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Using a System for Projectile Acoustic Location During a 35 mm AM-35 Naval Gun Tests for the Naval Armament System

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Abstract. The paper is a continuation of the cycle of presentations of the results for the research task commenced in 2018, at the 12th International Armament Conference (Poland), with the aim of developing a method and system for assessing firings at surface targets, during implementation of R&D project no. O ROB 0046 03 01. The paper presents simulation test results and experimental characteristics of the pressure disturbances caused by the motion of a 35 mm TP-T projectile on the basis of which the sensor parameters and configuration on the surface target were selected. A description of the adopted design solutions for the firing assessment system were presented.

Finally, selected performance results were presented for the projectile acoustic location system used to assess 35 mm combat firings of the AM-35 naval gun during Naval Armament System qualification tests.
Keywords: firing assessment system, projectile acoustic location, AM-35 gun, Naval Armament System

1. INTRODUCTION

In 2018, during the 12th International Armament Conference (Jachranka, Poland), theoretical assumptions were presented for the method of assessing surface target firings [1], conducted using a 35 mm AM-35 naval gun of the Polish Naval Armament System (OSU-35), equipped with an acoustic projectile location system. The premise for research on developing a system for assessing surface target firing effectiveness was that a projectile fired towards a target, moving at supersonic speed, generates a number of peculiar wave-like physical phenomena in the air. Such phenomena provide information regarding the projectile type and its motion parameters, which facilitate determining the position of the projectile in space, on the basis of signals collected at selected measurement points, located on the surface target.

Firing assessment systems today are often developed based on acoustic methods [2-5]. Slow parameter changes in the projectile flight medium, as compared to its speed, facilitate real-time transmission of measurement data via a relatively low-bandwidth and thus low-cost radio link. In addition, the small size of the sensors used makes it possible to place them on a moving surface target platform.

The objective of this paper is to present the adopted technical assumptions and applied design solutions for an acoustic projectile location system dedicated to the assessment of artillery combat firings with a 35 mm AM-35 naval gun, during Naval Armament System qualification tests.

The main functionalities of the projectile acoustic location system described herein are still under development. Intensive work is under way to increase the accuracy of determination of projectile flight coordinates by minimising errors in measurement of the N wave arrival time at individual sensors located on the target caused by its inclination (i.e. failure to meet the condition of projectile path perpendicular in relation to the plane created by the aperture of the sensor measurement system) as a result of changeable sea conditions [6]. Software methods are also being developed for the computational reconstruction of scenarios for artillery shelling and use of recorded results of firings to assess the training of the crews [7].

2. PREMISES FOR ACOUSTIC PROJECTILE LOCATION SYSTEM APPLICATION

A projectile, moving within an elastic medium, causes local and temporary disturbance in the medium balance. The resulting disturbance may move within this medium. The spread of elastic waves within an unlimited medium consists in exciting vibrations in the increasingly more distant parts of this medium. This is referred to as acoustic wave propagation. The essence of this phenomenon is the disturbance energy propagation without transferring the medium mass. The wave propagation capability is a characteristic property for all elastic media, i.e. air [8]. The projectile motion thickens the air, which spreads in space at the speed of sound *c* [9-10].

When the projectile moves at velocity V_p greater than the speed of sound ($V_p > c$), it excites the spherical acoustic wave faces which, by focusing, form the surface of a Mach cone (Fig. 1) with the opening angle α determined from the following relationship:

$$\alpha = \arcsin\frac{1}{M} \tag{1}$$

where: M – Mach number determined from the following relationship $M = V_p / c$.

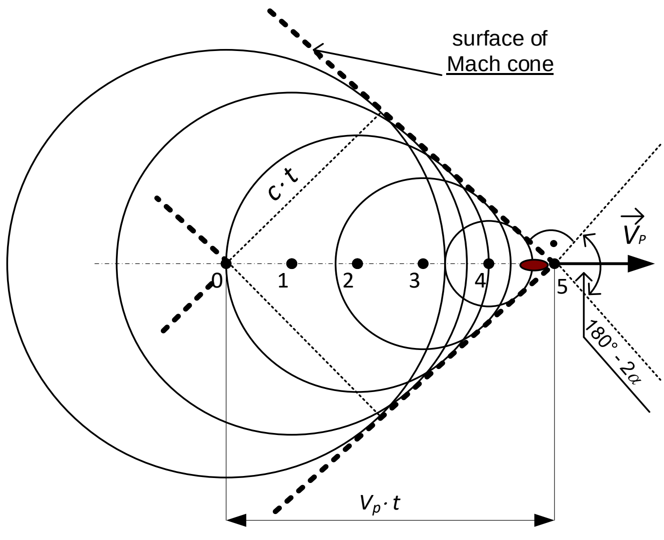

Fig. 1. Generating medium disturbances caused by supersonic projectile movement

Each point of the projectile flight path is a vertex of the Mach cone, which moves at the velocity of the projectile. The resulting disturbance is referred to as a shock wave [10-13] or ballistic noise [14-15].

