Autonomous Seismic Sensor with a New Temporal Method of a Moving Person Detection

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***Abstract*—The article presents an autonomous seismic sensor developed to detect a moving person using temporal characteristics of a seismic signal. In order to exclude false alarms associated with moving animals, an additional temporal informative classification feature of the seismic signals from a moving person was introduced into a person detection algorithm, in contrast to known seismic sensors. This feature is associated with a difference in a movement nature of humans and animals. Sensor tests have shown that it has a significant probability of the correct person detection along with low power consumption. It is shown that such characteristics can be achieved using a relatively simple temporal method of the moving person detection. The range of use of the developed sensor is the protection of various objects, border and remote monitoring of the people movement.**

Keywords—moving person detection, seismic signal characteristics, sensor construction, temporal algorithm, sensor tests

I. Introduction

Seismic sensors for the detection of moving people and vehicles (SSD) are passive type sensors since they do not contain the radiofrequency radiation sources. Considering also their small size, such sensors become invisible for various search and detection means. SSD and systems based on them are widely used both for a various objects guard and for reconnaissance purposes. The most common SSD nowadays are those that use spectral or time-frequency signal processing methods with learning (SVM - support vector machine) or self-learning (neural network) algorithms for the purposes of moving objects classification [1] - [4]. The advantage of such SSD is determined by their high (over than 0.92) probability of a recognition of moving objects. However, the use of these methods and algorithms leads to a considerable increase in the information and energy consumption that is extremely undesirable for many SSD operating modes. For example, an autonomous remote seismic sensor, both separately operating and being a part of the so-called UGS (unattended ground sensor), which autonomously works for a long time in the detection mode of violators of borders and sections of certain territories, must have the minimal energy consumption [5]. Therefore, in these cases, the most preferred sensors are those that use temporal parameters of seismic signals, as this leads to the simplest operation algorithms and minimal power consumption [6], [7]. In such SSD, the temporal parameters of seismic pulses generated by a moving person — a pulse width, and a pulse repetition period — are used as informative classification features. Such sensors are simple and energy efficient. However, they can not effectively separate the seismic pulses from humans and close to them in temporal parameters pulses from medium and large animals. This fact reduces the reliability of the person identification by such sensors and leads to a high percent of false alarms.

This article presents the developed autonomous seismic sensor that uses an additional temporal classification feature of the seismic signal from a moving person and as a result has a significant value of the probability of the correct person detection along with the low power consumption.

II. Temporal Classification Features of the Seismic Signal from a Moving Person

Experimental studies of seismic signals were performed using the designed digital recorder with a signal sampling frequency of 600 Hz. It includes an industrial vibrations transducer DN-3-M1, which was mounted on a small platform with a cone for installation in the ground. It was found that the seismic signals from a moving person have the periodic bipolar pulse character in the form of packets, with a decrease in the envelope of the pulses sequence when a person passes in the direction from the recorder (Fig. 1). The pulse width depends on many factors, and for steppe soil varies from 80 ms to 300 ms. The pulse repetition period depends on the speed of a moving person and varies from 0.3 s to 1.2 s. The signals spectra from a person moving on the steppe ground at the distance of 15 m from the recorder contain frequencies approximately from 3 Hz to 100 Hz (Fig. 2, a curve of normal thickness).

The above results are in qualitative agreement with the results obtained in other works [8] – [11]. But in this work, the spectra of signals at various distances from a person were additionally analyzed. It was found that the higher frequencies of the spectrum are lost as this distance

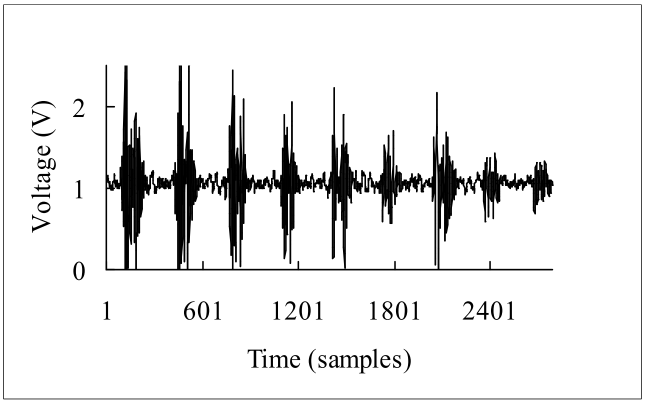

Fig. 1. Seismic signal from a person walking away from the recorder.

