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Theoretical and Experimental Testing of the Factors of Mortar Projectiles Trajectory for a New Fire Control System

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Abstract. The paper presents the results of theoretical and experimental tests aimed at developing sets of data. These sets are necessary for compiling firing tables and the operating algorithm for the ballistic computer of a fire control system intended for the mortar system currently used by the Polish Armed Forces as well as the mortar system currently under development. Economy, time saving and the development of numerical methods justify the use of computer simulations for the process of developing software for fire control systems. The theoretical results can only be used for this purpose if their level of compliance with experimental results of live fire tests is acceptable.
Keywords: mechanics, external ballistics, theory of firing, artillery weapons

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1. INTRODUCTION

In recent years there has been a rapid development of fire control systems for artillery and mortar units. This phenomenon can also be observed in Poland, where intensive development work is underway to provide cal. 98 mm and 120 mm mortar units with modern fire control systems. This objective requires development and adaptation of suitable physical and mathematical models, which are the basis of the algorithms essential for proper programming of ballistic computers in the fire control systems for these mortar types. Due to the high costs of experimental research (live firing range tests) and the high onerousness and complexity of their performance (i.e. restricted access to artillery firing ranges, adverse weather conditions, and other), computer-aided simulation tests are the basic type of research in the development process of fire control system algorithms.

Available domestic and foreign reference literature lacks the data necessary for the development of suitable ballistic computer algorithms applied in the fire control systems of mortars and other artillery weapons. This is most likely due to their military applications. It was necessary to conduct own simulation tests, verified by live firing at an artillery range.

The experimental results (obtained by live firing range testing according to an original methodology) were used to validate the algorithms being developed. The validated algorithms were applied to determine the basic indicators (trajectory factors) of projectiles, inclusive of the ballistic and meteorological variables of firing conditions: initial projectile velocity V_0, elevation angle Θ_0 at the moment of the shot, propellant charge temperature $t_{\text{ład}}$, projectile mass m, mortar barrel wear, and variable weather conditions. The research results were also used in the compilation of the firing tables for specific mortar shells.

2. PROCEDURE ADOPTED FOR MODELLING PROJECTILE MOTION IN A DISTURBED ATMOSPHERE

The term modelling is interpreted in this paper as a process of building a physical model (physical modelling) and formulating a mathematical model (mathematical modelling) which represents the investigated physical phenomenon which is the motion of the examined mortar shell.

The projectile physical model is a system comprising certain physical concepts, selected with the following criteria: the known structure of the modelled shell, the properties of individual elements of this object, understanding of the essential laws of physics, and understanding of the influences of the external environment [1, 3].

The aerodynamic model of the shell and the essential geometric characteristics of its physical model are shown in Fig. 1. Figs. 2 to 4 illustrate selected aerodynamic characteristics of three mortar projectile types, namely: a high-explosive fragmentation mortar shell (HE), an illumination mortar shell (ILL) and a smoke mortar shell (SM).

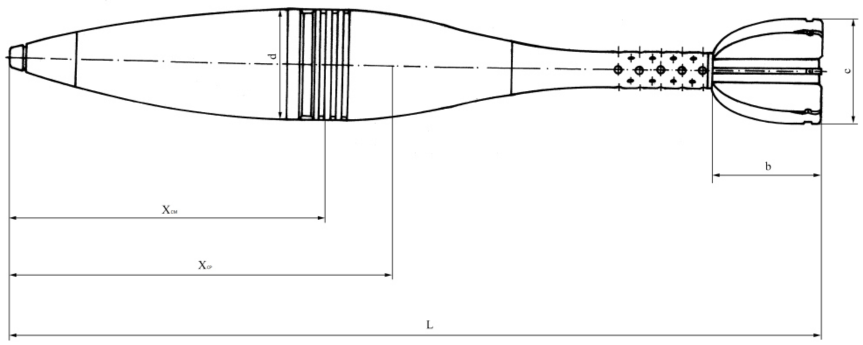

Fig. 1. Aerodynamic model and essential geometric characteristics of the examined mortar shell

