Semiconductor Physics, Quantum Electronics & Optoelectronics, 2025. V. 28, No 4. P. 486-492.

Optoelectronics and optoelectronic devices

Methodology of measurement of soil nanovibrations using a laser Doppler vibrometer for the detection of buried explosive objects

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Abstract. The work aims to develop an advanced acousto-optical method for detection of explosive objects buried in the soil. It is based on measuring mechanical nanovibrations of the soil using a laser Doppler vibrometer (LDV). The non-destructive peculiarity of the method and the possibility of remote sensing are of particular importance in the context of humanitarian demining. This work provides a detailed examination of the design, operating principle, and mathematical background for the signal processing of the LDV developed at the V. Lashkaryov Institute of Semiconductor Physics of the National Academy of Sciences of Ukraine. It is theoretically shown that for this device, the precision of vibration measurement is tenths of a nanometer within the vibration frequency range of 50…1000 Hz. The method of device calibration and determination of the empirical coefficients for calculating the amplitude of the measured vibrations is described. An example of a laboratory experimental study of the vibrations of a surface of moist soil with a buried full-size plastic simulant of Soviet anti-personnel mine ПМН-2 stimulated by acoustic wave irradiation is presented.

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

https://doi.org/10.15407/spqeo28.04.486
PACS 42.79.Jq, 42.79.Qx, 43.60.+d, 81.70.Cv

Manuscript received 12.08.25; revised version received 26.10.25; accepted for publication 26.11.25; published online 15.12.25.

1. Introduction

Laser Doppler vibrometry is a modern technology that provides precise determination of the frequencies and amplitudes of object displacements, measuring mechanical vibrations [1]. It finds wide applications in industry, engineering, scientific research, biology, and medicine [2]. The basis of the method is the detection of the Doppler frequency shift that occurs when light is scattered by a moving surface. This frequency shift is directly proportional to the speed of the surface motion, allowing for convenient and contactless measurement of vibration speed. The fundamental advantage of using laser Doppler vibrometers (LDV) compared to traditional vibration sensors (namely, accelerometers, strain gauges, *etc.*) is the ability to measure nanovibrations with high precision and without physical contact, meaning that the measurement process does not affect the sample and does not create a mass load. It allows the analysis of fragile surfaces without affecting the natural dynamics of the system, which is extremely relevant when analyzing biomedical samples, electronic components, and microstructures such as MEMS. For example, we demonstrated the feasibility of using the laser heterodyne interferometric techniques for the detection of nanometer displacement of nerve fibers [3] and for the evaluation of vibration amplitudes for microparticles of dust in gas or liquid media [4]. The remote character of LDV operation also allows for measurement of vibrations in hard-to-reach or hazardous locations (namely, on hot surfaces, rotating components, high-frequency ultrasonic instruments, *etc.*) and on objects of various sizes.

The non-destructive character of LDV and its ability to remotely probe nano- and micro-vibrations of the soil surface become particularly significant in the context of humanitarian demining, where physical contact is impossible or dangerous. The existing methods of contactless detection of explosive objects (EO) buried in the ground have significant limitations. For example, metal detectors are ineffective against non-metallic EO [5], optical and thermal imaging methods are highly dependent on soil conditions and weather [5, 6], and the use of search dogs is limited by the animal's emotional state, training level, and dog trainer skills [6]. Meanwhile, the laser-acoustic method using LDV allows for the detection of both metallic and non-metallic EO in the soil with high precision [7–12], while the remote character of the measurement ensures increased safety for the operator. Specifically, the use of a scanning LDV system had demonstrated a 95% probability of detecting antitank mines with a false alarm rate of 0.03/m² in a field blind test [7].

In the laser-acoustic method, the LDV registers vibrations of the soil surface (seismic waves) excited by external influences (mechanical shakers, pulsed laser radiation, or sound waves generated by a loudspeaker) [1]. An explosive object buried at a depth of several centimeters is detected by a higher amplitude of soil vibrations above it compared to neighboring soil. The acoustic response of most antipersonnel and antitank landmines demonstrates well-defined resonances in the frequency range from 50 Hz to 1 kHz, which depend on mine geometry, material, and upper casing design. Therefore, scanning the vibrations of the soil surface in the resonance frequency range allows for creating a 2D map of its location in the soil [8]. The use of a multi-beam LDV significantly accelerates the measurement process and implements hardware capabilities to reduce the effect of both the external acoustic vibrations and movement of the LDV on sensor sensitivity [9]. In a simplified theoretical model of soil-mine interaction presented in [10], the soil-mine system was considered as a system of discrete elements with equivalent physical parameters, and the spectral characteristics of vibrations of some models of buried EO and their dependence on the depth and properties of the soil were analyzed.

