Identification of firearms by acoustic spectra of shots

Vadym Tiutiunyk
Department of Information Technology Security
Kharkiv National University of Radio Electronics
Kharkov, Ukraine
E-mail: tutunik_v@ukr.net

Alexander Levterov
Department of Management and Organization of Civil Defence
National University of Civil Defence of Ukraine
Kharkov, Ukraine
E-mail: alionterra@gmail.com

Olha Tiutiunyk
Department of Informatics and Computer Engineering
Simon Kuznets Kharkiv National University of Economics
Kharkov, Ukraine
E-mail: tutunik.o@ukr.net

Dmytro Usachov
Department of Management and Organization of Civil Defence
National University of Civil Defence of Ukraine
Kharkov, Ukraine
E-mail: usachovrabotadsns21@gmail.com

Abstract **– The work is aimed at creating an artificial intelligence system for monitoring terrorist emergencies and automated identification of the use of various types of firearms in an urban area by the parameters and characteristics of acoustic spectra of shots. The authors propose a method for identifying acoustic spectra of shots by characteristic frequencies (extremes of amplitude-frequency characteristics) and comparing the energy of the spectrum. The paper presents an example of the application of the proposed method for the identification of shots from a 9 mm Makarov pistol, a Fort-14R traumatic pistol, and a 5.45 mm AK-74 rifle. The study of the spectral characteristics of firearms shots contributes to a broader understanding of the processes occurring during terrorist threats and will contribute to the further development of acoustic analysis methods for various purposes, including military, law enforcement, and civilian applications.**

Keywords—emergency monitoring, terrorism, firearms identification, acoustic signal from a gunshot, signal filtering, spectral analysis, amplitude-frequency response, spectral energy, spectral subtraction, situation center, anti-crisis decision support.

I. INTRODUCTION

Today, terrorism as a socially dangerous activity consisting in the deliberate and purposeful use of violence, through hostage-taking, arson, murder, intimidation of the population and authorities or other attacks on the life and health of innocent people or threats of criminal acts to achieve criminal goals, is considered to be a danger with a high level of social and material damage.

Terrorist activity is inextricably linked to the illegal possession and use of firearms. Thus, according to the Office of the Prosecutor General of Ukraine, between February 2022 and October 2023, many objects were seized in the country: firearms – 5950 units (smoothbore – 111; rifled – 2376; other firearms – 3463); grenade launchers and rocket systems – 138; ammunition – 2643155 units; grenades – 4911; mines – 151; improvised explosive devices – 91; cold steel – 1315; gas and pneumatic weapons – 49; explosives – 4869.2948 kg. During this period, 3,626 criminal offenses were committed with rifled firearms; 172 with smoothbore firearms; 490 with cold steel; 262 with gas and pneumatic firearms; 86 with explosives; and 26869 with ammunition [1].

Based on the analysis of these dangerous events, it should be noted that today the process of detecting the use of firearms and passing information about the place of occurrence, type of weapon and consequences of emergencies in existing security systems is carried out manually, with great inertia and low reliability.

This points to the need to urgently resolve the issues of including into the national security system, vertically from the facility to the state levels of management, various functional elements of the territorial automated system of monitoring emergencies and components of the system of situation centers, which are tightly interconnected at the information and executive levels to make appropriate anti-crisis decisions to solve various functional tasks of detecting, identifying, preventing and eliminating terrorist acts related to the illegal possession and use of small arms [2, 3].

II. PECULIARITIES OF FUNCTIONING OF THE SYSTEM OF GROUND-BASED STATIONARY MEANS OF AUTOMATED CONTROL OF ACOUSTIC SPACE, SITUATION CENTER, COMMUNICATION AND TELEMETRY INFORMATION TRANSMISSION SUBSYSTEM, AS WELL AS THE SUBSYSTEM FOR IMPLEMENTATION OF ANTI-CRISIS SOLUTIONS FOR PREVENTION, LOCALIZATION AND ELIMINATION OF THE CONSEQUENCES OF EMERGENCIES IN THE CITY

The functional diagram of the system of ground-based stationary means of automated control of acoustic space, the situation center, the communication and telemetry information transmission subsystem, as well as the subsystem for implementing anti-crisis solutions to prevent, localize and eliminate the consequences of emergencies, is shown in Fig. 1 [4].

