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Detection of buried mines and other explosive devices using a single-beam laser Doppler vibrometer

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Abstract. This work is a part of an ongoing global effort aimed at humanitarian demining. Its purpose is to develop a laser-acoustic method for detecting buried landmines and other explosive devices as well as to create a domestic system capable of detecting various types of mines, including plastic ones. In this work, a laboratory stand, which included a single-beam laser Doppler vibrometer operating in the stop-stare measurement mode and a model of a minefield were created. The acoustic responses of three types of plastic simulants of explosive devices, namely anti-personnel landmines ПМН-2 and ПФМ-1 as well as a grenade ПІРО-5Г, buried in sand and a substrate, were detected. The difference in the acoustic characteristics of the investigated soil-mine systems was identified. The effect of sand moisture on the amplitude and resonance frequency of the vibrations was demonstrated. The obtained results give hope for high potential of the used laser-acoustic method for detecting plastic explosive devices. The results of the work are expected to be useful for humanitarian demining of the territory of Ukraine.

Keywords: buried landmine detection, laser Doppler vibrometer, humanitarian demining.

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1. Introduction

For decades, the problem of detecting and disarming landmines and other explosive objects buried in soil existed all over the world [1]. With the beginning of the Russia's military aggression against Ukraine, this problem became relevant for our country as well. According to the State Emergency Service of Ukraine, about one-third of the country's total area (156,000 km^2) is contaminated with dangerous items, and clearing this area from mines and explosive war remnants will require decades and tens of billions of USD. Demining territories is a prerequisite for a safe and normal life for millions of Ukrainians who suffered from the consequences of the war. This difficult task covers not only detecting and eliminating mines, but also restoring infrastructure and agriculture.

Landmines are usually categorized into antipersonnel (AP) mines designed to injure, maim and kill humans, and antitank (AT) mines intended to immobilize or destroy vehicles and their occupants. The AT mines are typically 30 cm or larger, weigh several kilograms and are buried at depths of up to 30 cm below the surface. The AP mines are usually 10 cm or smaller, weigh a few hundred grams and are laid on the surface or buried at a depth of 4…50 mm below the ground surface. More than 650 AP mine types exist around the world. As was mentioned in [1], the production cost of an AP mine is roughly between 1 and 30 USD, while the cost rate of clearing one mine ranges between 300-1000 USD depending on the mine infected area and the number of generated false alarms.

Currently, there are several methods of detecting landmines: biological, electromagnetic, optical, nuclear, acoustic and mechanical [2]. Each of these methods is effective under certain conditions depending on the type of mine, explosive material and soil.

The most common non-contact mine sensor is a metal detector, which uses the electromagnetic induction phenomenon. Such mine detectors exist both in manual execution [3–5] and fixed on air [6, 7] or ground [8] mobile systems with different degrees of autonomy. Use of drones makes it possible to increase the speed and safety of detecting explosive devices [6, 7]. However, all the electromagnetic mine detectors, regardless of modification, have a major common drawback, namely they are ineffective for detecting plastic mines due to the small metal content. Attempts to increase their sensitivity usually lead to high false alarm rates due to the large number of metal objects, such as shrapnel, casings, *etc.*, scattered across the minefields [3].

To solve the problem of finding non-metallic explosive devices, new methods of detecting mines, including plastic ones, have been developed, such as infrared (IR) thermography [9], detecting by using quadrupole resonance of nuclear energy [10] and neutron logging [11].

For example, a possibility of detecting mines by analyzing thermal images of the surface has been investigated in [12–14]. Due to the fact that the area of a soil with a buried landmine has different thermophysical parameters from those of the surrounding environment, it can stand out on the thermal image. Despite the laboratory success of this method, it was established that the reliability of its results is strongly influenced by such factors as the depth of the landmine, presence of vegetation on the surface, and the time of day when the images are taken. Moreover, the type of the soil, its moisture content and density also have a significant impact on the ability to detect mines.

In recent years, close attention has been paid to the development of the laser-acoustic method, which makes it possible to detect explosive devices of various types [15–18]. The method consists in exciting vibrations of the soil and measuring the vibration characteristics of its surface at several points using a laser Doppler vibrometer (LDV). The advantages of this method are high detection probability and very low false alarm rates. The complexes that use such method are still under development and are not commercially available. However, they have a huge potential for development.

