol. 5794, p. 665.