The main indicator of the effectiveness of the operational acoustic monitoring subsystem of the emergency zone in the city is the reliability of the

978-x-xxxx-xxxx-x/22/$31.00 ©2024 IEEE

identification of the hazard source by type and place of occurrence.

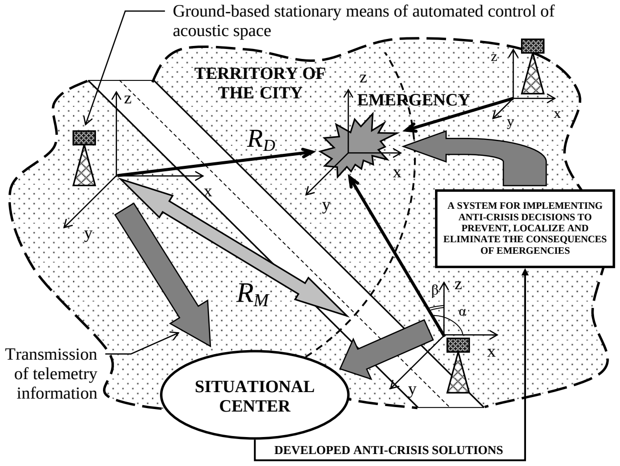

Fig. 1. Diagram of the functioning of the system of ground-based stationary means of automated control of acoustic space, situation center, communication and telemetry information transmission subsystem, as well as the subsystem for implementing anti-crisis solutions to prevent, localize and eliminate the consequences of emergencies

The factors that can affect the reliability of acoustic identification of a hazard source can be divided into three groups. The first group includes factors that directly characterize the dynamics of changes in the indicators of the development of the hazard source. The second group of factors includes the tactical and technical characteristics of acoustic space control equipment (metrological and operational indicators of information acquisition and processing equipment). The third group of factors includes the geographical and physical and chemical characteristics of the hazard source and the environment for the propagation of the information acoustic signal [5].

The neutral mode of sound propagation (Fig. 2, a) is characteristic of relatively short distances and line of sight. Thus, at the point of penetration of a ground-based stationary means of automated control of acoustic space, there is an interference of direct (emitted by the source of terrorist actions) and reflected from the Earth's surface rays.

Under conditions of surface propagation in the atmosphere of sound from a source of terrorist actions over long distances, the characteristics of acoustic waves are determined mainly by refraction on gradients of temperature and wind speed, which leads to the emergence of a waveguide mode (Fig. 2, b) and an anti-waveguide mode (Fig. 2, c). n the first case, the rays bend downward with multiple reflections from the Earth. This mode of sound propagation is characterized by relatively small values of sound attenuation. Otherwise, the rays are bent upwards and the acoustic shadow zone appears near the Earth at a certain distance from the emergency source. Therefore, only very weak sound scattered by turbulent inhomogeneities in the upper atmosphere penetrates this zone. These two modes of sound propagation operate mainly at distances exceeding 1 km.

At the same time, the territory of a large city is characterized by the functioning of a dynamically branched building system over a large area of the globe's surface, where various atmospheric processes occur locally and probabilistically, and there is a large concentration of objects of various functional purposes, buildings and structures with different numbers of floors, vehicles, roads, etc. per unit area. All these factors contribute to the emergence of interference (see Fig. 9) for the effective reception of information signals from acoustic space monitoring devices. Therefore, considering the conditions of acoustic monitoring over the disaster area in the territory of such a city, it is advisable to install acoustic space monitoring devices at distances not exceeding 1 km.