A disturbance in the form of a shock wave means the projectile spreads along straight lines perpendicular to the Mach cone surface, creating a system of shock and rarefaction waves moving together with the projectile [16] (Fig. 2).

The set-up of this system depends on the projectile shape, its dimensions and the angle of attack relative to the analysed projectile flight plane or Mach number.

The characteristic pressure distribution, the idealised form of which is shown in Fig. 3, corresponds to the wave system shown in Fig. 2. In fact, the pressure course shown in Fig. 3 has a finite growth time for the front and rear impact wave slopes.

The first pressure spike Δp corresponds to the course of the shock wave front face, the linear drop within length L corresponds to the passage of rarefaction waves, while the second pressure spike $\Delta p'$ corresponds to the passage of the rear shock wave face.

In the literature [13], [18], this system of shock and rarefaction waves is referred to as the N-type wave, or N wave, with the values of Δp and $\Delta p'$ as its amplitude and L as its length. The N wave duration T can be determined from the following relationship: $T = L / c$.

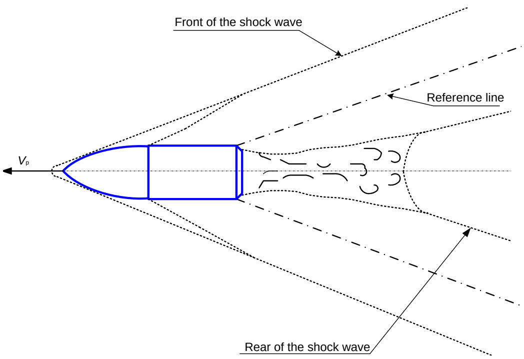

Fig. 2. System of waves generated by a projectile in supersonic motion [17]

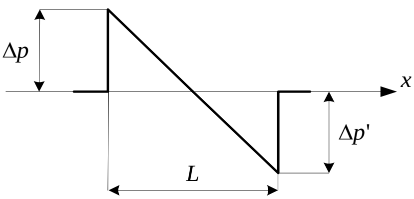

Fig. 3. N-wave pressure distribution

In the case of a moving projectile, the propagation of the generated acoustic wave in the atmosphere depends on the value of:

- projectile kinematic parameters (i.e., velocity and direction);
- characteristic atmosphere parameters (i.e., density, pressure and humidity);
- weather conditions (i.e., temperature, wind force and direction, precipitation intensity).

The relationships, taking into account the impact of projectile geometric values (calibre, length) which describe changes in N wave amplitude Δp and duration T are expressed by the Whitham model equations [19]:

$$\Delta p = 0.53 \cdot p_0 \cdot (M^2 - 1)^{1/8} \cdot r^{\xi_1} \cdot \frac{d_p}{l_p^{1/4}} \qquad (2)$$

$$T = 1{,}82 \cdot \frac{r^{\xi_2}}{c} \cdot \frac{M}{(M^2 - 1)^{3/8}} \cdot \frac{d_p}{l_p^{1/4}} \qquad (3)$$

where: r – distance perpendicular to the projectile flight path;
ξ_1 and ξ_2 – Whitham coefficients.

The above considerations show that the distribution of the N wave pressure can be identified on the basis of the characteristic physical values of the medium disturbances resulting from the supersonic movement of projectiles.

The N wave propagation distance significantly affects the disturbance amplitude and duration. As the distance increases, the amplitude decreases and the N wave duration increases. The Δp and T parameter values for disturbances caused by the supersonic motion of projectiles depend on their geometric dimensions and flight velocity.

For the purposes of simulation and experimental tests of the characteristics of the pressure disturbances generated by the supersonic motion of a 35 mm calibre projectile, it was assumed that:

- the projectile moves through an open space, and the medium disturbances caused form a free acoustic field;
- the projectile is a source of disturbance $s(t)$;
- the medium is simultaneously a medium of disturbance transmission $s(t)$ and a source of interference $N(t)$.

In projectile acoustic location systems, it is assumed that information concerning projectile coordinates relative to the target is included in the generated acoustic wave - in its space-time and spectral characteristics, which depend primarily on the projectile kinematic parameters [20].