A laser Doppler vibrometer based on heterodyne processing of a scattered signal was created at the V. Lashkaryov Institute of Semiconductor Physics of the National Academy of Sciences of Ukraine. This device was successfully used for precise measurements of dust particle vibrations [19] and displacements of biological objects [20]. The purpose of this work is to study the possibility of an LDV to detect the landmines, including the plastic AP ones, buried in soil, for further creation of an LDV based laser-acoustic mine detection complex.

2. Methodology

2.1. Experimental setup

The setup of a laboratory stand of a laser-acoustic mine detection complex is shown in Fig. 1. It includes an LDV, a control and information processing unit and a model of a minefield with a source of sound waves.

The radiation of a He-Ne laser *1* with a wavelength of 0.63 μm falls on a beam splitter *2*. *Via* optical elements, the reflected radiation is formed into a probing beam, which is directed by a mirror *8* onto the ground surface in the minefield model III. The radiation that passes through the beam splitter *2* is formed into a beam of an optical heterodyne. A part of the radiation scattered from the soil reaches the surface of a splitter-mixer *9*, where it intersects with the heterodyne radiation. Interference of these waves produces an alternating current of a photodetector *13* at an intermediate frequency, which is an information signal. This signal is sent sequentially to the input of an A/D converter *14*, a digital receiver *15*, and one of the computers of the block II, where its amplitude and spectral characteristics are processed and analyzed.

When the area is irradiated with acoustic waves from a source of sound waves *18*, the energy is coupled into a seismic motion in the subsurface of the ground. Interaction of a landmine buried in the soil with the elastic ground waves causes its vibration. As a result of mechanical resonances and greater mechanical elasticity of the buried object to the neighboring soil, the amplitude of the soil vibrations directly above the landmine at resonant frequencies exceeds the vibration amplitude of the surrounding area. An object hidden in the soil is revealed by the amplitude-spectral differences of the vibrations of the surface above it.

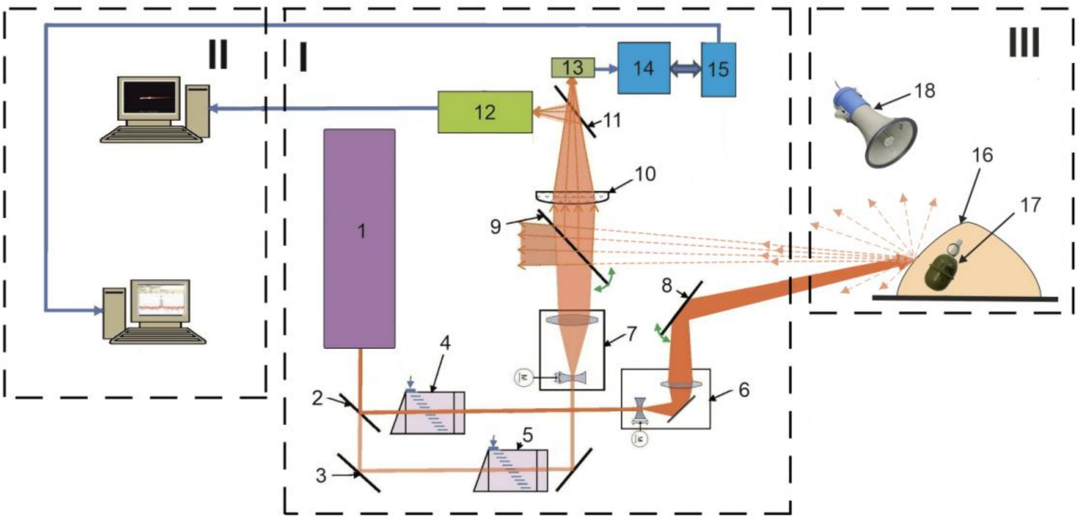

Fig. 1. Setup of the laboratory stand of a laser-acoustic mine detection complex. I – laser Doppler vibrometer, II – control and information processing unit; III – model of a minefield. Designations in the figure: *1* – laser, *2* – beam splitter, *3* – mirror, *4*, *5* – acousto-optic modulators, *6*, *7* – beam expanders, *8* – mirror, *9* – light splitter-mixer, *10* – lens, *11* – light splitter, *12* – television camera, *13* – photoreceiver, *14* – A/D converter, *15* – digital filter/receiver, *16* – ground, *17* – buried object, and *18* – source of sound waves.

