Laser Doppler sensing in acoustic detection of buried landmines

Vyacheslav Aranchuk, James Sabatier, Ina Aranchuk, and Richard Burgett
University of Mississippi
145 Hill Drive, University, MS 38655
aranchuk@olemiss.edu

Abstract: Acoustic detection of buried landmines employs low frequency elastic waves excited in the ground and a laser Doppler vibrometer (LDV) for vibration mapping of the ground surface. The technique has shown excellent performance in field tests with few false alarms or missed targets. A critical issue in acoustic landmine detection is the speed of ground vibration measurement. The speed of a moving LDV beam is limited by two fundamental factors: the speckle noise and the required spatial and frequency resolutions of the ground vibration measurements. This paper discusses the methods of speckle noise mitigation and time multiplexing of multi-beam LDV channels that allow increasing the speed of ground vibration measurements.

Keywords: laser Doppler vibrometer, landmine detection, acoustic, laser-acoustic sensing.

1. Introduction

Laser-acoustic techniques that employ low frequency elastic waves in the ground have been successfully used for detecting buried landmines [1-3]. The method consists of excitation of the ground with elastic waves in the frequency range from about 50 Hz to 1000 Hz, and obtaining a vibration map of the ground surface using a non-contact vibration sensor. Airborne sound created by loudspeakers, or seismic waves created by mechanical shakers, can be used to excite the ground vibration. The interaction of a buried landmine with the elastic waves causes the landmine to vibrate. Due to the mechanical resonances of the landmine and the higher mechanical compliance of the landmine compared to the nearby soil the vibration amplitude of the ground surface above a landmine is higher than the vibration amplitude of the surrounding area. A LDV is used to measure the vibration of the ground in many points to create a vibration image of the ground surface. The presence of a buried landmine can be detected by an amplitude anomaly in the vibration image. LDV-based acoustic landmine detection has demonstrated a high probability of detection with very low false alarm rates in field tests. A critical issue in acoustic landmine detection is the speed of ground vibration measurement. Using a single beam point-by-point scanning LDV in landmine detection results in a long measurement time. To reduce the measurement time a Multi-Beam LDV (MB-LDV) [3] has been developed and used for landmine detection. The MB-LDV provides parallel measurement of vibration in 16 points arranged in a linear array and can create a vibration image of the ground by scanning the beams. The speed of moving beams is limited by two fundamental factors: the speckle noise and the required spatial and frequency resolutions of the ground vibration measurements. This paper describes the methods of speckle noise mitigation and time multiplexing of MB-LDV channels that allow increasing the speed of ground vibration measurements.

2. Ground Vibration Imaging Using MB-LDV

The layout of the MB-LDV system used for landmine detection is shown in Figure 1(a). 16 laser beams are focused onto the ground along a line and can scan the ground in the direction perpendicular to the line of the beams. The back scattered light is optically mixed with reference beams on 16 photodetectors creating 16 frequency modulated signals with the carrier frequency 100 kHz. The frequency deviation is proportional to the velocity of the ground. The frequency modulated signals are demodulated in the 16 channel Phase-Locked Loop (PLL) frequency demodulator. The outputs of the PLL demodulator are proportional to the vibration velocity of the object at the point of measurement. The PLL output signals are then simultaneously digitized with a 16 channel A/D card in a computer, and the velocity spectrum of each beam is calculated in the software. A vibration image of the object can be created at any selected frequency band by scanning the beams in the transverse direction. Figure 1(b) shows an example of a vibration image of a buried landmine.