3. SIMULATION AND EXPERIMENTAL TESTS OF THE PARAMETERS OF DISTURBANCES GENERATED BY A 35 MM TP-T PROJECTILE

3.1. Simulation tests

The assumed parameters are for the simulation tests of a 35 mm training projectile, manufactured by MESKO S.A. (Poland) with a tracer (i.e., 35 mm TP-P projectile), intended for training exercises using ammunition with parameters corresponding to the combat ammunition ballistics (e.g. for an AM-35 gun). This ammunition is used for target practice at a distance of up to 4,000 m.

Basic data and technical parameters of a 35 mm T-PT projectile were determined on the basis of the manufacturer's catalogue brochure [21].

During the simulation calculations, the following values of the projectile parameters were assumed: characteristic diameter (calibre): d_p = 34.94 mm, length l_p = 180 mm; initial velocity while firing from a ballistic barrel: V_0 = 1180 ± 15 m/s [21].

One of the most important kinematic characteristics of the projectile is its velocity distribution, i.e., V_p, as a function of the distance travelled x, which can be approximated with the following linear equation [2]:

$$V_p(x) = V_{p0} + \kappa \cdot x \tag{4}$$

where: V_{p0} – initial velocity of the projectile,
κ – ballistic coefficient < 0.

In the expression (4), the coefficient κ is the characteristic value of a given projectile and is determined experimentally.

The projectile velocity along the flight path can also be determined on the basis of indications from the radar speed measurement system or from ballistic boards, specifying, on this basis, the target approach time.

The kinematic parameters of the projectile, i.e., initial velocity V_{p0}, instantaneous velocity V_p and target approaching time, were recorded repeatedly during experimental firings with the AM-35 gun.

In order to describe the 35 mm TP-T projectile acoustic signature during supersonic motion, the following parameters were assumed, i.e., pressure increase Δp, N wave duration T and the following form of the describing function:

$$s(\Delta p, T, t) = \Delta p \cdot f(t, T), \tag{5}$$

where values Δp and T are calculated on the basis of the Witham model described with equations (2) and (3), while the function $f(t, T)$ is determined from the following relationship:

$$f(t, T) = 1 - 2t/T; \quad dla\ 0 \le t \le T. \tag{6}$$

Equations (2), (3), (5) and (6) constitute an idealised form of describing the medium disturbances, as they do not take into account the relationship of atmospheric attenuation and refer only to the idealised distribution of N wave pressure.

For such a defined form of N wave pressure distribution, its characteristic values were determined on the basis of simulations - see Table 1.

Table 1. Values of characteristic wave N parameters

r [m]	Δ*p* [Pa]	Δ*p* [dB]	*T* [ms]	*r* [m]	Δ*p* [Pa]	Δ*p* [dB]	*T* [ms]
0.05	38284.5	185.6	0.184	*1*	4048.1	166.1	0.390
0.1	22764.1	181.1	0.219	*5*	1210.7	155.6	0.583
0.2	13535.6	176.6	0.261	*10*	719.9	151.1	0.694
0.3	9986.4	174.0	0.289	*20*	428.0	146.6	0.825
0.4	8048.3	172.1	0.310	*40*	254.5	142.1	0.981
0.5	6808.0	170.6	0.328	*80*	151.3	137.6	1.167

In order to illustrate the calculation results for the data presented in Table 1, an idealised form of pressure distribution characteristics and N wave duration was plotted as a function of distance *r* from the projectile flight path (Fig. 4) and distributions of characteristic parameters for pressure increase Δ*p* and duration *T* of the N wave as a function of distance *r* from the projectile flight path (Fig. 5) were determined.