The developed physical model served as a basis for the adaptation of the mathematical model, published in [1, 2, 3], etc. The mathematical model is a set of equations which describe the dynamic properties of the physical model to enable simulation of those properties (i.e. the projectile trajectory factors) along the projectile–trajectory. The projectile space of motion, the projectile linear coordinates x_g, y_g, z_g and angular coordinates Ψ, Θ, Φ, the linear velocity components u_k, v_k, w_k, the angular velocity components p, q, r, and the components of the force and moment acting on the projectile are shown in Figs. 5 and 6, respectively. The mathematical model comprises:

a) dynamic equations of the projectile mass centre movement (i.e. longitudinal motion, transverse motion and lift motion);
b) dynamic equations of the projectile motion around its mass centre (i.e. roll, pitch and yaw);
c) kinematic equations of the projectile movement;
d) kinematic equations of the projectile motion relative to its mass centre.

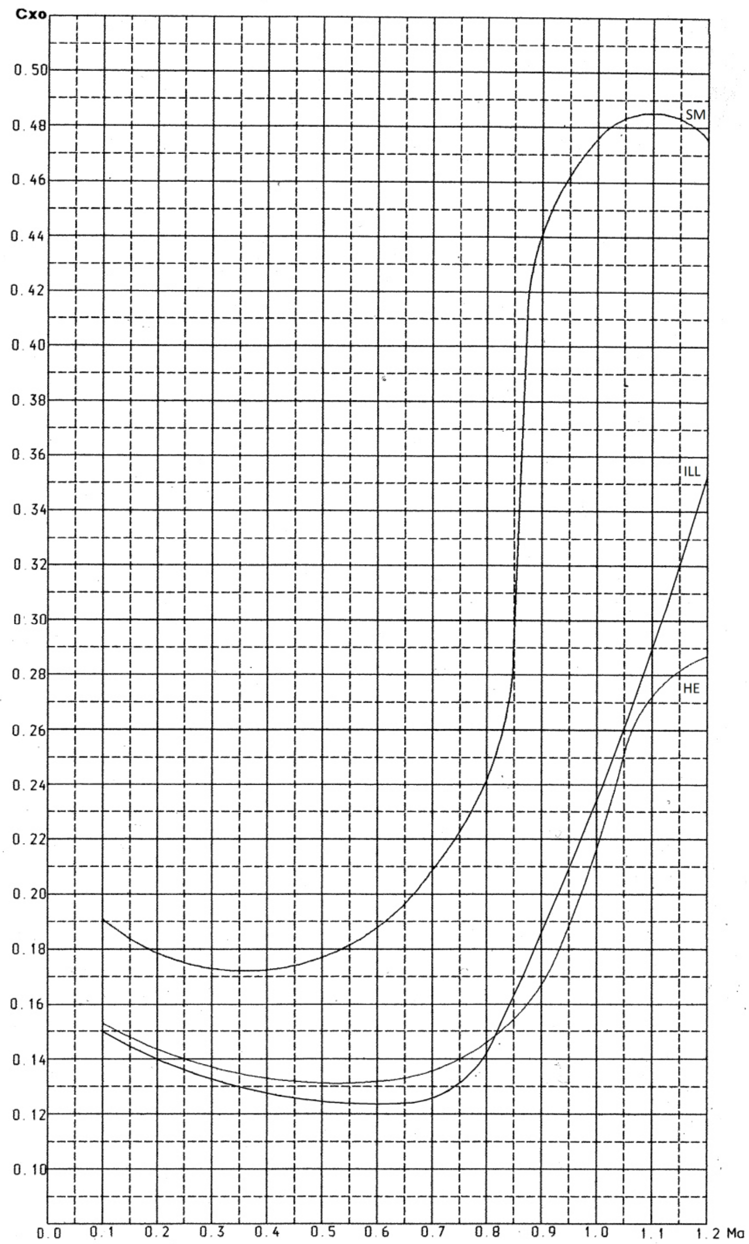

Fig. 2. Drag coefficient C_{xo} when angle of attack α is zero, referenced to the cross sectional area vs. Mach number