In our previous papers [11, 12], we have demonstrated that objects hidden in the soil exhibit a complex oscillation structure that depends on the interaction between the soil and the object, as well as on their respective properties (type of soil, its humidity, type of buried object). In the laboratory tests with plastic simulants of explosive devices buried in the containers with soils of different types, we demonstrated that the nature of the spectra of acoustic vibrations of the soil surface allows us to draw unambiguous conclusions about the presence or absence of buried EO.

Determination of the motion parameters (oscillations or displacements) of an object using an LDV is based on measuring the Doppler component characteristics of the laser radiation signal scattered by the surface of the object. This paper examines in detail the methodology for measuring the vibrations of a scattering surface using a single-beam LDV developed at the V. Lashkaryov Institute of Semiconductor Physics of the NAS of Ukraine. In this context, the design of the LDV complex is considered, the mathematical back-ground for processing optical signals of LDV is provided, and the results of experimental laboratory tests of the developed complex are presented.

2. Principle of LDV operation

2.1. LDV optical layout

Optical layout of the LDV complex is depicted in Fig. 1. The complex consists of LDV, a computer for controlling the laser measuring device and visualization of the object under investigation, and a computer for processing and visualizing the investigation results. LDV is built on a biaxial scheme, where the transmitting and receiving optical axes are arranged non-parallel and intersect at the studied object. This scheme eliminates the influence of the surface of a transparent protective screen or window

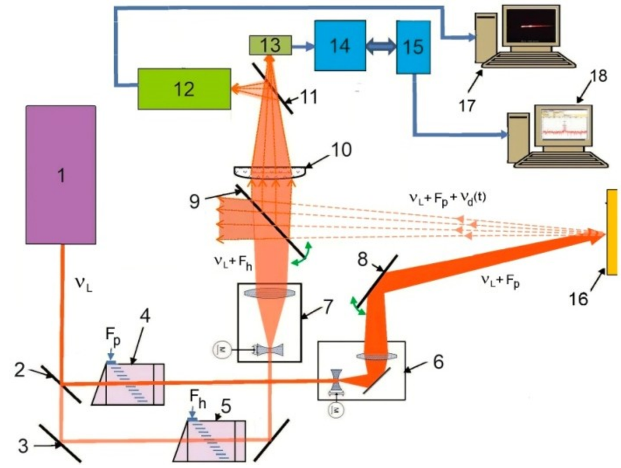

Fig. 1. 1 – He-Ne laser, 2 – beam splitter, 3 – mirror, 4, 5 – acousto-optic modulators, 6, 7 – beam expander, 8 – mirror for guiding a probe beam to an object, 9 – beam splitter for combining scattered radiation and heterodyne radiation on the photodetector, 10 – lens, 11 – beam splitter, 12 – TV-camera, 13 – photodetector, 14 – A/D converter, 15 – digital filter/receiver, 16 – surface of the studied object, 17 – computer for setup, 18 – computer for data visualization.

when examining an object behind it. For precise focusing of the LDV on the studied object, the developed design allows changing the angle between the axes when the distance to the object changes.

The laser Doppler vibrometer operates as follows. The radiation of the He-Ne laser (1) with a frequency ν_L (wavelength λ_L = 0.63 μm, power of radiation is equal to 5 mW) falls on a beam splitter (2) positioned at a 45° angle to the laser beam. The reflection coefficient of the beam splitter is 70%. Further, using optical elements, the reflected radiation is formed into a probe beam. Passing through the acousto-optic modulator (4), the radiation diffracts on an acoustic wave excited by a quartz generator at a frequency of F_p = 80 MHz. As a result, approximately 70…90% of radiation acquires a frequency equal to $\nu_L + F_p$. This radiation is then directed to a beam expander (6). By changing the distance between the lenses of the expander, the probe beam is focused on the surface of a studied object (16). The beam is moved along the surface of the object to select the desired area using a mirror (8) mounted on a two-axis drive consisting of two piezoelectric motors.

