Laser Doppler Vibrometer-Based Acoustic Landmine Detection Using the Fast M-Sequence Transform

Ning Xiang, *Member, IEEE,* and James M. Sabatier, *Member, IEEE*

***Abstract*—Acoustic landmine detection using a laser Doppler vibrometer (LDV) has demonstrated success in recent field tests. However, low detector signals and speckle noise are still challenging problems in the LDV-based acoustic-to-seismic detection of buried landmines. This letter describes the use of binary maximum-length sequences as the acoustic excitation for achieving high SNRs of scanning results. Some relevant issues associated with the detection system design and experimental field results are discussed.**

***Index Terms*—Fast M-sequence transform (FMT), landmine detection, maximal-length sequences.**

I. INTRODUCTION

AN ACOUSTIC-TO-SEISMIC (A/S) coupling-based detection technique that utilizes a laser Doppler vibrometer (LDV) has shown success in recent field tests [1]–[3]. When sound waves penetrate the surface of the ground, they excite seismic motion. If a landmine is present in the subsurface of the insonified patch, the transmitted waves will interact with the buried landmine, resulting in distinct changes of the ground surface vibration due to the resonance of the soil–mine system [4], [5]. This technique senses the distinct A/S coupled vibrational changes on the ground surface using an LDV device. Ability of sensing the surface vibration in a noncontact remote sensing manner and capability for achieving a reasonable standoff distance are major advantages of the LDV in the landmine detection application. Low SNRs in the case of low-level velocity signals and laser speckle pattern-induced noise are still challenges in the use of the LDV-based system. These kinds of noise seriously limit the performance of acoustic landmine detection systems. Selection of excitation signals and analysis methods then becomes critical for efficient detection performance with respect to detection ability and operational speed.

Buried antitank landmines typically respond to the acoustic excitation in a frequency range between 60–400 Hz [2]. Impulsive excitations can cover a broad band, but are significantly limited by signal energy. Single-tone excitation can have significant signal power only at a given harmonic frequency. Covering the frequency range of interest while stepping through the entire bandwidth with the required frequency spacing [2], [3] will strongly limit operational speed. In addition, a detection system will eventually be developed on a moving vehicle platform, and stepping through the entire bandwidth can only be pursued when a measuring point on the ground surface can be considered as stationary or nearly stationary. The single tone excitation, therefore, provides too limited usefulness in real landmine detection practice.

In order to characterize the vibrational changes caused by buried landmines reliably and efficiently, broadband signals with rich signal power (low peak factor or high crest factor) need to be used as excitation signals for both a high SNR and a wide frequency coverage. Among a number of useful perturbation signals, such as chirp signals, random phase noise, maximum-length sequences (M-sequences) are broadband pseudorandom signals with a high crest factor. Since the early 1980s, the M-sequence measurement technique has been widely accepted in audio engineering and architectural acoustics applications [6]. This technique, however, has not yet been widely used in subsurface sensing. This note applies a fast M-sequence transform (FMT) for acoustic landmine detection. Section II briefly describes the sensing principles of the laser Doppler vibrometer device. In Section III, we introduce basic properties of M-sequences pertaining to the acoustic landmine detection. In Section IV, we discuss relevant design issues when applying the M-sequences for the laser Doppler vibrometer-based landmine detection system. Experimental field results are discussed in Section V.

II. LASER DOPPLER VIBROMETER

The current acoustic landmine detection system employs a single-point interferometer. The LDV emits a laser beam onto the vibrating surface of the ground area under test. The surface movement with a vibration velocity $v(t)$ causes a Doppler frequency shift of the reflected laser light. The LDV used in this work yields frequency-modulated (FM) in-phase (I) and quadrature (Q) signals in the base band

$$\begin{cases} I(t) = A_{\mathrm{IQ}}(t)\cos[\varphi(t)] \\ Q(t) = A_{\mathrm{IQ}}(t)\sin[\varphi(t)] \end{cases} \tag{1}$$

with

$$\varphi(t) = \frac{4\pi}{\lambda_L}\int_{-\infty}^{t} v(\tau)\,\mathrm{d}\tau. \tag{2}$$