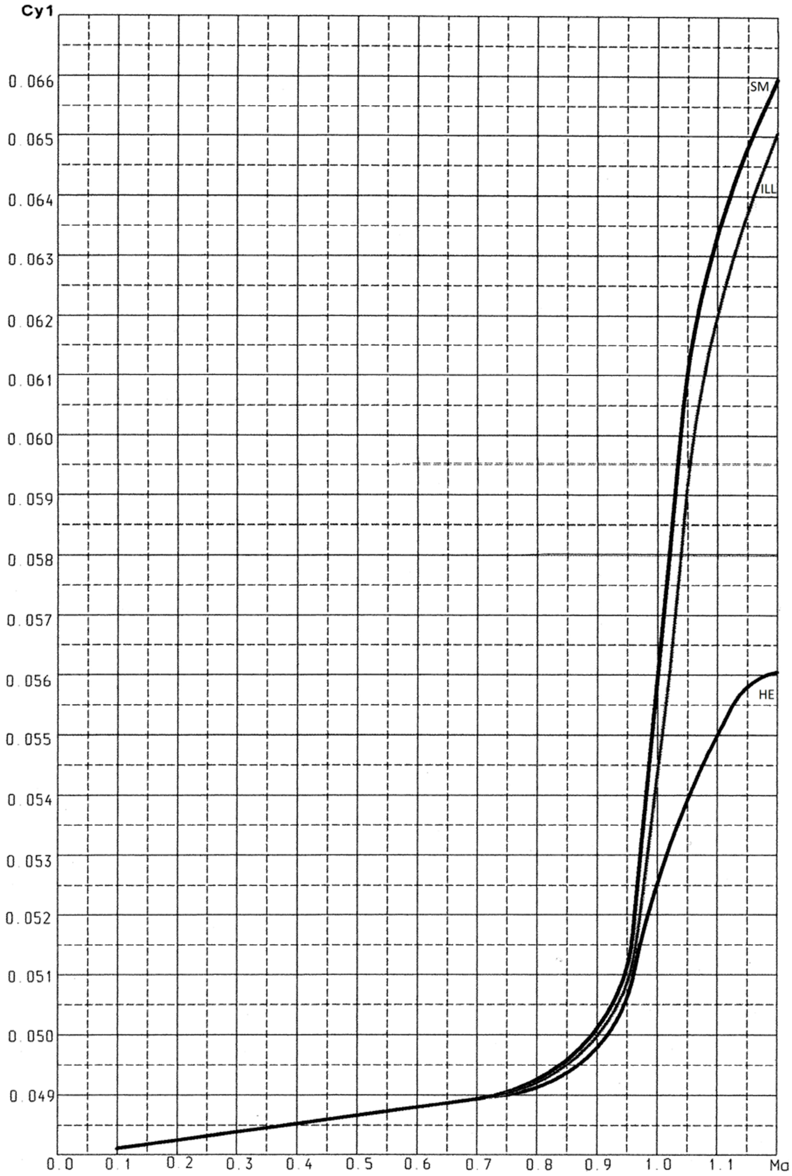

Fig. 3. Projectile lift coefficient in a coordinate system related to the projectile and referenced to the cross sectional area vs. Mach number

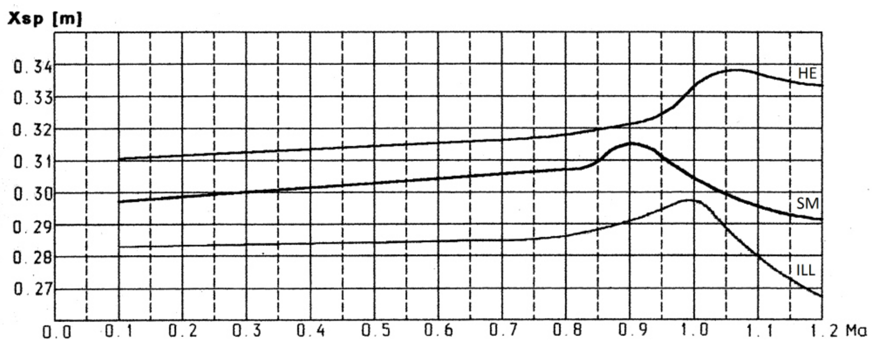

Fig. 4. Centre of the aerodynamic pressure relative to the projectile tip vs. Mach number