In turn, the radiation that passes through the beam splitter forms the optical heterodyne beam. Reflecting from the mirror (3) and passing through the acousto-optic modulator (5), the radiation diffracts with the acoustic wave, which is excited by a quartz generator at a frequency of F_h = 70 MHz. Approximately 70…90% of this radiation is converted into radiation with a frequency of $\nu_L + F_h$. The power of the heterodyne radiation can be regulated by the quartz generator. This radiation is then directed to the beam expander (7).

Part of the radiation scattered by the investigated surface falls on the entrance window of the LDV.

By changing the distance between the expander lenses, the wave fronts of the heterodyne radiation and the received scattered radiation are matched (aligned). The change in distance between the lenses is achieved by moving the negative lens using a stepper motor. Both expanders (6, 7) are designed according to the Galilean scheme, meaning they have a negative curvature lens at the input and a positive curvature lens at the output.

The heterodyne radiation and scattered radiation intersect at the beam-splitter mixer (9), whose transmission coefficient is 30%. The scattered radiation reflected by the beam splitter and the transmitted heterodyne radiation go to the lens (10) (Sigma 18-200). The photodetector (13) (S6468-Hamamatsu) is positioned in the focal plane of the lens (10). In the biaxial scheme, when changing the distance to the object, there is a change in the relative positions of the spots of scattered radiation and heterodyne radiation on the plane of the photodetector. The overlapping of these spots on the photodetector plane is achieved by rotating the beam-splitter mixer (9), which is mounted on a two-axis drive consisting of two piezo motors. Spot alignment control and selection of an observation point on the surface of the object are carried out using a TV camera (12) (Logitech Quick Camfor Notebooks Pro), which uses part of the total light flux (heterodyne radiation, scattered radiation, object image) branched by a beam splitter (11). Spot alignment is carried out at a reduced by approximately 10^5 times the heterodyne radiation power. After the alignment, the heterodyne radiation power is increased to the operating value equal to 100 μW.

As a result of the mixing of the optical heterodyne radiation with the radiation scattered by the surface of the studied object, an alternating current of the photodetector appears, which is described by the equation [1, 4]:

$$i(t) = K\cos[2\pi(\nu_h - \nu_s)t], \quad (1)$$

where K is a variable that changes slightly over time and depends on the heterodyne radiation power, the scattered radiation power, the average energy of photons of the interacting fields, the photodetector characteristics *etc.*; ν_h and ν_s are the frequencies of the heterodyne radiation and the radiation scattered by the object, respectively.

As the studied object moves, the frequency of the scattered radiation changes relative to the frequency of the incoming radiation by the value determined by the Doppler frequency shift:

$$\nu_d(t) = 2V_r(\nu_L + F_p)/c, \quad (2)$$

where $V_r(t)$ is the radial component of the object's velocity relative to the photodetector, and c is the speed of light. Since $\nu_L >> F_p$ and considering $\nu_L/c = 1/\lambda_L$, the expression (1) is simplified to

$$\nu_d(t) \approx 2V_r(t)/\lambda_L. \quad (3)$$

Thus, the frequency of radiation scattered by a moving object is determined by the expression:

$$\nu_s(t) = \nu_L + F_p + 2V_r(t)/\lambda_L. \quad (4)$$

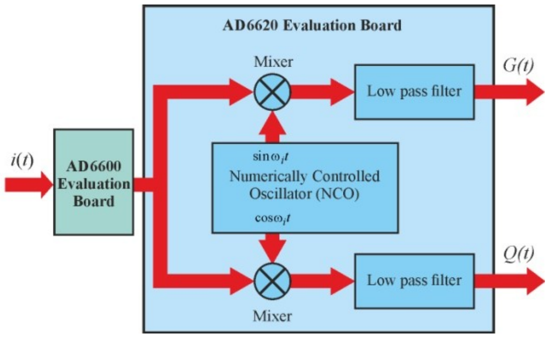

Fig. 2. Block diagram of the signal processing system. $i(t)$ is the photodetector alternating current, $G(t)$ and $Q(t)$ are the quadrature components of the phase-modulated signal.