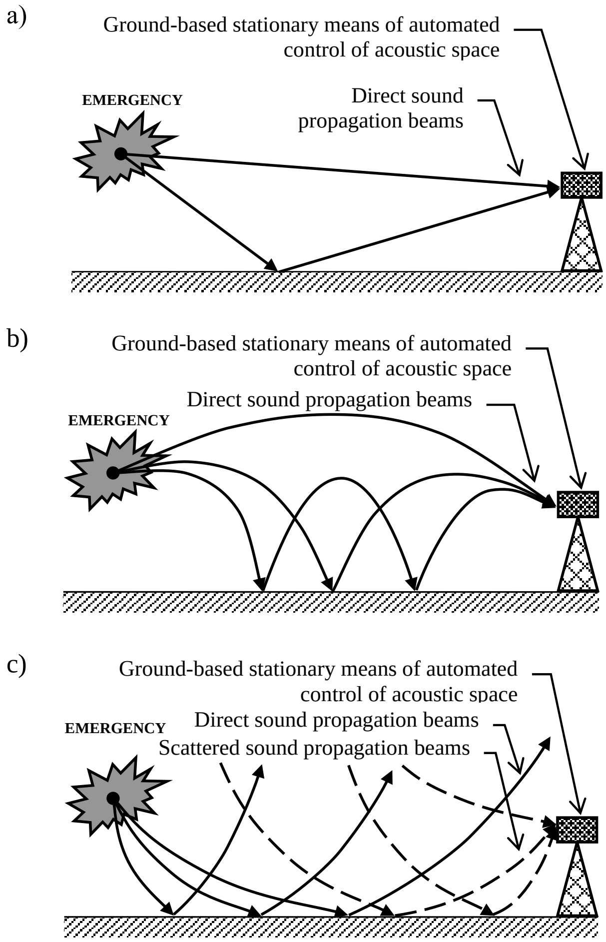

Fig. 2. Radiation patterns of sound propagation in the atmosphere from sources of terrorist actions to ground-based stationary means of automated control of acoustic space in various meteorological conditions: a) neutral mode; b) waveguide mode (only “top-down” rays are shown); c) anti-waveguide mode

In such conditions, it becomes necessary to analyze the efficiency of the functioning of acoustic space control means in the mode of weak sound refraction, which can be attributed to the case of direct propagation of a sound wave to the observation point. In this mode (see Fig. 2, a), only two rays arrive at the observation point: a direct ray that has no turning point and a ray reflected from the Earth, where the ray pattern of sound propagation is characterized by negligible curvature of the ray trajectories. The calculation of sound pressures in this case can be performed using the formula:

$$L_{R_M}(f) = L_s(f) + L_{abs}(f) + L_t(f) + \\ + L_e(f) + L_{div}(f) + L_{pat}(f), \qquad (1)$$

where is R_M – the radius of the zone of probabilistic acoustic identification of terrorist actions, $L_{R_M}(f)$ – is the sound pressure level at the input of a ground-based stationary means of acoustic space control at the frequency f from the source of terrorist actions that occurred on the border of the zone of reliable acoustic identification, $L_s(f)$ – is the sound pressure from the source of terrorist actions, recalculated to the sound pressure at a distance of one meter from the source, $L_{abs}(f)$ – contribution of classical and molecular sound absorption in the atmosphere, $L_t(f)$ – contribution of turbulent sound attenuation, $L_e(f)$ – the contribution of ground sound attenuation (takes into account the effect of interference of direct and reflected waves), $L_{div}(f)$ – the contribution of angular divergence, $L_{pat}(f)$ – an additive that takes into account the characteristics of the radiation pattern of the acoustic space control device.

Equation (1) expresses the law of energy conservation and is an energy balance equation. All the components of the right-hand side of this equation, except for the component $L_s(f)$, are usually negative. For reliable acoustic identification of the source of terrorist actions and determination of the location of this source in the city, the following conditions must be met: $R_D \le R_M$.

III. DEVELOPMENT OF A METHOD FOR DETECTING THE PROCESS OF USING FIREARMS AND ESTABLISHING THEIR TYPE BASED ON THE RESULTS OF THE ANALYSIS OF ACOUSTIC SPECTRA OF SHOTS

The method of automatic detection of the process of using firearms and establishing their type is based on the peculiarities of determining the maximum values of the amplitude-frequency characteristics of acoustic signals from shots in the characteristic frequency ranges.

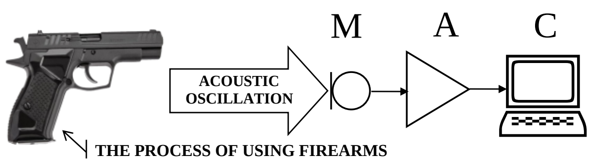

Fig. 3. Diagram of a laboratory setup for studying the amplitude-frequency characteristics of acoustic vibrations in the process of using firearms: M – microphone; A – amplifier; C – computer with appropriate software

The development of the method is based on experimental studies of the amplitude-frequency characteristics of acoustic vibrations of firearms shots. To conduct the laboratory studies, we used a laboratory setup, the block diagram of which is shown in Fig. 3.

During the experiment, data were collected on the acoustic signals of shots fired from a 9 mm Makarov pistol, a 9 mm Fort-14R traumatic pistol, and a 5.45 mm AK-74 assault rifle, as potentially possible means for committing terrorist acts. The amplitude-frequency characteristics of three shots fired from each of these weapons are shown in Figs. 4–6.