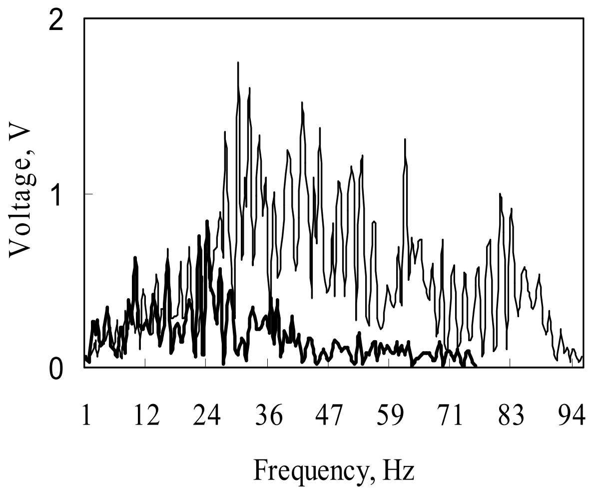

Fig. 2. Spectra of seismic signals from a person moving on the steppe soil at the distance from the recorder of 15 m (the curve of normal thickness) and 25 m (the thickened curve).

increases (Fig. 2, the thickened curve). This effect is associated with the action of a near-surface layer of soil, in which the surface Rayleigh wave propagates from the ground source of seismic vibrations. The noted layer absorbs the high seismic signal frequencies more strongly, that is, plays the role of a low-pass filter [12], [13]. It should also be taken into account that the soil's properties depend on the natural and climatic factors [14], [15]. As a result, the seismic signal spectrum does not remain strictly constant, even for the same distance to a moving person and for the same soil type.

From the analysis of the seismic signals characteristics, a feature space is determined - a set of informative signal parameters for the moving person classification. Taking into account the above dependence of the seismic signals spectra on the distance to a moving person and the soil state that leads to a classification error, the features of the signals spectral characteristics were not used as the classification features for the person detection. Significant information and energy expenditure of the spectral methods, which are not desirable for the autonomous (remote) seismic sensors, were also taken into account. Therefore, the following temporal classification features of seismic signals from a moving person were selected: the pulse repetition period T_i ranging from 0.3 s to 1.2 s and the seismic pulse width τ_i ranging from 80 ms to 300 ms.

A temporal method to detect a moving person in the known seismic sensors [6], [7] is based on the determination of τ_i and T_i from the seismic pulses registered by sensor, and the comparison of these values with the corresponding time intervals specified in the sensor's processor memory for a certain number of sequentially registered pulses N. If the both measured values of τ_i and T_i fall into the indicated ranges of the corresponding parameters in each of N consecutive pulses, the sensor generates the logical unit signal about the person detection. Significant disadvantage of this algorithm is the high probability of false alarms, mainly due to the inability to reject the seismic signals from medium and large animals if they penetrate the sensor control zone. This is due to the fact that the values of τ_i and T_i of such seismic signals fall into the corresponding ranges specific to humans. As a result, the seismic sensor has the high probability of false alarms.

In order to exclude the false signals associated with moving animals, the third temporal classification feature of the seismic signals from a moving person is introduced into the person detection algorithm. This feature is associated with a difference in the movement nature of humans and quadrupeds, which follows from the differences in biomechanics of their movements. An additional operation is introduced into the seismic sensor's microcontroller to determine the ratio T_{imax} / T_{imin} (the maximum and minimum values of the pulse repetition period) after five consecutive seismic pulses that have passed the selection criteria for the values of τ_i and T_i.

The ratio (A): $T_{imax} / T_{imin} < 1.25$ corresponds to the person detection. The seismic sensor will generate the logical unit signal about the person detection, only if the registered values of τ_i and T_i correspond to the ranges of these values specified in the sensor's microcontroller memory in each of five consecutive pulses, and if the ratio (A) is satisfied at N = 5.

The ratio (B): $T_{imax} / T_{imin} > 1.25$ corresponds to the animal detection. The seismic sensor will not generate the signal about the person detection, not only if the measured values of τ_i and T_i do not correspond to the ranges of these values specified in the sensor's microcontroller memory in each of five consecutive pulses, but if they correspond, however the relation (B) is satisfied at N = 5. The person detection signal is not generated, and the detection process starts again.