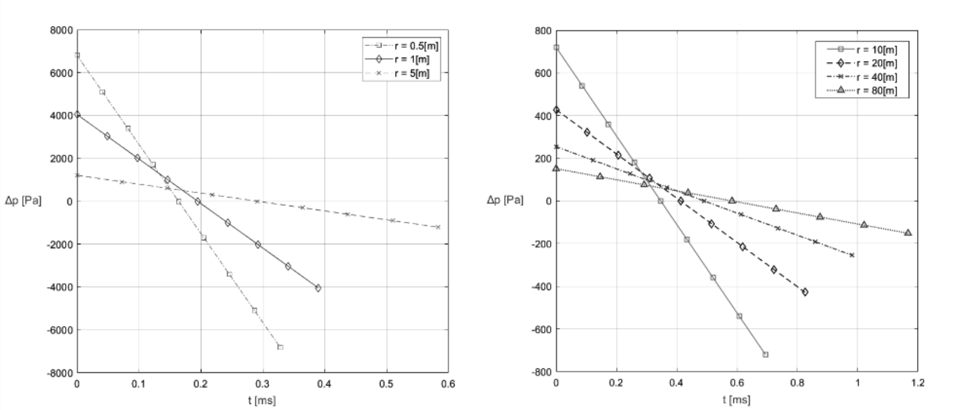

Fig. 4. Pressure distributions and N wave duration for a 35 mm TP-T projectile: at distances: 0.5÷5 [m] (left) and 10÷80 [m] (right).

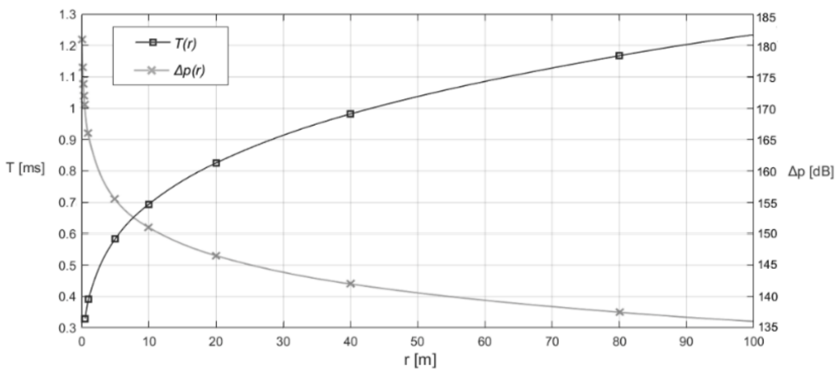

Fig. 5. Distribution of amplitude Δ*p*(*r*) and duration *T*(*r*) of pressure disturbances caused by 35 mm TP-T projectiles at the distance of 0.5÷80 [m]

Simulation tests for the characteristics of pressure disturbances generated by the 35 mm TP-T projectile in supersonic motion show that the maximum pressure level at the acoustic sensor input may exceed 180 dB, and, at a distance of 30 m from the sensor, this level even exceeds 140 dB. The maximum and minimum level of the N wave pressure value determines the dynamics for the measurement sensors used. The simulations performed show that, in order to ensure at least a 30 m projectile detection range, a decrease in the sound intensity level of the recorded signals amounting to approx. 40 dB should be taken into account.

3.2. Experimental tests

Practical verification of the determined simulation parameters and characteristics of pressure disturbances for the motion of a 35 mm TP-T projectile and the pre-adopted parameters of acoustic sensors took place in winter 2018, during experimental tests at the Ustka (Poland) firing ground. The subject of experimental tests was to identify the actual pressure parameters generated by 35 mm TP-T projectiles and to verify the suitability of pre-selected sensors for acoustic signal processing, and also to analyse the viability of detection and determination flying projectile coordinates.

During the tests, an AM-35 gun (Fig. 6a) was fired towards objects located on the ground, i.e., targets located at the following distances: 100, 500 and 1000 [m] (Fig. 6b).

(a) (b)

Fig. 6. Experimental firings at the Ustka firing ground, in 2018:
a) 35 mm A-35 gun; b) arrangement of targets

Examples of N waveform results recorded by six different types of measuring sensors are presented in Fig. 7.

The tests conducted showed that the development of an acoustic location system for 35 mm calibre projectiles requires the precise selection of sensors. Their incorrect selection could result in significant distortion of the signal, which would translate into subsequent errors in detection and projectile position determination.