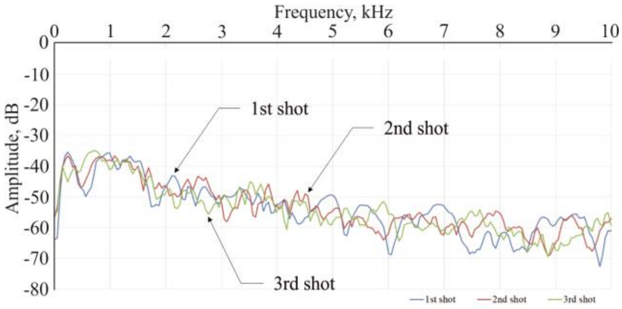

Fig. 4. Spectra of shots from a 9 mm Makarov pistol

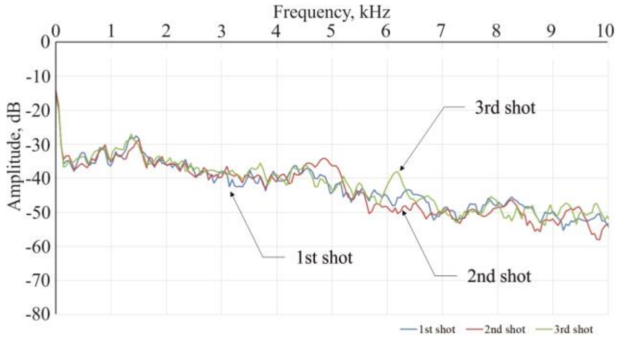

Fig. 5. Spectra of shots from the "Fort-14R" traumatic pistol

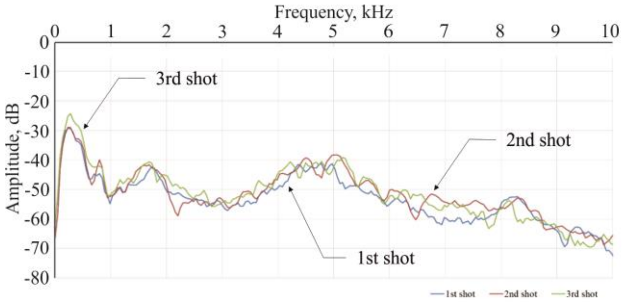

Fig. 6. Spectra of shots from the AK-74 rifle of 5.45 mm caliber

Based on the results of the comparative analysis of the results of the experimental studies shown in Figs. 4-6 of the experimental results, the average characteristic of the acoustic spectrum of a shot for the native types of the studied firearms was compiled by determining the characteristic frequencies with the maximum amplitude values. The results of processing the experimental data are given in Table 1.

To identify the acoustic spectrum of a gunshot, the following algorithm is proposed: 1) separation of the "useful" signal from the background of interference; 2) frequency (spectral) description of the received signal; 3) determination of the characteristic frequencies (at which frequencies the harmonic amplitudes exceed the established threshold value – see Fig. 7) of the obtained spectrum; 4) comparison of the obtained results with the firearms identification database.

The number of harmonics whose amplitude exceeds the established threshold value is defined as

$$K_{ex} = \left\{ A_S''(f_i) = 0 \middle| sign\left(A_S''(f_i)\right) > 0 \right\}, \qquad (2)$$

where is $A_S(f)$ – is the envelope function of the received signal spectrum.

TABLE I. CHARACTERISTIC FREQUENCIES OF SHOT SPECTRA OF THE RESEARCH FIREARMS SAMPLES

Types of weapons	**№ shot**	**Characteristic frequencies (kHz)**					
		f_1	f_2	f_3	f_4	f_5	f_6
Makarov 9 mm pistol	1	0,4	1,2	2,9	4,1	7,2	10,6
	2	0,8	1,6	2,4	3,9	8,5	11,5
	3	0,4	1,3	3,0	4,0	9,5	12,5
AK-74 5.45 mm	1	1,1	1,8	2,5	5,9	8,8	16,3
	2	1,3	1,9	2,8	3,9	7,9	10,1
	3	1,7	3,2	5,4	8,2	9,9	14,3
Fort-14R	1	0,9	1,5	2,7	7,2	7,2	10,5
	2	0,6	1,7	2,9	2,9	7,7	11,9
	3	0,8	1,9	3,4	3,4	8,0	14,7