The indicated ratios (A) and (B) are based on different biomechanics of human and animal movements, in particular, on the unevenness of the quadrupeds tread associated with their walking (running) on four legs and, therefore, with different distances between the front (hind) legs and the front and hind legs [16]. The criterion of 1.25 was determined from the analysis of moving humans and animals seismograms. It was experimentally established that for a walking or running person, the T_{imax} / T_{imin} ratio does not exceed 1.25 for any five consecutive pulses, and for a walking or running medium or large animal, this ratio is not less than 1.25 [17]. The seismogram of a moving person is presented earlier in Fig. 1, and the seismogram of a moving

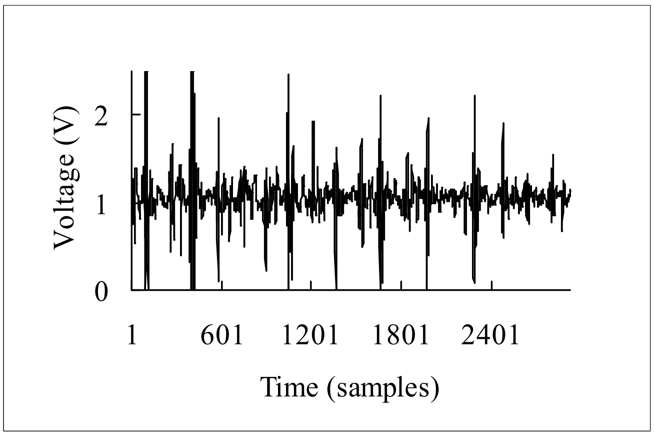

Fig. 3. Seismic signal from a horse walking away from the recorder.

horse is presented in Fig. 3. 600 counts of the analog-to-digital converter of the seismic signal recorder correspond to 1 second. It can be established from Fig. 1 that the value of T_{imax} / T_{imin} ratio for a person is 1.17. And it can be established from Fig. 3 that the value of this ratio for a horse is 1.32. A significant difference in the uniformity of human and animal movements was also observed earlier [18], [19]. However, the idea to use this fact for the moving person detection was realized only in this work.

III. Seismic Sensor Design and Testing

Constructions of the autonomous (remote) SSD typically include: a low-frequency geophone or piezoelectric transducer, a seismic signal processing unit, and a radio transmitting unit [5]. This article presents the developed autonomous seismic sensor without a radio transmitting unit. Sensor consists of a seismic piezoelectric transducer and a seismic signal processing unit. The photo of the experimental model of the autonomous seismic sensor is shown in Fig. 4. Compared to the small-sized geophones, piezoelectric transducers register the seismic vibrations with a lower frequency. On this basis, the membrane type piezoelectric seismic transducer has been designed and manufactured for the seismic sensor. It has been mounted on a small platform with a cone for installation in the ground (Fig. 4). The amplitude-frequency characteristic of the transducer is presented in Fig. 5. As can be seen from the Fig. 5, transducer has a sensitivity of $5\cdot10^{-2}$ $Vm^{-1}s^{2}$ in the frequency range from 3 Hz to 160 Hz. The top frequency of the transducer's operating frequency range is quite sufficient for the correct conversion of the seismic signals from a moving person, since the upper frequency of these signals does not exceed 100 Hz at distances over 15 m [9].

The signal from the seismic transducer enters the gain and active filtering scheme of the seismic signal processing unit. Then the signal is digitized by the analog-to-digital converter of the processing unit's microcontroller and enters the processing into the microcontroller computing core. The sampling frequency of the input signal is 700 Hz. An adaptive threshold principle in the processing unit is used to separate the informative seismic signal from the seismic noise [9]. The start of detection begins from the moment the

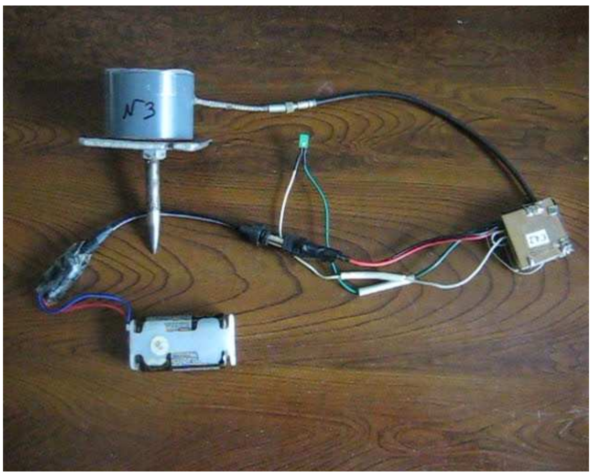

Fig. 4. Experimental model of the autonomous seismic sensor for the moving person detection.