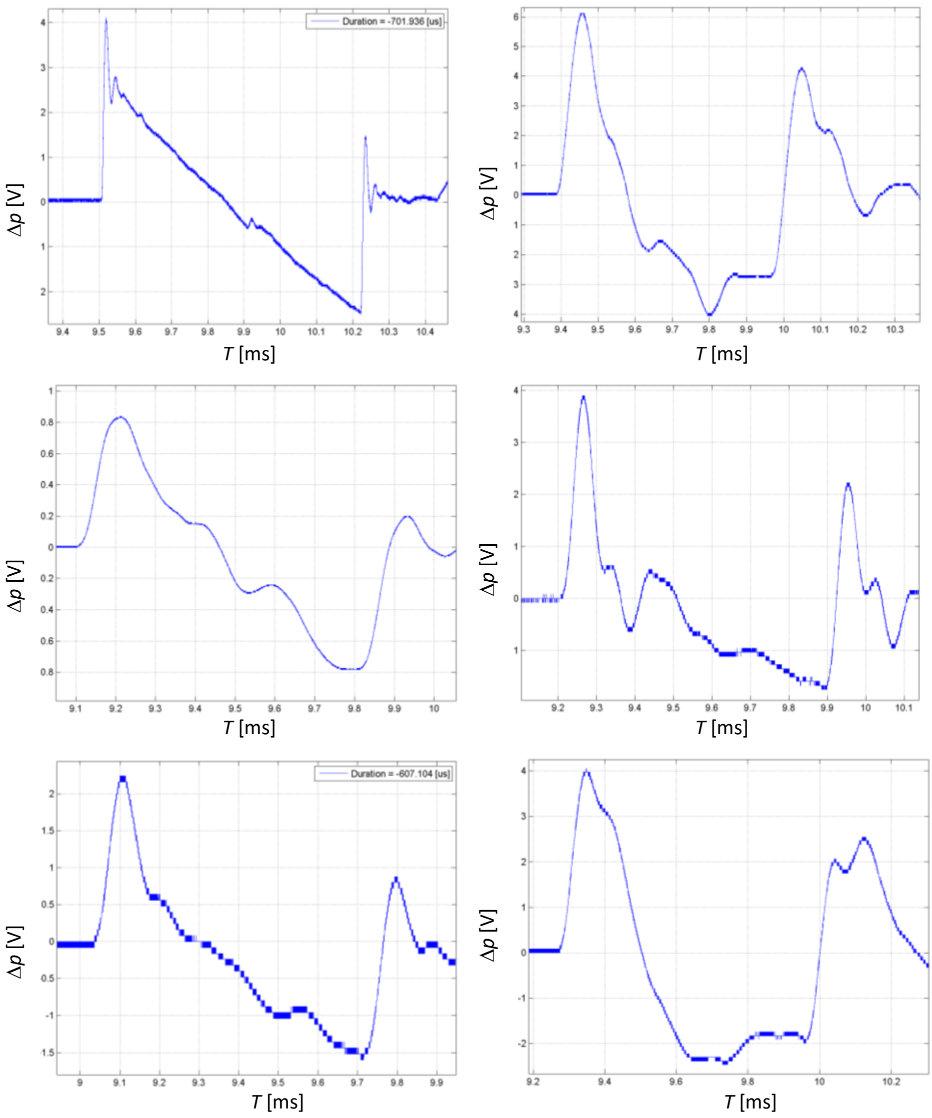

Fig. 7. Examples of N waveforms resulting from movement of a 35 mm TP-T projectile recorded with different sensors at a distance of 10 m from the flight trajectory [23]

Among the sensors subjected to testing, the best results were obtained from the one whose N wave recording is shown as the first upper left waveform in Fig. 7. Its dynamic range makes it possible process acoustic disturbance in the form of the N wave with an amplitude $\Delta p \leq$ equal to 165 dB. Its sensitivity (7 mV/Pa) allows the maximum detection range to be obtained of approx. 35 m for 35 mm calibre projectiles.

The analysis of the results obtained during continuous firing (burst firing) showed that interference caused by N wave disturbances and reflected waves is an important problem; therefore, the recorded signal must be subjected to additional processing.

The results of the 35 mm T-PT projectile velocity tracking by means of a Weibler SL-525PE Doppler radar[1] (Fig. 8) indicate that the average initial projectile velocity was 1168.6 m/s (~1170 m/s), and the standard deviation of the initial velocity was 3.67 m/s.

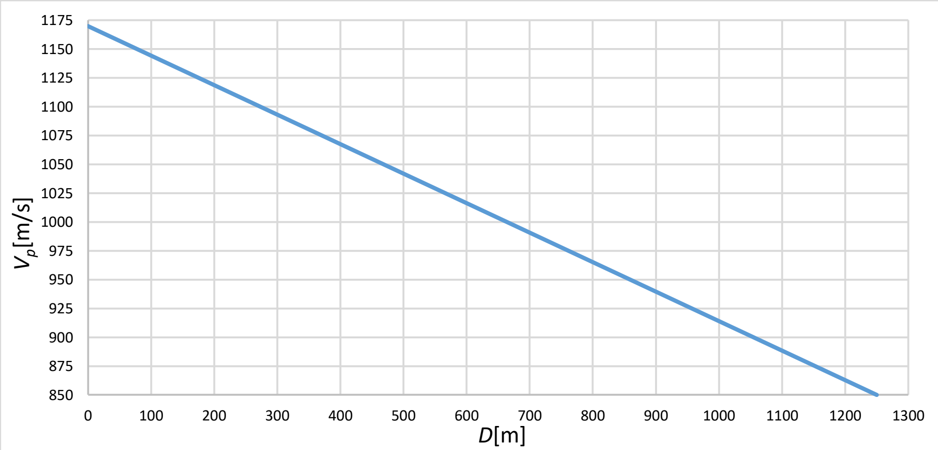

Fig. 8. Graph presenting radial velocity of the projectile as a function of the distance covered [24]