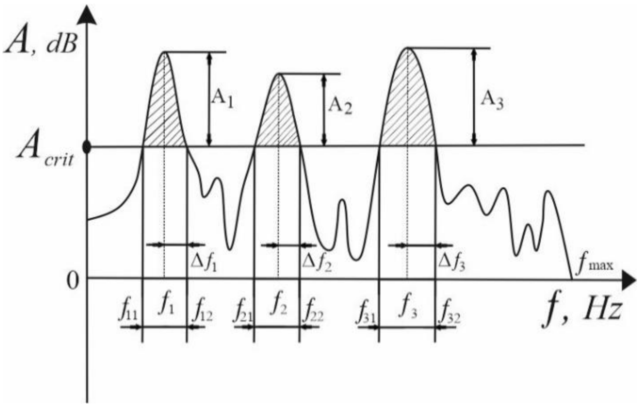

Fig. 7. Determination of the characteristic frequencies of the shot spectrum and determination of the spectrum energy at the corresponding harmonics: A_i – amplitude of the i harmonic of the spectrum; f_i – frequency of the i harmonic of the spectrum; Δf_i – permissible range of fluctuations in the frequency of the i harmonic of the received signal spectrum (see Table 1); A_{crit} – set threshold value for the amplitudes of the spectrum harmonics (determined on the basis of statistical data of received signals for different types of weapons)

For each type of weapon, the energy of the spectrum of the received signal exceeding the threshold value is defined as:

$$E_P = \int_0^{f_{max}} A_P(f)\,df ,$$

where is A_P – envelope function of the spectrum exceeding the threshold value.

The process of identification of weapons is subject to the following conditions:

$$E_P \le \int_{f_{1.1}}^{f_{1.2}} A_1(f)\,df + \int_{f_{2.1}}^{f_{2.2}} A_2(f)\,df + \ldots + \int_{f_{n.1}}^{f_{n.2}} A_n(f)\,df .$$

To smooth the spectrum and ensure the appropriate accuracy and reliability of firearms identification based on the spectral energy of the received signal exceeding the threshold value, the paper uses the Hamming window weighting function, which helps to reduce distortions arising from signal spectrum discontinuities and has the following form:

$$w(n) = 0,54 - 0,46\cos(2\pi n/N - 1),$$

where is $w(n)$ – the value of the Hamming window for the sample n, N – the number of samples in the signal, n – the sample index, $n = 1, 2, \ldots, N-1$.

The Hamming window was applied to the signal $x(n)$ by multiplying each count by the corresponding window value, namely:

$$x_h(n) = x(n) \cdot w(n),$$

where is $x_h(n)$ – the value of the output signal for reference n, which is processed by the Hamming window, $x(n)$ – value of the input signal for reference n.

When processing the received acoustic signals of shots from the same weapon, shifts (deviations) in their spectral characteristics are observed (Fig. 8). These shifts are caused by factors such as changes in environmental conditions, uncertainties in measurement techniques, and random or systematic errors. A more detailed determination of the acoustic spectrum of shots should take into account various parameters, such as bullet weight, amount of powder in the cartridge, bullet velocity when leaving the barrel, barrel length and temperature, etc.

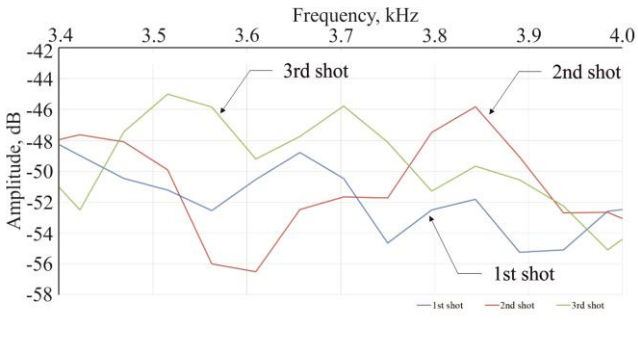

Fig. 8. Shifts in the spectral characteristics of shots fired from a 9 mm Makarov pistol

As a result of a series of shots, it can be observed that the spectra shift in the frequency range by a small amount. We assume that the permissible deviation Δf_i for spectrum identification is equal to 5 % ($\Delta f_i = 0,05 f_i$).