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λ_L is the wavelength of the laser light. $A_{\mathrm{IQ}}(t)$ denotes amplitude fluctuations in I-, Q-signals. $v(t)$ is determined by

$$v(t) = \frac{\lambda_L}{4\pi} \frac{I(t)Q'(t) - I'(t)Q(t)}{I^2(t) + Q^2(t)} \tag{3}$$

with I', Q' being the time-derivative of I, Q, respectively. The FM demodulation using (3), along with an appropriate low- or bandpass filter as a followup device, yields the instantaneous surface velocity $v(t)$ of the vibrating point on which the laser beam is shining. It has been implemented in real-time operation in the current work.

III. FAST MAXIMUM-LENGTH SEQUENCE TRANSFORM

An n-stage linear shift-register can generate binary periodical sequences of maximal period length of $L = 2^n - 1$ [6]. These sequences are referred to as maximal-length sequences (M-sequences), and n is said to be the degree of the sequences. The autocorrelation function of M-sequences is a two-valued delta-like function implying its broadband power spectral density. M-sequences possess highly similar random properties as random noise, but they are periodically deterministic and have a strict time structure within its period. Due to their broadband pseudorandom nature, M-sequences are one of the signal classes suitable for the LDV-based A/S landmine detection technique. From the acoustic excitation to the seismic response on the ground surface, it can be treated to a certain extent as a time-invariant system under test (SUT) possessing an impulse response $h(i)$. Using a periodic bipolar M-sequence $\{m_i\}$ as the input signal of the acoustic-to-seismic SUT, one period of its output signal $\{v_i\}$ is the surface velocity response to the acoustic M-sequence excitation, received after the SUT arrives at its steady state. The normalized periodic cross-correlation function between $\{m_i\}$ and $\{v_i\}$ results in the impulse response of the SUT [6]

$$\mathbf{h} = \frac{1}{L+1} \mathbf{M} \cdot \mathbf{v} \tag{4}$$

where

$$\begin{aligned} \mathbf{h} &= [h(0), h(1), \ldots, h(L-1)]^T \\ \mathbf{v} &= [v_0, v_1, \ldots, v_{L-1}]^T \end{aligned}$$

are column vectors of L elements, $\mathbf{M}$ is a $L \times L$ square matrix, and its row elements consist of the M-sequence $\{m_i\}$ being used. In the relevant literature, (4) is referred to as *M-sequences transform* [7]. $\mathbf{M}$ is permutationally similar to Hadamard matrix

$$\mathbf{M} = \mathbf{P}_2 \mathbf{H} \mathbf{P}_1 \tag{5}$$

where $\mathbf{H}$ is a Sylvester-type Hadamard matrix of dimension $2^n \times 2^n$. $\mathbf{P}_1$ and $\mathbf{P}_2$ denote permutation matrices. Equation (5) implies an efficient algorithm for performing the FMT by adopting the fast Hadamard transform [7]. A computation of the fast Hadamard transform, requiring only $L \times n$ additions, is more efficient than a fast Fourier transform. Determination of the subsequent permutation matrices has been well documented in [6] and [7].

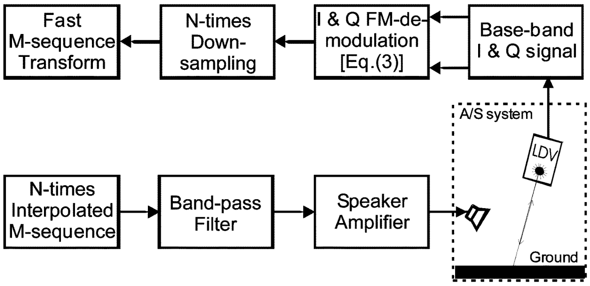

Fig. 1. LDV-based acoustic/seismic landmine detection system with M-sequence processing scheme.