Based on the linear approximation of the projectile velocity change presented in Fig. 8 as a function of the distance covered, it is possible to determine the value of the directional coefficient m of inclination of characteristic $V_p(D)$ from the following relationship:

$$m = (V_p(D) - V_{p0})/D \quad (7)$$

From the extreme values read from the graph in Fig. 8, it appears that V_{p0} = 1170 m/s, and $V_p(D)$ = 850 m/s for D = 1250 m, the directional coefficient m is m = -0.256 [1/s]. The approximated instantaneous velocity value of the 35 mm TP-T projectile and the Mach speed and angle at the surface target for typical target firing distances from the range of D_c = (1000 - 3500) [m] then amounts to, respectively (see Table 2):

[1] Weibler SL-525PE radar parameters: operating frequency 10.4 - 10.55 GHz; beam width 9 x 9°; antenna output power 0.4 W; antenna gain 25 - 30 dB; max. noise level 2 dB; radial speed range of tracked projectiles 30 - 3000 m/s; tracking range of 35 mm calibre projectiles: 1200 m.

Table 2. Calculation results: V_p, M and α

D_c [m]	1000	1500	2500	3250	> 3250
V_p [m/s]	914	786	530	338	< c
M	2.76	2.37	1.60	~1	< 1
α [°]	22	26	40	~ 90	-

The velocity values for the 35 mm TP-T projectile presented in Table 2 show that, during firings at a surface target in marine conditions, there is a distance range (3250 - 3500 [m]) in which the projectile velocity decreases to subsonic values, i.e. in such a case, the form of recorded medium pressure disturbances is not characteristic for the N wave.

4. SYSTEM DESIGN ASSUMPTIONS ADOPTED

The system for assessing the results of firings from a 35 mm AM-35 gun consists of the following components: artillery projectile locator together with a control and measurement subsystem for pressure disturbance parameters caused by moving projectiles, and a management unit (located on board a ship). An artillery projectile locator was placed on a surface target which, during firings, is towed by a tow cutter, under the conditions of marine artillery firings. The functional diagram of the system is shown in Fig. 9.

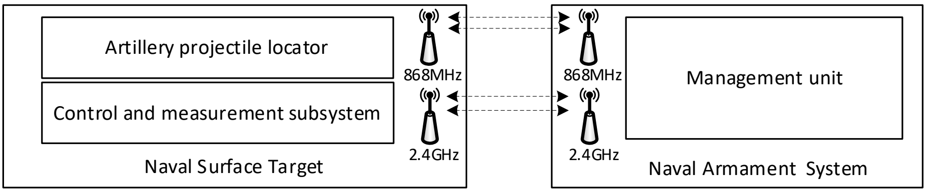

Fig. 9. Functional diagram of surface target firing result assessment system [25]

The main tasks of the developed system include:

– detection, within a zone with a radius of 20 m and at a firing distance of up to 3500 m of 35 mm TP-T projectiles flying at supersonic speeds and measurement of wave pressure parameters caused by their movement;
– processing of telemetry data and determining projectile coordinates in relation to the surface target;
– real-time visualization of surface target firing results;
– recording and archiving data from ship artillery firings;
– providing information necessary assess the quality of firings from a 35 mm AM-35 gun.

A hyperbolic location algorithm was assumed to solve the problem of determining the coordinates of projectile hitting the surface target. In order to determine the coordinates of projectile hitting the surface target and its local velocity, the following sensor set-up was adopted - see Fig. 10.