The influence of shot characteristics on the sound spectrum is an important task in the study of acoustic characteristics of shots. This can be useful for determining the characteristics of a weapon by its sound, as well as for analyzing the acoustic environment in combat conditions.

The most important factor that affects the characteristics of small arms shot spectra is the barrel temperature. When fired, the powder charge is converted into gases and high-temperature combustion products. These gases create a strong pressure necessary to push the bullet through the barrel. As a result, the barrel is heated significantly, which can significantly affect the characteristics of the sound spectrum.

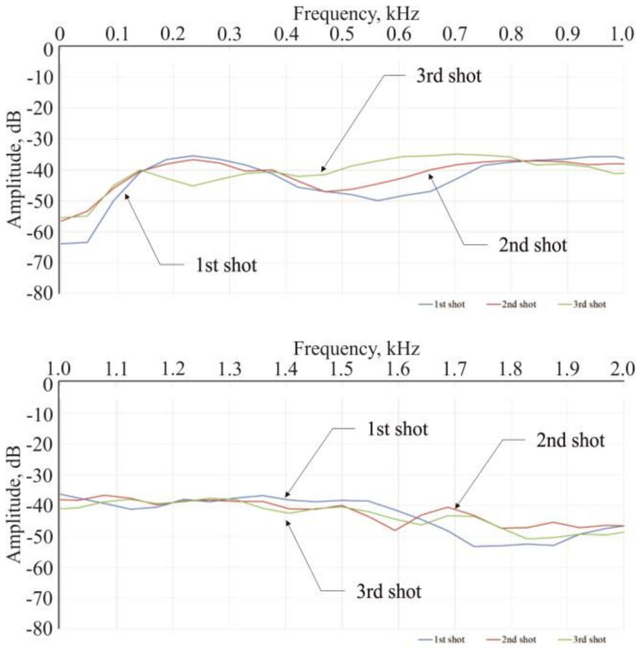

Fig. 9. The area of identical spectral regions of three shots from a 9 mm Makarov pistol

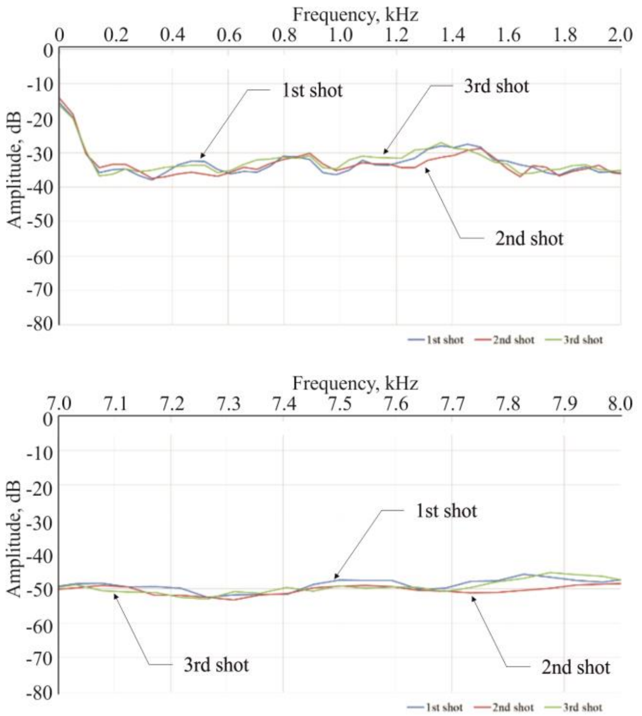

Fig. 10. The area of identical parts of the spectra of three shots of the “Fort-14R” traumatic pistol

After conducting a number of studies of the shots and analyzing their spectra, it is clear that the acoustic parameters of the three shots (a 9 mm Makarov pistol, a Fort-14R traumatic pistol, and a 5.45 mm AK-74 assault rifle) are different, but we can see that the spectrograms are quite similar in certain parts of the spectrum (Figs. 9–11).