The phase change of the radiation scattered by a moving object will have the form:

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

Let us introduce the concept of the intermediate frequency, which is described as $\nu_i = F_h - F_s$. As a result, expression (1) takes the form:

$$i(t) = K\cos\left(2\pi\left(\nu_i t + \frac{2}{\lambda_L}\int_{t_0}^{t} V_r(\tau)d\tau\right)\right). \quad (6)$$

The signal from the photodetector output enters the input of the information converter (Fig. 2), which consists of an analog-to-digital converter Evaluation Board AD6600PSB (Analog devices, USA) and a digital receiver Evaluation Board AD6620PSB (Analog devices).

The AD6600PSB is an analog-to-digital converter with a controlled gain. The digital signal codes produced by it are fed to the AD6620PSB. The most important functions of the AD6620PSB are digital heterodyning, quadrature component formation, and digital filtering. The frequency of the digital heterodyne is set automatically or manually before the measurement starts. In the absence of shifts and oscillations of the scattering surface, the frequency of the output signal is zero. The filter band is set by the user.

2.2. Basic equations and theoretical justification of methodology

Let us determine the amplitude of oscillations of the scattering surface, a. To do this, in equation (5), let's express the phase change in terms of the circular frequency of surface vibration motion, Ω:

$$\Delta\varphi(t) = a\frac{4\pi}{\lambda_L}\sin\Omega t. \quad (7)$$

Then, by entering a notation $A = 4\pi \cdot a/\lambda_L$ and using the circular frequencies, Eq. (1) for the photodetector current can be presented in the following form:

$$i(t) = K\cos(\omega_i t - A\sin\Omega t), \quad (8)$$

where $\omega_i = 2\pi\nu_i$ is the circular intermediate frequency.

To determine the amplitude, we perform some transformations of expression (8) for the output current of the photodetector. This expression can be rewritten in the following form:

$$i(t) = K\left[\cos\omega_i t \cdot \cos(A\sin\Omega t) - \sin\omega_i t \cdot \sin(A\sin\Omega t)\right]. \quad (9)$$

The Fourier series expansion in terms of Bessel functions will have the form:

$$i(t) = K\left\{\begin{array}{l}\cos\omega_i t\left[J_0 A + 2\sum_{k=1}^{\infty} J_{2k} A\cos 2k\Omega t\right] - \\ -\sin\omega_i t\left[2\sum_{k=1}^{\infty} J_{2k-1} A\sin(2k-1)\Omega t\right]\end{array}\right\}. \quad (10)$$

After trigonometric transformations, we obtain the following expression:

$$i(t) = K\left\{\begin{array}{l}J_0 A\cos\omega_i t + \\ +\sum_{k=1}^{\infty} J_{2k} A\left[\begin{array}{l}\cos(\omega_i + (2k-1)\Omega)t - \\ -\cos(\omega_i - (2k-1)\Omega)t\end{array}\right] + \\ +\sum_{k=1}^{\infty} J_{2k} A\left[\begin{array}{l}\cos(\omega_i + (2k-1)\Omega)t + \\ +\cos(\omega_i - (2k-1)\Omega)t\end{array}\right]\end{array}\right\}. \quad (11)$$

For the argument values of the Bessel functions, which satisfy the condition $A = 4\pi \cdot a/\lambda_L \le \pi/2$ (amplitude of oscillations $a \le \pi/8$), we can limit oneself to the first terms of the expansion:

$$i(t) = KA\left\{J_0\cos\omega_i t + J_1\left[\cos(\omega_i + \Omega)t - \cos(\omega_i - \Omega)t\right]\right\}. \quad (12)$$

The first term in the expression in curly brackets is a signal at an intermediate circular frequency ω_i with an amplitude proportional to J_0A, and the second and third terms are the signals at the surface oscillation frequencies Ω and proportional to J_1A. Assuming that the amplitude of the response is

$$I_0 = 20 \cdot \lg KJ_0 A, \quad (13)$$

and the amplitude of the response at the frequency of surface vibrations is

$$I_1 = 20 \cdot \lg KJ_1 A, \quad (14)$$

we will get:

$$\Delta I = I_0 - I_1 = 20 \cdot \lg(J_0/J_1). \quad (15)$$

From this, we can determine the amplitude of the oscillations. For oscillation amplitudes, the values of the Bessel functions can be represented in the form $J_1 A \approx 1$, $J_1 A \approx 2\pi \cdot a/\lambda$. In this case:

$$\Delta I = I_0 - I_1 = 20 \cdot \lg(\lambda/2\pi a), \quad (16)$$

and the expression for the amplitude takes the form

$$a = (4\pi/\lambda) \cdot 10^{-\Delta I/20}. \quad (17)$$

With a laser wavelength of $\lambda = 0.63$ µm, we will have $a \approx 100 \cdot 10^{-\Delta I/20}$ nm.