2.2. Theoretical justification of the methodology

Measurements of oscillations or displacements carried out by laser interferometric devices as the devices that compare the displacement of an object with the laser radiation wavelength, are of a primary nature, *i.e*. they do not require comparing with other standards. The methods of determining the movement parameters (oscillations or movements) of a scattering object using a laser heterodyne meter are based on measuring the characteristics of the spectral components of the intermediate frequency signal. A detailed theoretical description of these methods is given in [21]. Here, we briefly present theoretical justification of the method used in this work.

Interference of the radiation of the optical heterodyne with the radiation scattered by the surface of the object under study produces an alternating current of the photodetector described by the following equation:

$$i(t) = K\cos[(\omega_h - \omega_{scat})t] \, . \qquad (1)$$

Here, K is the parameter that slightly changes over time and depends on the power of the local-dyne radiation, the power of the received scattered radiation, the quantum efficiency of the material of the photoreceptor sensitive plane, *etc*., and ω_h and ω_{scat} are the circular frequencies of the heterodyne radiation and the radiation scattered by the object, respectively.

When the object under study moves, the frequency of the scattered radiation changes relative to the frequency of the incident radiation by the value determined from the Doppler frequency shift:

$$\nu_d(t) = 2(\nu_h + F)_s V_r(t)/c \, , \qquad (2)$$

where $V_r(t)$ is the radial component of the object speed relative to the radiation receiver, ν_h is the frequency of the heterodyne radiation, F_s is the frequency of the acousto-optic modulators *4* and *5* (see Fig. 1), and c is the speed of light, respectively. Since $\nu_h >> F_s$, the expression (1) can be simplified in the following form:

$$\nu_d(t) \approx 2V_r(t)/\lambda \, , \qquad (3)$$

where λ is the heterodyne radiation wavelength. Hence, the frequency of the radiation scattered by the moving object is determined by the following expression:

$$\nu_{scat}(t) = \nu_h + F_s + 2V_r(t)/\lambda \, . \qquad (4)$$

The phase change of the scattered radiation due to the movement of the object has the following form:

$$\Delta\phi(t) = \frac{4\pi}{\lambda}\int_{t_0}^{t} V_r(\tau)d\tau \, . \qquad (5)$$

Introducing circular intermediate frequency $\omega_i = 2\pi(F_h - F_s)$ turns the expression (1) into

$$i(t) = K\cos\left[\omega_i t + \frac{4\pi}{\lambda}\int_{t_0}^{t} V_r(\tau)d\tau\right] . \qquad (6)$$

It can be seen from Eq. (6) that the photodetector current carries information about the speed of the object.

3. Experiments on detecting buried landmines

Fig. 2 shows an actual view of the LDV (a) and the minefield model (b). The LDV and the minefield model were placed on separate massive vibration-resistant bases without direct mechanical contact between them. The distance between them was at least 2 m. The control and information processing computers also had no mechanical contact with the units I and III.

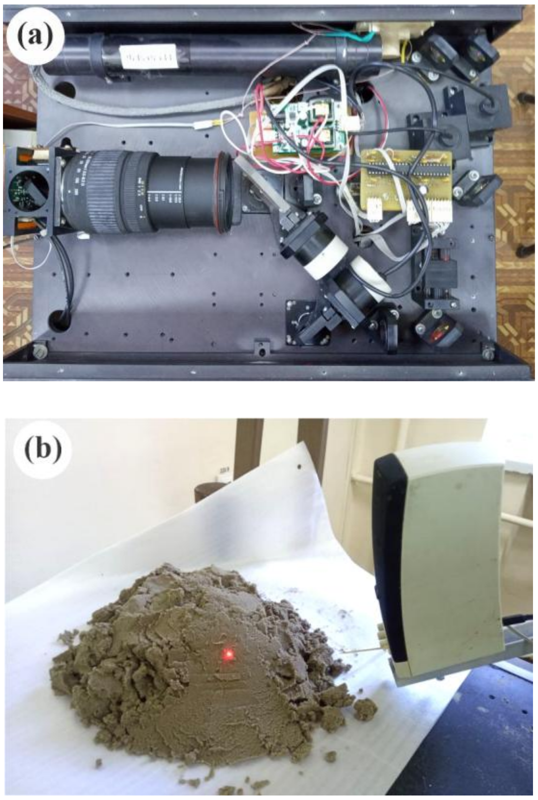

Fig. 2. Photos: a – laser Doppler vibrometer; b – minefield model. For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.