IV. SYSTEM DESIGN

An A/S SUT is defined between the input of the sound source and the surface velocity response to the acoustic excitation sensed by the LDV. The excitation signal is designed to cover an acoustic frequency range up to 400 Hz, and a sampling rate f_A of 0.9–1.5 kHz is considered pertinent. Fig. 1 illustrates an implementation design for the current work. M-sequences are generated inside a personal computer-based system and sent out periodically through the digital-to-analog converter. On the input of the analog-to-digital converter, the FM baseband I- and Q-signals, carrying the surface velocity response to the M-sequence excitation, need to be sampled. The FM baseband I- and Q-signals should be sampled at a sampling frequency f_{IQ} around 50–80 kHz for possible Doppler shifts up to 20 kHz. M-sequences are generated at the update rate f_{IQ} without using a clock divider, but repeating each of M-sequence data point $N-1$ times, with N being an integer ratio of $N = [f_{\mathrm{IQ}}/f_A]$. In this way, the resulting update rate of M-sequence excitation becomes f_A. After the FM demodulation of I- and Q-signals using (3) followed by a bandpass filter with the limit frequencies, say, between 60–400 Hz, the demodulated responses are N-times downsampled (see Fig. 1). This results in the response to the original M-sequence excitation in the acoustic frequency domain. One period of the response is fast M-sequence transformed to provide the impulse response of the SUT directly in the time domain.

V. FIELD EXPERIMENT RESULTS

The implemented FMT measurement technique along with the efficient FM demodulation method has been extensively tested under the field conditions since 1999. In this section, we only discuss some representative results. Fig. 2 illustrates representative single-point measurement results in a U.S. Army test lane. An antitank metal M15 landmine was buried 7.5 cm deep in Lane 13. Fig. 2(a) illustrates the impulse responses from an on- and off-target measurement. An M-sequence of degree 9 was used for the FMT. The sampling rate f_{IQ} for the measurements of I- and Q-signals was 58.88 kHz, and a downsampling rate of 64 was selected, leading to a resulting sampling rate f_A of 920 Hz for the acoustic excitation/response domain. A bandpass filter between 60–280 Hz was used for the M-sequence excitation and for the FM demodulation after using (3). Three averages were taken before the FMT. An SNR of 30 and 25 dB were achieved for the on- and off-target impulse response, respectively. Fig. 2(b) illustrates the corresponding magnitude spectra of two impulse responses. The

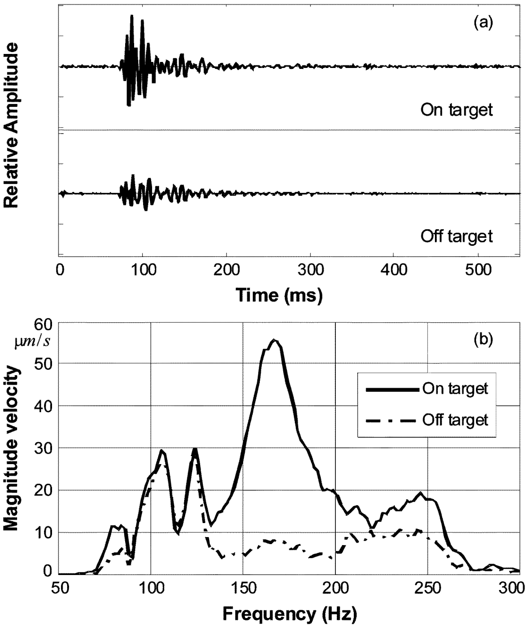

Fig. 2. Field results on an antitank metal M15 landmine buried 7.5 cm deep. (a) Impulse responses of on- and off-target using the M-sequence. (b) Magnitude spectra of on- and off-target.

sound pressure level of the acoustic excitation was adjusted to be 100 dB(C) on the ground surface. Using impulsive excitation at the same peak amplitude with three averages, the SNR amounts to less than 9 dB. As shown in Fig. 2(b), the M15 antitank landmine exhibited a strong resonance around 165 Hz from the broad-band excitation. Two peaks between 60 and 130 Hz, being present in both on- and off-target spectra, have been identified due to deep ground layers [2].