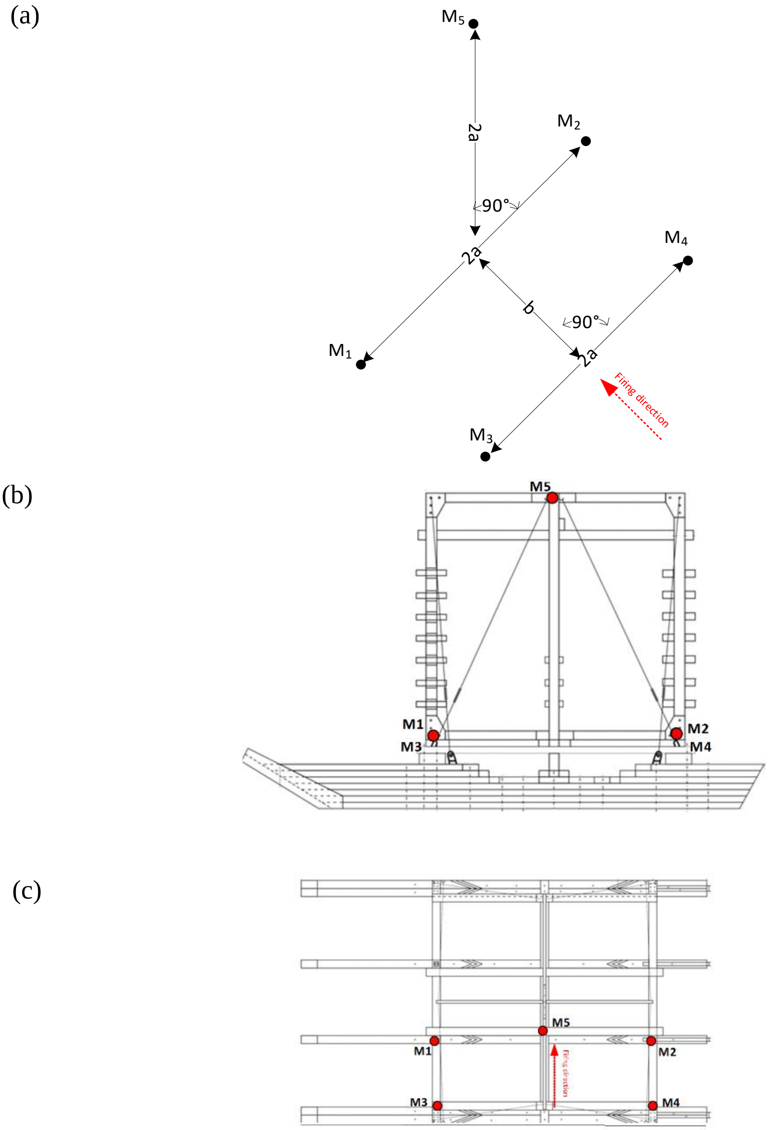

Fig. 10. Diagram of sensor locations on the surface target:
a) sensor set-up (M1-M5) on the target: a = 2 m, b = 1.4 m; b) target side view; c) target top view

To calculate the coordinates of projectile hitting the target, it is required that at least three sensors in the system are correctly activated. However, such a result may be encumbered with a certain error which, in marine conditions, depends on many factors [6]. In the case of the assumed set-up of five sensors, when one shot is fired and the disturbance wave face reaches all sensors located on the target, the system can determine ten different results, which are then subjected to automatic correction in order to refine them and indicate the most probable firing result.

Apart from enhancing accuracy, such a redundant approach to solving the problem of projectile coordinate acoustic location additionally increases the reliability of the measurement system in case any of the sensors is damaged, e.g., as a result of firing.

5. PRACTICAL IMPLEMENTATION AND SYSTEM OPERATION

Initial installation and integration of developed elements of the projectile acoustic location systems was performed at the naval port in Gdynia (Poland). The installation works consisted in placing the adopted set-up of measuring sensors with their cabling and antenna system (Fig. 11a-c) on the surface target. The last operation consisted in connecting the projectile locator systems to the power supply systems located in the box (Fig. 11d).

For evaluation and imaging of firing results, the coordinate determination system shown in Fig. 12a was assumed in the management unit software. The smallest graduation of the result imaging screen grid is a square with a side of 2 × 2 [m], the starting point of the coordinate system is the centre of the surface target with coordinates (x, y) = (0.0). The x coordinates on right from the point (0.0) are recorded with a positive sign and the ones on the left with a negative sign, while the y coordinates above the point (0.0) were recorded with a positive sign and the ones below with a negative sign.

Correct operation of the sound system of the acoustic projectile location system was checked during combat firings in marine conditions. For example, 12 shots were fired in series at the surface target from a distance of 2600 m towards the target, and the system detected 8 projectiles. The results of this series of firings are presented in Table 3 and shown in Fig. 12b.