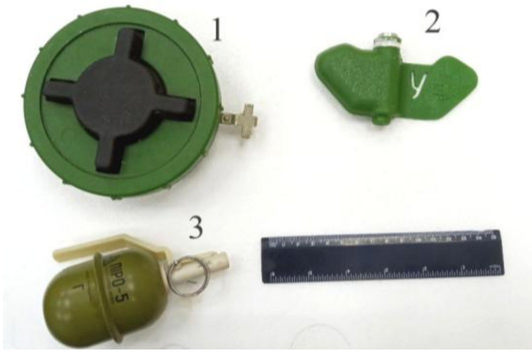

Fig. 3. Photos of the simulants used in the experiments: *1*, *2* – reduced plastic models of AP mines ПМН-2 and ПФМ-1, respectively, *3* – training simulation grenade ПРО-5Г.

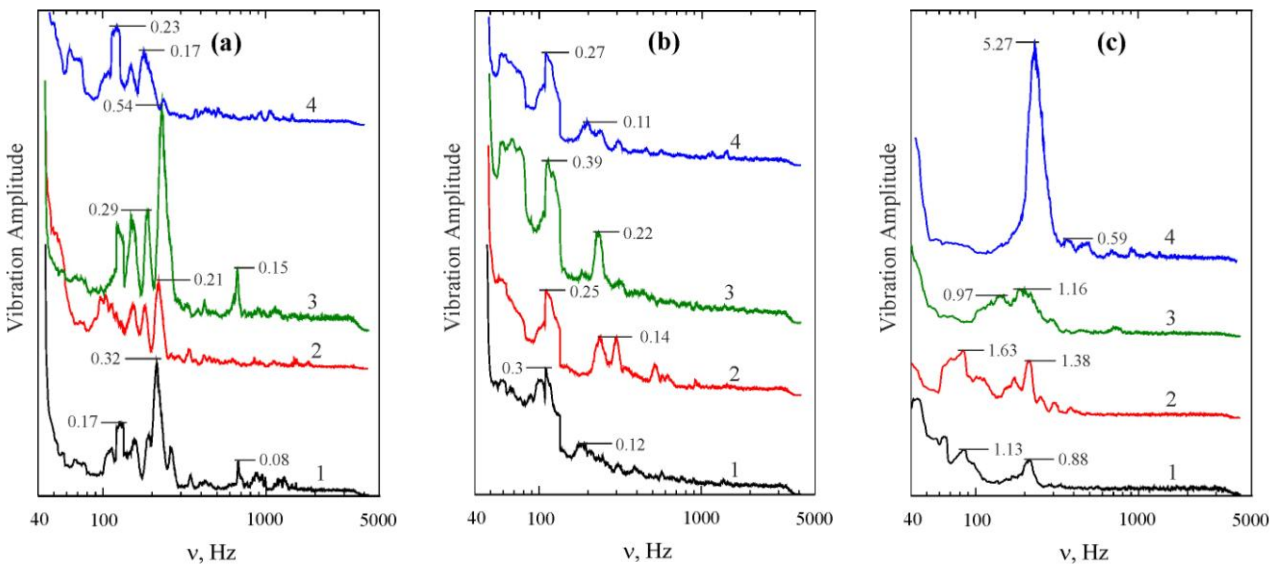

Fig. 4. Frequency dependences of soil vibrations measured above the simulant buried at 16–20 mm: a – dry sand; b – wet sand, and c – dry substrate; *1* (black) – soil without the simulant; *2* (red) – soil with the simulant of a landmine ПМН-2; *3* (green) – soil with the simulant of a landmine ПФМ-1; *4* (blue) – soil with the training simulant of a grenade ПІРО-5Г. The frequency dependences measured above the different simulants are shifted along the ordinate axis for better clarity. The marked resonance amplitudes are given in the arbitrary units.

In order to assess the noise level of the experimental setup, a test object – a massive metal cylinder with a reflectivity approximately equal to the reflectivity of the soil – was installed at the place of the object under investigation (hidden object in the soil). The noise level measured with a sound level meter was 39 dB near the cylinder and 42 dB near the LDV.

The acoustic response of the simulants of explosive devices placed in natural (non-cleaned and non-sieved) sand and a substrate consisting of a mixture of high-quality peat, sand, limestone material and fertilizers was investigated. The following objects were studied: reduced plastic models of AP mines ПМН-2 and ПФМ-1 (petal) as well as a training simulation grenade ПІРО-5Г (imitation of a grenade of the soviet model РГД-5). These objects are shown in Fig. 3. Selection of the objects for the research was defined by their geometric similarity to real explosive devices, their materials of manufacture (metal and plastic) and dimensions, which had to correspond to the size of the minefield model.