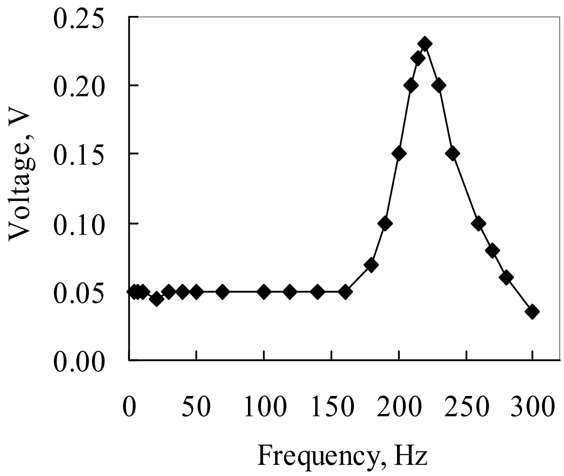

Fig. 5. Amplitude-frequency characteristic of the piezoelectric seismic transducer at a = 1 ms^{-2}.

seismic signal exceeds the detection threshold. And the algorithm of recognition of a moving object begins to operate. If the signal is absence more than 15 s (the threshold is not exceeded), an energy saving (standby) mode is installed. In this mode, the comparison of the input signal with the detection threshold occurs every 10 ms. If the threshold is not exceeded, the microcontroller remains in low power standby mode. A program for constructing a signal envelope based on the principle of a full-wave rectifier with a low-pass filter was used to establish the temporal parameters of seismic impulses from a moving person, and a microcontroller's timer also was used.

There is a LED in the processing unit to indicate the result of detection and recognition. If the detected signal is recognized as a person, the LED will turn on for 1 s. The block is powered by either two alkaline batteries AA or a single lithium battery, which creates a constant voltage of 3 V. The seismic transducer and the seismic signal processing unit are connected by a 50 ohm wave impedance cable.

The testing of the experimental model of the seismic sensor was carried out on the steppe soil, and the sensor was located in a dug hole. The person speed varied from a slow walking to a running. The glow of the sensor's light-emitting diode indicated about the person detection. To experimentally verify that the proposed person detection method is correct, the seismic sensor was manufactured in two versions. In the first version, only the values of τ_i and T_i were determined, and the signal about the person detection was generated after confirming that these values corresponded to their specified ranges in each of five consecutive seismic pulses. The seismic sensor in the second version was performed with the new person detection method, where in addition to the determining and confirming the values of τ_i and T_i, the ratio T_{imax} / T_{imin} was also determined and confirmed. The sources of the seismic signals were humans and animals (horse, goat). The number of passes of each source was 25. In the first sensor version, the false alarms were observed in 92 % during the passage of animals, and in the second sensor version they were observed in 8 %. When a person passed, the percent of the false alarms was approximately the same (8%) in the both sensor versions.

The proposed temporal method of the person detection also protects the developed sensor from other impulse disturbances, for example, from periodic at N < 5 (in the same ranges of τ_i and T_i) or non-periodic seismic and ground-induced sound pulses. The sensor testing with the new temporal method of the person detection showed that the detection and recognition of a moving person is carried out with a rather high probability (> 0.9) at distances up to 30 m. At the same time, the power consumption of the sensor without indication is 8 mW in the detection mode and 0.25 mW in the standby mode. This allows the sensor to work in autonomous mode for more than 6 months. The small energy consumption of the seismic sensor is provided by using a low-power microcontroller. Its use is possible due to the use of the temporal method of the seismic signals processing that do not require significant information and energy expenditure.

The developed sensor has small size (90 cm^3) and weight (0.18 kg). Therefore, it is difficult to detect it even without digging into the ground.

IV. CONCLUSIONS

The autonomous seismic sensor for the moving person detection has been developed and tested. Using the designed digital recorder to register seismic signals, the temporal and spectral characteristics of the signals from a moving person were determined and analyzed. It is shown that the use of the spectral characteristics to identify a moving person is limited due to a significant effect of absorption in the soil on the seismic signals. Taking this into account, the temporal parameters of the seismic pulses generated by a moving person were used as informative classification features. An additional (compared to known temporal methods) temporal classification feature of the seismic signals from a moving person was introduced into the sensor algorithm to exclude false alarms associated with moving animals. This feature is associated with a difference in the biomechanics of humans and quadrupeds movements.

Sensor tests have shown that the proposed new temporal method to detect a moving person allows the autonomous seismic sensor to have a high value of the probability of the human recognition along with low power consumption. These characteristics are very important for autonomous remote sensors and have been achieved using the relatively simple temporal method of signal processing, without the use of complex and energy expenditure modern signal processing methods, especially with learning and self-learning algorithms for the purposes of classification of moving objects. The range of use of the developed sensor is the protection of various objects, border and remote monitoring of the people movement.

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