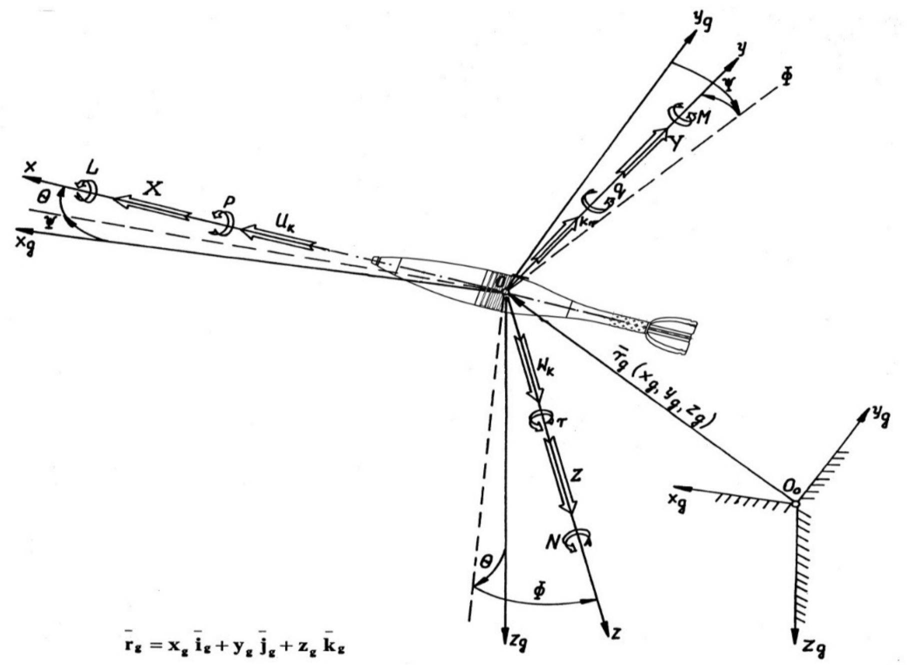

Fig. 5. Assumed linear coordinates x_g, y_g, z_g; angular coordinates Ψ, Θ, Φ; coordinate rates of change u, v, w, p, q, r; components of the forces and moments of the external forces acting on the projectile in the coordinate system related to the projectile $0xyz$ [4, 5]

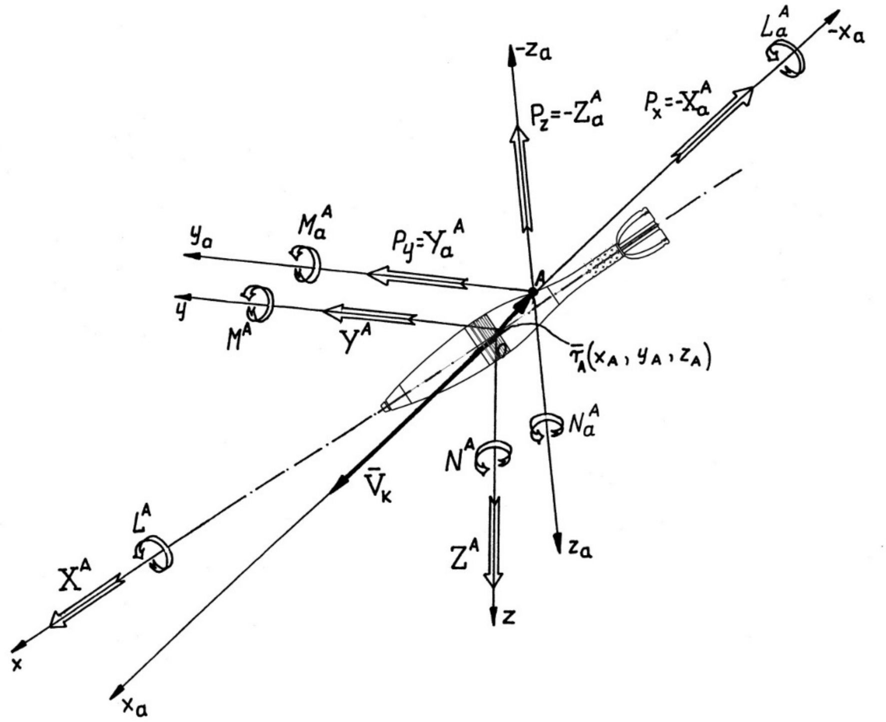

Fig. 6. Forces and moments of the aerodynamic forces acting on the projectile in flight, ref. PN-83 [4, 5]