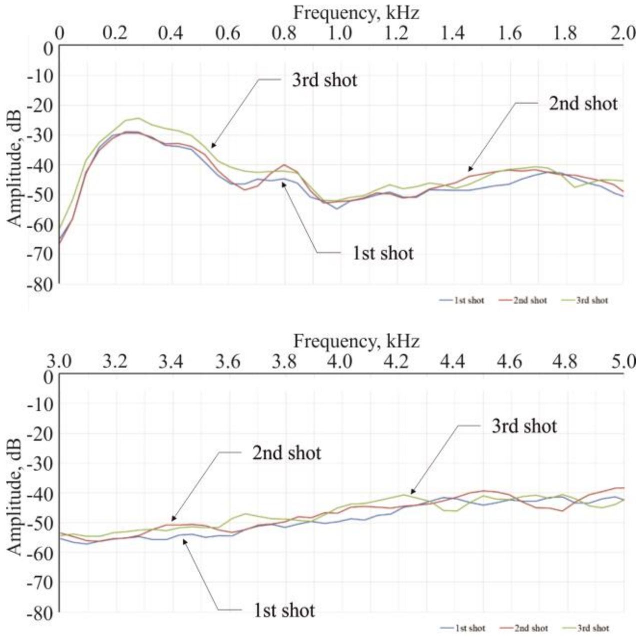

Fig. 11. The area of identical parts of the spectra of three shots of the AK-74 rifle of 5.45 mm caliber

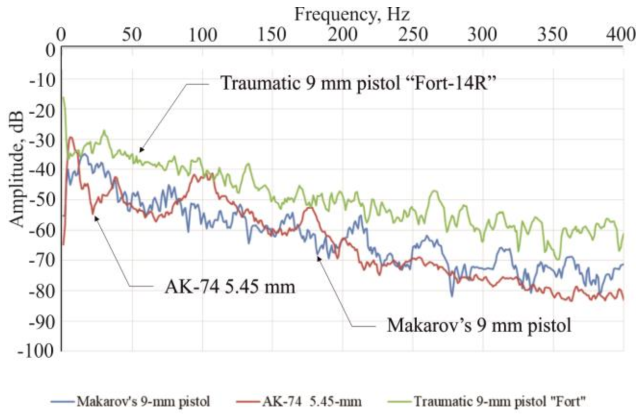

Fig. 12. General spectrogram of three shots from a 9 mm Makarov pistol, a Fort-14R traumatic pistol, and a 5.45 mm AK-74 assault rifle

During the experiment, the threshold amplitude was used to filter the signals to determine the characteristic frequencies at which the signal amplitude exceeds the set threshold value. If the result is positive, the frequency is retained, otherwise it is discarded. This process is repeated for the entire frequency range. The identification of the process of using a firearm is carried out by establishing a certain number of matches between the obtained and reference spectra. If four or more matches are found, it can be assumed that the spectrum in question corresponds with a probability of at least 80 % to the reference spectrum. At the same time, the detection accuracy is 80 %, since the spectra can be shifted and the amplitudes can differ.

To improve the accuracy of acoustic spectrum identification, the method of spectrum subtraction was used in this work. This involves comparing the spectrum obtained in the current experiment with the reference spectrum obtained experimentally after a series of more than 50 shots. For example, let's take three spectra of shots from small arms (Fig. 12) and compare it with the reference spectrum shown in Fig. 13.

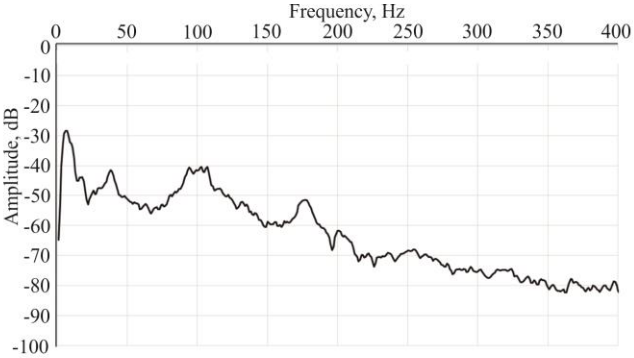

Fig. 13. Spectrogram of the reference shot spectrum

The reliability of the experimental results was checked using the Student's t-test, which is designed to assess the statistical significance of differences between sample means, and also takes into account the limited sample size and provides more accurate estimates of the significance of differences. Within the established limits of 5 % deviation, the results of the study are still considered reliable.

Taking this into account, the maximum permissible interval value S_p was introduced in the study. Within these intervals, the amplitude-frequency characteristics of the shots are considered reliable for further analysis and interpretation (Fig. 14).