Scanning measurements were carried out on a plastic VS 2.2 antitank landmine buried 5 cm deep in a gravel lane. Twelve parallel lines were defined covering an area of 60 cm × 60 cm, resulting in a line spacing of 5.5 cm. Along each horizontal line, the laser was moved at a constant speed of 0.1 m/s while the seismic response to the periodic acoustic M-sequence excitation was measured. An M-sequence of degree 9 was used for this measurement. Along each horizontal line, 12 segments were taken equidistantly without averaging. These segments are fast M-sequence transformed, and their magnitude spectra were then exploited for RMS velocity values over a grid of 12 × 12 points, with a spatial resolution of 5.5 cm. When using an M-sequence of degree 9 at an acoustic sampling frequency of 920 Hz, one signal period corresponds to 0.55 s. A moving speed at 0.1 m/s can be considered as "reasonable," since each of 12 signal segments without overlap is taken when forming each image point. Different degrees of sequences can be selected for different moving speeds. Fig. 3 illustrates two grayscale images in both two-dimensional and three-dimensional presentations, evaluated in two adjacent frequency bands from 100–160 Hz. The target can be localized at the middle-left part of the images.

The FMT technique as implemented has already shown several advantages: higher SNR in comparison with impulse excitation, broadband identification, and a low computational load as the experiment results have substantiated. In addition, moving beam scanning results demonstrated that the M-sequence technique can also be applied in this slightly "time-variant" system for the landmine detection purpose as long as the laser beam moves at a reasonable speed. The moving beam measurement using the implemented FMT technique paves a solid road to developing the LDV-based A/S landmine detection system on a vehicular moving platform.

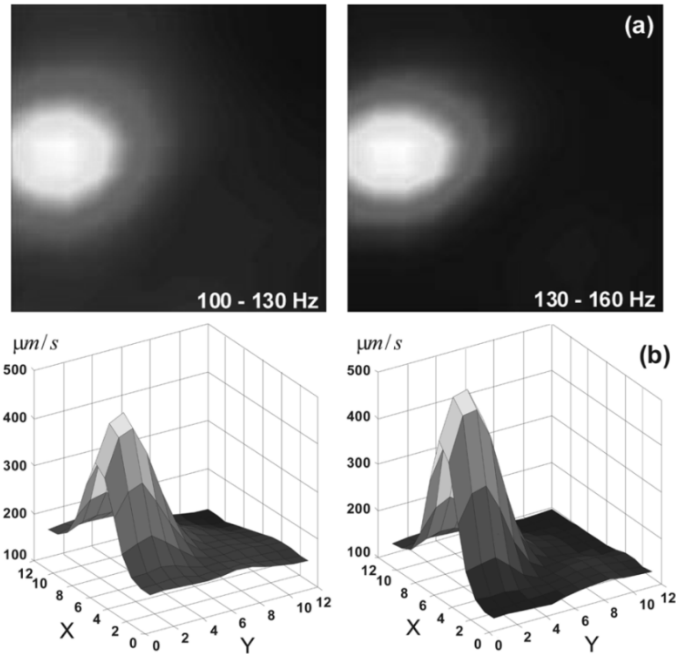

Fig. 3. Scanning results on an antitank plastic VS 2.2 landmine buried 5 cm deep. (a) Two-dimensional grayscale images, two adjacent subbands ranging from 100–160 Hz are analyzed. (b) Three-dimensional representations of (a).

VI. CONCLUSION

Binary maximum-length sequences (M-sequences) have been applied to the laser Doppler vibrometer-based acoustic landmine detection technique as acoustic excitation signals. An acoustic-to-seismic coupling system is considered as the system under test. A large number of impulse responses of this system can be determined efficiently over the scanned patches for detecting buried landmines. Due to their pseudorandom nature, high signal power and inherent noise immunity, M-sequences together with the fast M-sequence transform are of practical significance for an efficient, reliable landmine detection.

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