Acoustic waves were emitted by an audio speaker (see Fig. 2), which received a sound signal in the form of white noise from a personal computer. The sound volume near the surface was 92...94 dB.

Fig. 4 presents the results of the measurements of surface acoustic vibrations spectra of dry and wet sand as well as dry substrate without the simulant (empty) and with the simulant. The thickness of the soil layer above the simulant was 16…20 mm. As can be seen from Fig. 4, the vibration spectra of different soils (curves *1*) have a number of acoustic resonances in the frequency range below 1 kHz. These resonances may be due to the small size of the soil pile used in the experiment (Fig. 2b). The vibration amplitude in the resonances is higher for the dry sand and dry substrate as compared to the wet sand.

This agrees well with the results presented in [22]. It has been supposed that introduction of moisture results in soil consolidation and increase of the soil shear stiffness. Therefore, the resonance frequency shifts upward and the vibration velocity (amplitude) decreases. In the presence of a mine simulant, the amplitude and frequency of the acoustic resonances changes depending on the types of soil and simulant. These changes in the vibration spectra are caused by both higher mechanical stiffness of the landmine simulant compared to the soil and its own acoustic resonances. At the same time, some resonance maxima significantly exceed the amplitude of oscillations of the empty soil surface.

Thus, by comparing the amplitude of soil vibrations at multiple points of the investigated surface, it is possible not only to detect a buried object, but, if a database is available, to determine its type and brand.

4. Conclusions

In this work, laboratory studies of the possibility of detecting mine simulants buried in soil using a laser-acoustic complex based on the laser Doppler vibrometer developed at the V. Lashkaryov Institute of Semiconductor Physics of the National Academy of Sciences of Ukraine were carried out. A laboratory stand was created. The stand included both the LDV and a model of a minefield – a pile of soil (sand or substrate) with or without the simulants of explosive devices placed inside. Analysis of the obtained results showed that when acoustic vibrations of the soil surface are excited, their spectra differ significantly depending on the presence and type of a buried object as well as on the soil moisture. This indicates that the used laser-acoustic method provides a high capability for detecting both metal and plastic AP landmines and other explosive devices buried in soil.

Further scientific and technical activities will be focused on increasing the sensitivity and reliability of the information obtained by the complex. This will include transition to a multi-beam probing scheme for surface scanning, increasing the power of laser and acoustic excitation, *etc*. It is expected that the developed laser-acoustic system will be possible to use for humanitarian demining on the territory of Ukraine.

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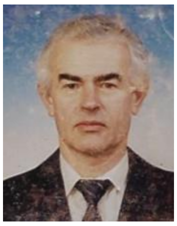

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Soloviev E.O.: investigation.
Serozkin Yu.G.: conceptualization, formulation of the problem, methodology, resources, investigation, validation, data curation, formal analysis, visualization, writing – review & editing.
Nastych V.M.: resources, writing – review & editing.

All authors have discussed the results of the work.

Виявлення прихованих у ґрунті мін та інших вибухових пристроїв за допомогою однопроменевого лазерного допплерівського віброметра

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Анотація. Дана робота є частиною глобальних зусиль, спрямованих на гуманітарне розмінування. Її метою є розробка лазерно-акустичного методу пошуку прихованих мін та інших вибухонебезпечних предметів, а також створення вітчизняного комплексу, який дозволяє виявляти міни різного типу, в тому числі пластикові. В роботі було створено лабораторний стенд, який містив лазерний допплерівський віброметр та макет мінного поля. Виявлено акустичні відгуки трьох типів макетів пластикових вибухових пристроїв, а саме протипіхотних мін ПМН-2 та ПФМ-1, а також гранат ПІРО-5Г, занурених у пісок та субстрат. Виявлено різницю в акустичних характеристиках досліджуваних систем ґрунт-міна. Продемонстровано вплив вологи на амплітуду та резонансну частоту коливань. Отримані результати дозволяють сподіватися на значні перспективи лазерно-акустичного методу для виявлення пластичних вибухових пристроїв. Очікується, що результати роботи будуть корисні для гуманітарного розмінування території України.

Ключові слова: виявлення закопаних мін, лазерний допплерівський віброметр, гуманітарне розмінування.