2.3. Signal processing

The further procedure of signal processing is carried out in two stages. In the first stage, the signal spectrum from a stationary object is analyzed using the “AD6620 Monitor” test program, and the digital heterodyne is tuned. Then the quadrature components of the phase-modulated signal are recorded as follows:

$$G(t) = B(t)\sin\Delta\varphi(t), \quad (18)$$

$$Q(t) = B(t)\cos\Delta\varphi(t) \quad (19)$$

and the phase change, $\Delta\varphi(t)$, is calculated as

$$\Delta\varphi(t) = \arctan\frac{G(t)}{Q(t)}. \quad (20)$$

For plotting the dependence of the object’s movement on time, $a(t)$, the received data array is processed by the program Matlab:

```
F_ID = fopen('Addersoffile *.pcm');
S = fread(F_ID,'double')*R;
M = [transpose([0.T:T:length(S)*T]),S];
plot(M(:,1),M(:,2));
title('1 KHz, 10 nm');
xlabel('Time, ms');
ylabel('Displacement, nm');
gridon
```

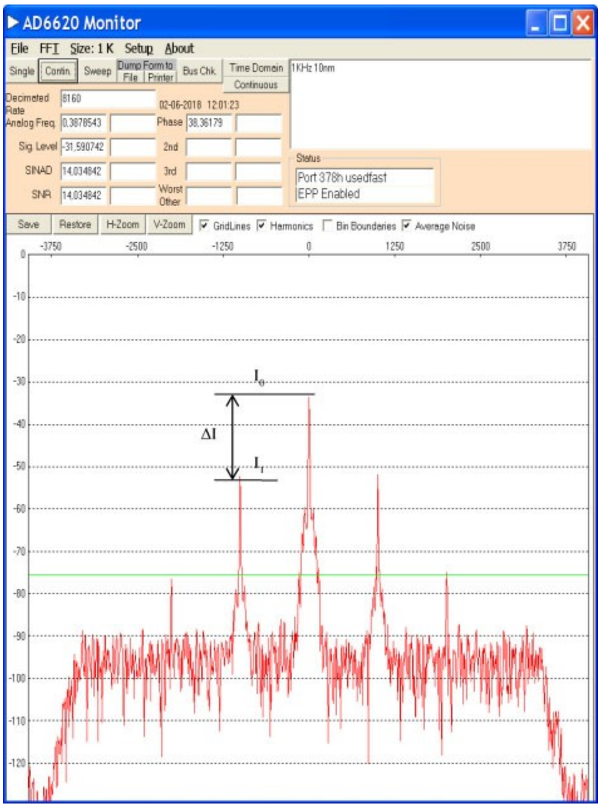

Fig. 3. The spectrum of the intermediate frequency signal from the surface of a piezoelectric element vibrating with an amplitude of 10 nm and a frequency of 1 kHz. The filter band was 3 kHz.