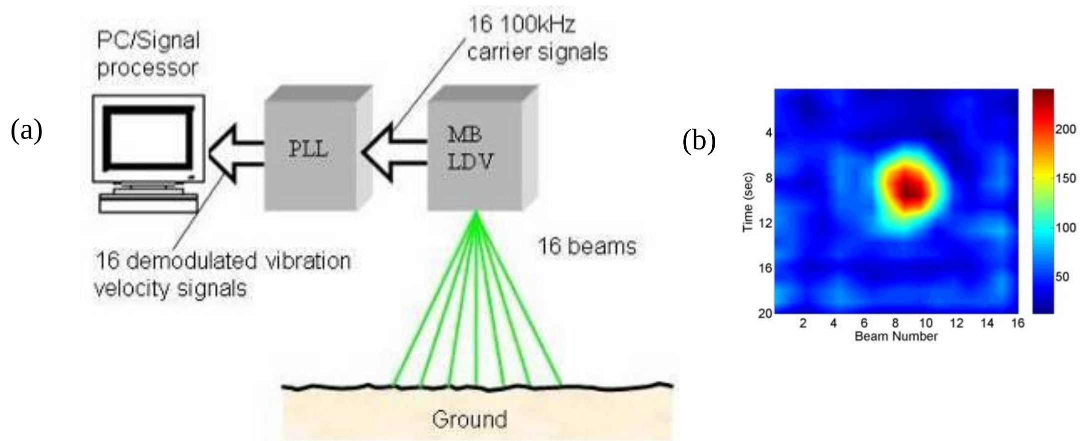

Figure 1. (a) Setup of scanning MB-LDV for acoustic landmine detection, (b) Vibration image of a buried landmine.

3. Speckle Noise Mitigation in a Continuously Scanning LDV

Scanning a laser beam across a target introduces noise in the vibrometer output due to dynamic speckles. When the laser beam moves across the target, the intensity and phase of speckle field change in a random way. This results in random fluctuations of the amplitude and phase of the Doppler signal. Dynamic speckles also cause spikes in the Doppler signal. Spikes results from dropouts in the Doppler signal due to low intensity of speckle field (dark speckle), and also from phase discontinuities in the vicinity of wavefront dislocations of the speckle field [4].

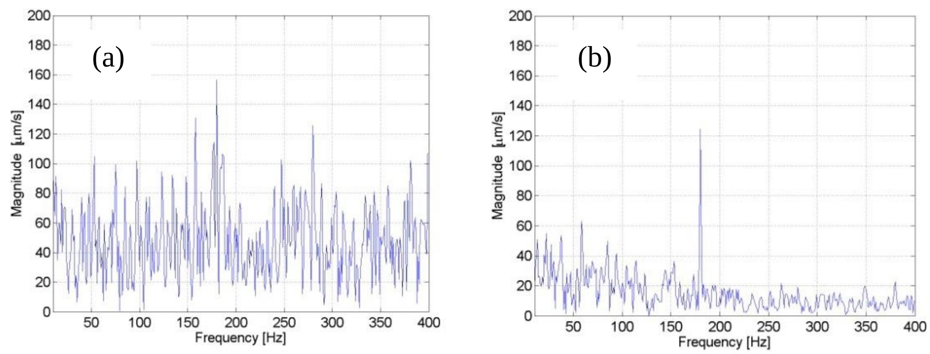

Figure 2. Spectrum of a continuously-scanning LDV velocity signal. (a) signal contains spikes; (b) spikes removed from the signal.

Normally the phase singularities coincide with dark speckles. Spikes alongside with random phase fluctuations of the Doppler signal result in speckle noise in the demodulated vibration signal [5]. The spike noise has a broadband energy spectrum, that makes filtering not efficient. The speckle noise can be reduced by removing spikes from the LDV signals.

We developed a method for spike detection and removal based on wavelet transform. The spikes in a LDV velocity signal are detected by their first level detail coefficients. After the locations of spikes are determined, those regions are replaced with interpolated values. Figure 2 shows and example of speckle noise reduction in a continuously scanning LDV signal. Figure 2 (a) shows a spectrum of a velocity signal of a continuously scanning LDV beam over a buried object excited with 180Hz single tone. Figure 2 (b) shows a spectrum of the same signal after removing spikes. One can see that removing spikes from the LDV signal allowed reduction of noise by approximately 10dB. Figure 3 shows an example of improving a vibration image of a buried landmine by removing spikes in signals of continuously scanning MB-LDV. The example shows that the removing spikes from a scanning LDV signals can significantly enhance the contrast of a vibration image of a buried object.