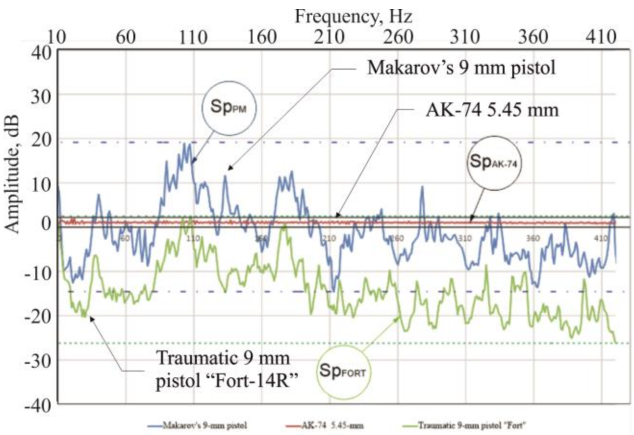

Fig. 14. Maximum permissible value of shot spectrograms

After applying the procedure of subtracting the reference spectrum from the experimentally obtained shot spectra (the results are shown in Fig. 15), it can be concluded that only one of the presented spectra approaches zero. This indicates that the received signal with a high probability of 0.95 corresponds to the reference signal, namely, a shot from a 5.45 mm AK-74 rifle.

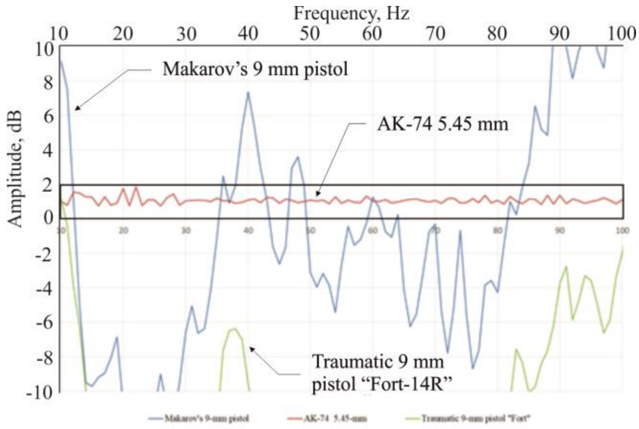

Fig. 15. Results of subtracting the reference spectrum from the experimentally obtained shot spectra

IV. Conclusion

In order to develop the scientific and technical foundations for the creation of a geographic information system for terrorist emergencies and automated identification of the use of various types of firearms in an urban area, the paper presents the results of a study of the characteristics of the acoustic spectra of shots from a 9 mm Makarov pistol, a Fort-14R traumatic pistol, and a 5.45 mm AK-74 assault rifle. The experimental results were processed in several stages: determination of characteristic frequencies when the threshold level of harmonic amplitudes of the received signal is exceeded; determination of the energy of such a spectrum; subtraction of the energy of the reference spectrum from the energies of the experimentally obtained shot spectra. This made it possible to identify the type of firearm by the received acoustic signal with a probability of 0.95.

References

[1] Single Report on Criminal Offenses: Office of the Attorney General (*in Ukrainian*). URL: https://gp.gov.ua/ua/posts/pro-zareyestrovani-kriminalni-pravoporushennya-ta-rezultati-yih-dosudovogo-rozsliduvannya-2

[2] O. Tiutiunyk, I. Ruban, and V. Tiutiunyk, "Development of Scientific Basis for Decision Support by Experts of the Situational Center Under Conditions of Uncertainty of Input Information in Emergency Situations", *IEEE Problems of Infocommunications. Science and Technology*, October, 2021, pp. 261–266.

[3] V. Tiutiunyk, I. Ruban, and O. Tiutiunyk, "Cluster Analysis of the Regions of Ukraine by the Number of the Arisen Emergencies", *IEEE Problems of Infocommunications. Science and Technology*, October, 2020, pp. 587–592.

[4] V. Tiutiunyk, O. Tiutiunyk, O. Teslenko, and N. Brynza, "Peculiar Properties of Creating a System of Support to Make AntiCrisis Decisions by Experts of the Situational Center at the Cyber Protection Object", *3rd International Scientific and Practical Conference on Information Security and Information Technologies*, September, 2021, pp. 47–56.

[5] V. Tiutiunyk, V. Kalugin, A. Levterov, O. Sydorenko, S. Starodubtsev, and D. Usachov, "Establishing the Nature of the Kinetic Effects of the High-Temperature Oxidation (Combustion) Process of Some Liquid Organic Matters by Acoustic Radiation", *Voprosy Khimii i Khimicheskoi Tekhnologii*, 2023, pp. 203–212.