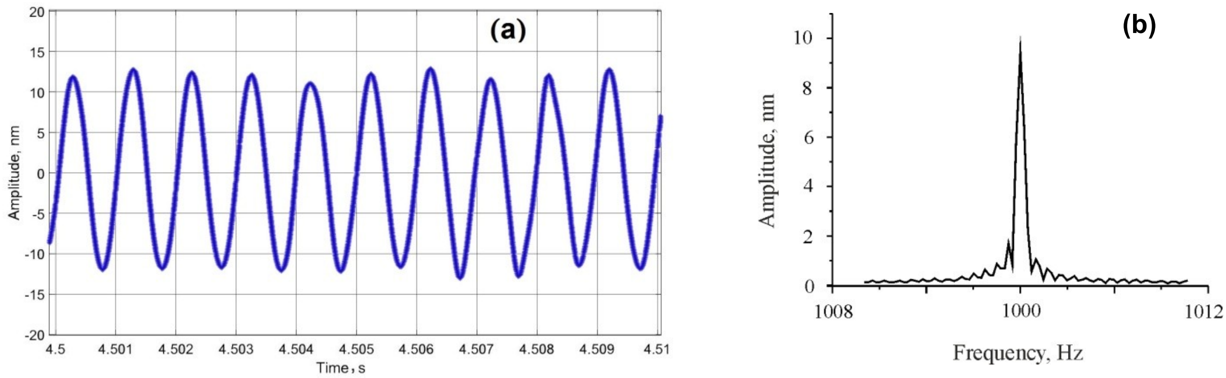

Fig. 4. Time (a) and spectral (b) dependences of the surface vibrations of a piezoelectric element with an amplitude of 10 nm and a frequency of 1 kHz. $R = 50$, $T = 0.125$.

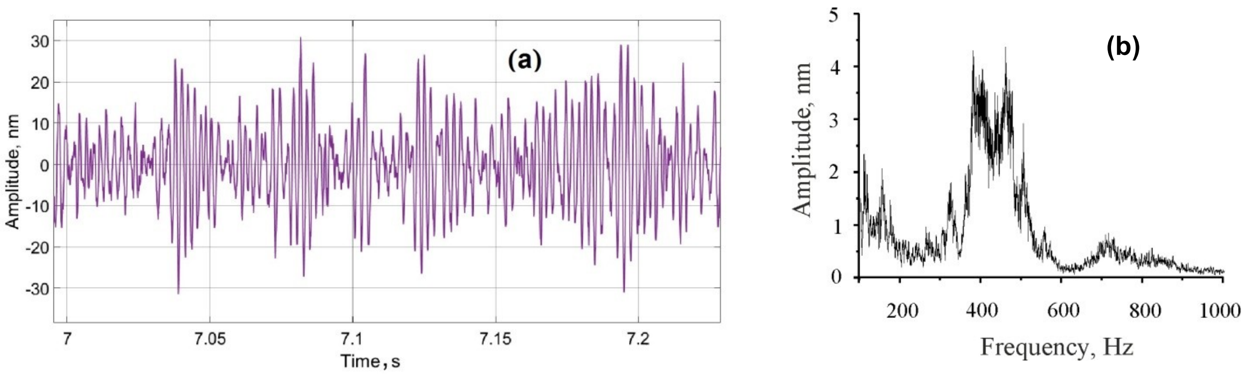

Fig. 5. Time (a) and spectral (b) dependences of ground surface vibrations above a simulant of ПМН-2 anti-personnel mine buried to a depth of 10 mm, under the influence of acoustic white noise with the loudness of 80 dB.

The core of the program includes coefficients R and T, which scale the amplitude and time axes, respectively. These coefficients are found experimentally by recording the motion of a test surface with the known circular frequency Ω and amplitude a.

3. Experimental results

To calibrate the LDV and determine the R and T coefficients of the program, the piezoelectric element oscillations spectrum with precisely specified surface motion parameters was recorded. The surface albedo was approximately 0.3-0.4. The distance from the surface to the LDV was 1 m. Fig. 3 shows the spectrum of the intermediate frequency signal from the surface of the piezoelectric element vibrating with an amplitude of $a = 10$ nm ($\Delta I = 20$, see Fig. 3) and a frequency of 1 kHz. The filter band was set at 3 kHz. The spectrum was obtained using the "AD6620 Monitor" test program.

The determination of the coefficients R and T was carried out by comparing the amplitude of the response at the frequency of surface oscillations (I_1) with the amplitude of the response at intermediate frequency (I_0) in the signal spectrum (see Fig. 3). The obtained amplitude values after data processing by the MatLab program corresponded to those set at the value of the coefficient R equal to 50. Coefficient T depends on the passband of the digital filter. For the set filter with a cutoff frequency of 3 kHz, the value of T is 0.125. The dependence of the surface oscillations of the studied piezoelectric element on time is presented in Fig. 4a, and the spectral dependence of the oscillation amplitude is shown in Fig. 4b.