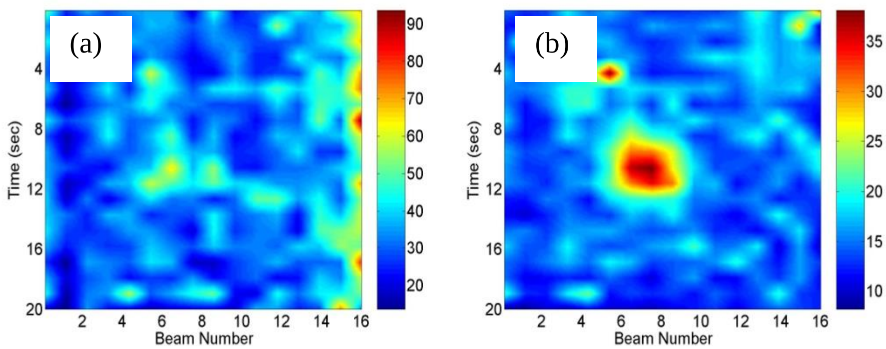

Figure 3. Velocity image of buried antitank mine before (a) and after (b) the wavelet threshold method of speckle noise reduction was applied.

4. Time-Multiplexed Multi-Beam Laser Vibrometry

Besides speckle noise, there is another fundamental limitation on speed of a continuously scanning or moving LDV, imposed by the required spatial and frequency resolutions of the ground vibration measurement. The maximum speed of a moving laser beam of the LDV is related to the required sensor spatial and frequency resolution through the expression [6]

$$V = s \cdot \Delta f \qquad (1)$$

where V is the speed of beam, s and Δf is the spatial and frequency resolution of the vibration measurement respectively. From expression (1) the beam must move over the target area of length s (spatial resolution cell) during the time $T=1/\Delta f$. Moving with a higher speed will worsen the spatial or frequency resolution, or both.

We developed a method of continuously measuring the ground vibration with the moving MB-LDV that allows one to overcome that speed limitation [7,8]. The method employs time division multiplexing (TDM) of laser beams of a row in the direction of motion of the platform. In this case the MB-LDV is moving along a linear array of N laser beams. With the proposed method, the speed of motion of the MB-LDV can be increased N times without worsening the spatial and frequency resolutions. The principle is shown in Figure 4(a). Only four beams are shown for simplicity. The distance between beams is equal to the required spatial resolution s. The beams move in the down track direction and measure the vibration of each space segment (spatial resolution cell) sequentially. The beams move N times faster than a single beam LDV. The duration t of a time signal produced by each beam during its motion over each space segment s is N times shorter than the required time T. Next, the time domain signals of each beam passing over a certain space segment s are combined together to obtain a time segment of required duration corresponding to that space segment. Then the spectrum of vibration is calculated for each combined time segment. The speed of beams V_N is N times higher than the speed of the single beam LDV defined by (1).