(b) (c) (d)

(a)

Fig. 11. Surface target with projectile acoustic location systems:
a) side view; b) M5 sensor; c) antenna system; d) box containing electronic equipment and power supply system

Table 3. Results of firing a 35 mm TP-T projectile at a distance of 2600 m

Projectile no.	Coordinates [m]		Projectile no.	Coordinates [m]	
	x	y		x	y
1	0.41	-1.32	5	-0.24	4.82
2	2.05	-0.03	6	1.77	2.69
3	0.85	3.03	7	1.34	-1.78
4	1.91	-0.67	8	2.04	0.87

(a) (b)

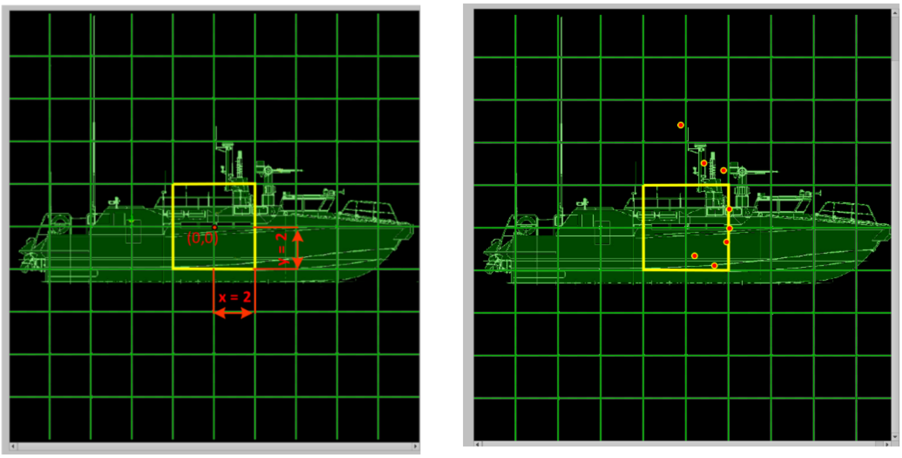

Fig. 12. Imaging the surface target with a virtual outline of the ship:
a) adopted system for determining projectile firing trace coordinates (surface target field marked yellow); b) imaging of the distribution of recorded firing results

6. CONCLUSIONS

The solution described in the paper, dedicated to assessing the firings of a 35 mm AM-35 naval gun, is an initial version of the projectile acoustic location system. Its use during Naval Armament System qualification tests gave satisfactory results, and, most of all, the collected results made it possible to assess the correctness of operation of the AM-35 gun and the quality its system integration with the ship systems. The use of the developed acoustic projectile location system during Armament System qualification tests made it possible, based on the collected results:

- to check and evaluate the firing capability of TP-T ammunition;
- verification and evaluation of the ability to engage surface targets;
- verification and evaluation of the AM-35 gun in terms of accuracy, spread and rate of fire;
- verification of the ranges and angular accuracy of the AM-35 gun's electric drives and interception and automatic target tracking systems.

In addition, based on the collected results, it was possible to indirectly infer the correctness of the AM-35 gun and the degree of integration of its systems with the ship, primarily in terms of the quality of operation:

- AM-35 gun's electric drives;
- mechanical and electronic angle limiters of the AM-35 gun;
- the ship's fire control system;
- systems for interception and automatic tracking of moving surface objects.

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Wykorzystanie systemu akustycznej lokacji pocisków podczas badań 35 mm armaty morskiej AM-35 Okrętowego Systemu Uzbrojenia

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Streszczenie. Artykuł jest kontynuacją rozpoczętego w 2018 r. na XII Międzynarodowej Konferencji Uzbrojeniowej cyklu prezentacji rezultatów zadania badawczego, którego celem było opracowanie metody i systemu oceny strzelań do celów nawodnych podczas realizacji projektu B+R nr O ROB 0046 03 01. W artykule przedstawiono wyniki przeprowadzonych badań symulacyjnych i doświadczalnych charakterystyk zaburzeń ciśnieniowych pochodzących od ruchu 35 mm pocisku TP-T, na podstawie których dobrano parametry czujników i ich konfigurację na tarczy celu nawodnego. Zaprezentowano opis przyjętych rozwiązań konstrukcyjnych systemu oceny strzelań. Na koniec przedstawiono wybrane wyniki działania systemu akustycznej lokacji pocisków wykorzystanego do oceny strzelań bojowych 35 mm armaty morskiej AM-35 podczas badań kwalifikacyjnych Okrętowego Systemu Uzbrojenia.
Słowa kluczowe: system oceny strzelań, lokacja akustyczna pocisków, armata AM-35, Okrętowy System Uzbrojenia