With account of the relevance of the problem of creating a reliable and operator-safe method of humanitarian demining, experimental studies of the seismic response to external acoustic excitation of a full-size (diameter 120 mm, height 54 mm) simulants of the ПМН-2 anti-personnel mine (SM) were carried out. The SM was buried in moist soil to a depth of 10 mm. Vibrations in the soil were excited using the acoustic white noise within the frequency range 50…1000 Hz delivered through the loudspeaker. The sound pressure level on the ground surface was 80 dB. In Figs. 5a and 5b, time and spectral dependences of the vibrations of the soil surface above the simulant of mine excited by external acoustic white noise are shown, respectively. One can see in Fig. 5a that the overall amplitude of the vibrations can reach nearly 30 nm.

The spectrum of the acoustic vibrations of the soil surface above the SM (Fig. 5b) is characterized by a series of resonance bands. The resonance vibrations within the frequency range lower than ~200 Hz are attributed to the vibrations of a homogeneous soil (without macroscopic inclusions) and hardware effects. The acoustic response, determined by the resonance reaction of SM to external excitation during its interaction with the surrounding soil, is characterized by two intense resonance bands at 396 and 465 Hz, as well as a series of weak bands at 321, 504, 556 Hz, and a broad band close to 714 Hz. The latter is likely a superposition of several closely spaced bands.

One can see that the presence of a buried object is manifested in its characteristic acoustic vibration spectrum. These features of the acoustic response of buried objects allow the use of LDV in humanitarian demining to detect explosive devices under the surface of the soil and to identify them with a high probability.

4. Conclusions

This work provides a detailed examination of the design, principle of operation, and mathematical background for signal processing of the laser Doppler vibrometer developed at the V. Lashkaryov Institute of Semiconductor Physics of the NAS of Ukraine. It is shown theoretically that the measurement accuracy of this device can achieve tenths of a nanometer within the vibration frequencies of 50…1000 Hz with a cutoff frequency of 3 kHz. The methodology for calibrating the device and determining empirical scaling coefficients for calculating the amplitude of measured vibrations is also addressed.

Considering the relevance of creating a reliable and operator-safe method for humanitarian demining, experimental studies of the seismic response of a full-size plastic simulant of the Soviet ПМН-2 antipersonnel mine, buried at a depth of 10 mm in moist soil, were carried out. A characteristic acoustic response of the soil surface, caused by the resonance reaction of the simulant to external excitation during its interaction with the surrounding soil, was obtained.

The results of theoretical calculations and experimental studies confirm the feasibility of using LDV in the field of humanitarian demining for the detection of explosive objects buried in the ground.

Acknowledgement

This work was supported by the National Research Foundation of Ukraine (Project # 2023.04/0088).

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Morozhenko V.O.: investigation, resources, formal analysis, visualization, writing – original draft preparation, review & editing.

Soloviev E.O.: resources, software.

Serozhkin Yu.G.: conceptualization, data curation, formal analysis, funding acquisition; methodology, resources, investigation, validation, visualization, writing – review & editing.

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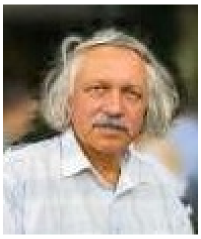

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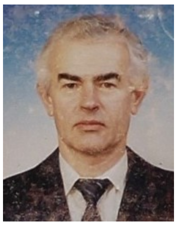

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Методологія вимірювання нановібрацій ґрунту за допомогою лазерного допплерівського віброметра з метою виявлення закопаних вибухонебезпечних предметів

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Анотація. Робота спрямована на розробку сучасного акусто-оптичного методу виявлення закопаних вибухонебезпечних предметів. Він базується на вимірюванні механічних нановібрацій ґрунту за допомогою лазерного допплерівського віброметра (ЛДВ). Неруйнівний характер методу та можливість дистанційного зондування мають особливе значення в контексті гуманітарного розмінування. У цій роботі детально розглядається конструкція, принцип роботи та математичний апарат для обробки сигналів ЛДВ, розробленого в Інституті фізики напівпровідників Національної академії наук України. Теоретично показано, що точність вимірювання коливань цього пристрою становить десяті частки нанометра при частоті коливань 50…1000 Гц. Описано методику калібрування пристрою та визначення емпіричних коефіцієнтів для розрахунку амплітуди вимірюваних коливань. Наведено приклад лабораторного експериментального дослідження сейсмічного відгуку повнорозмірного пластикового імітатора радянської протипіхотної міни ПМН-2, закопаного у вологому ґрунті.

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