$$V_N = N \cdot V = N \cdot s \cdot \Delta f \qquad (2)$$

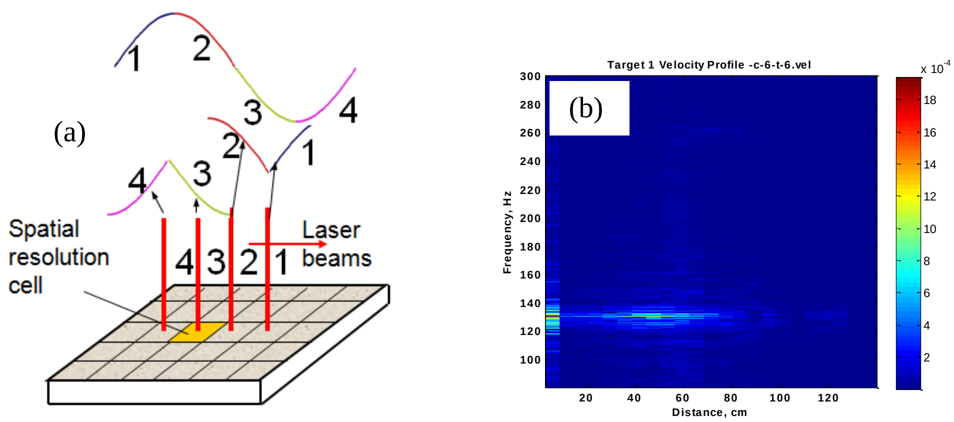

Figure 4. Principle of time-multiplexed laser vibrometry (a) and a vibration velocity profile of a buried plastic mine measured at 0.73 m/s speed.

The proposed concept of TDM of laser beams has been verified experimentally. The 16 beam MB LDV was used to obtain a velocity profile of the ground above a buried mine at a continuous motion. The MB LDV was moving along the line of beams over a buried mine. The vibration of the ground was created by shakers. The velocity profile of the ground surface was created by using the TDM method of 16 beams. Figure 4(b) shows an example of a vibration velocity profile in frequency space of a buried plastic landmine at 0.73 m/s speed of MB-LDV.

5. Summary

Methods for increasing the speed of ground vibration imaging by multi-beam LDV in acoustic landmine detection have been developed. The method of spikes removal in LDV signals allows reduction of speckle noise and increasing the speed of laser beams. The method of time-division multiplexing of multi-beam LDV channels allows increasing the speed of scanning laser beams without worsening the spatial and frequency resolutions of vibration measurement.

6. Acknowledgements

This work was supported by the US Army Research Office and the US Army Communications-Electronics Research, Development, and Engineering Center, Night Vision and Electronic Sensors Directorate.

7. References

[1] J.M. Sabatier and N. Xiang, "An Investigation of Acoustic-to-Seismic Coupling to Detect Buried Antitank Mines", IEEE Transactions on Geoscience and Remote Sensing, **39**, 1146-1154 (2001)

[2] N. Xiang and J.M. Sabatier, "An Experimental Study on Antipersonnel Landmine Detection using Acoustic-to-Seismic Coupling", J. Acoust. Soc. Am., **113**, 1333-1341 (2003).

[3] V. Aranchuk, A. Lal, C. Hess and J.M. Sabatier, "Multi-beam laser Doppler vibrometer for landmine detection" Opt. Eng. **45**, 104302-1-104302-10 (2006).

[4] V. Aranchuk, A.K. Lal, C.F. Hess, J.M., Sabatier, R.D. Burgett, I. Aranchuk, and W.T. Mayo "Speckle noise in a continuously scanning multi-beam laser Doppler vibrometer for acoustic landmine detection", Proceedings of the SPIE, Vol. 6217, Orlando, April 2006.

[5] V. Aranchuk, J.M. Sabatier, A.K. Lal, C.F. Hess, R.D. Burgett, M. O'Neill, "Multi-beam laser Doppler vibrometry for acoustic landmine detection using airborne and mechanically coupled vibration", Proceedings of the SPIE, Vol. 5794, p. 624-631, Orlando, March 2005.

[6] Xiang, N. and Sabatier, J.M., "Moving Speed of Linear Acoustic Landmine Detection System", Proceedings of the SPIE, Vol. 5794, p. 675-682 (2005).

[7] R. Burgett, V. Aranchuk, J. Sabatier, S. Bishop, "Demultiplexing multiple-beam laser Doppler Vibrometry for continuous scanning," Proceedings of the SPIE, 7303, 73030I-1, (2009)

[8] R. Burgett, V. Aranchuk, and I. Aranchuk, "Experimental investigation of buried landmine detection using time division multiplexing of multi-beam laser Doppler vibrometer channels", Proceedings of the SPIE, Vol. 8357, 83570H-1, Orlando, April 2012.