As a part of this work, the projectile trajectory factors in variable firing conditions were simulated with the mathematical model of the projectile [3] converted (adapted) to model of the motion within the trajectory plane (i.e. the motion on a horizontal earth plane $O_0x_gz_g$ intersecting the firing point and the point of impact). The authors hereof intend to present in a future paper the results of the projectile trajectory factors simulated with the spatial motion of the projectile.

3. RESULTS FOR THE PROJECTILE FLIGHT PARAMETERS SIMULATED WITH VARIABLE FIRING CONDITIONS

Figs. 7 and 8 show the examples of the results obtained from a computer simulation of projectile flight in the Earth's atmosphere with variable meteorological conditions of firing (air temperature t and longitudinal wind speed W_x), respectively for the initial projectile velocity $V_0 = 320$ [m/s] and the angle of elevation at the moment of shot $\Theta_0 = 85$ [°], and the trajectory turn at the moment of shot $\Psi_0 = 0$[°].

Tables 1 and 2 show the example results of live firing range tests (with each mean value determined from seven shots). The results were obtained with the DR-5000 Modified Point Trajectory Doppler radar unit from TERMA Elektronik A.S. (Denmark).

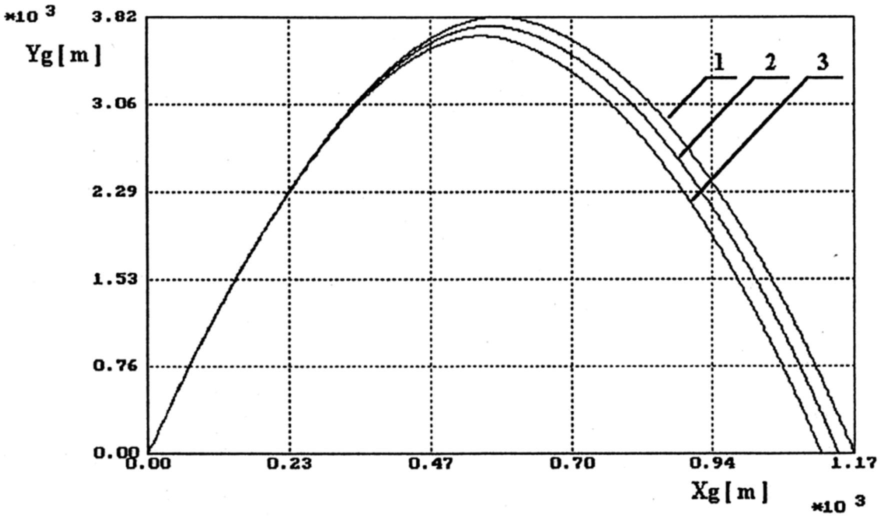

Fig. 7. Graph of the $Y_g = f(X_g)$ for angle of elevation $\Theta_0 = 85$ [°], velocity $V_0 = 320$ [m/s] and temperatures: 1 – $t = t_{nom}+15$ [°C]; 2 – $t = t_{nom} = 0$ [°C]; 3 – $t = t_{nom} - 15$ [°C]

Table 1. List of values of the essential projectile trajectory factors from live firing range testing of a cal. 98 mm mortar

Curve no. in chart	**Angle of elevation Θ_0 [°]**	**Initial projectile velocity V_0 [m/s]**	**Range X_g [m]**	**Maximum ordinate Y_g [m]**	**Air temperature deviation from the standard value t [°C]**
1	85	320	1172	3821	15
2	85	320	1147	3742	0
3	85	320	1118	3655	-15

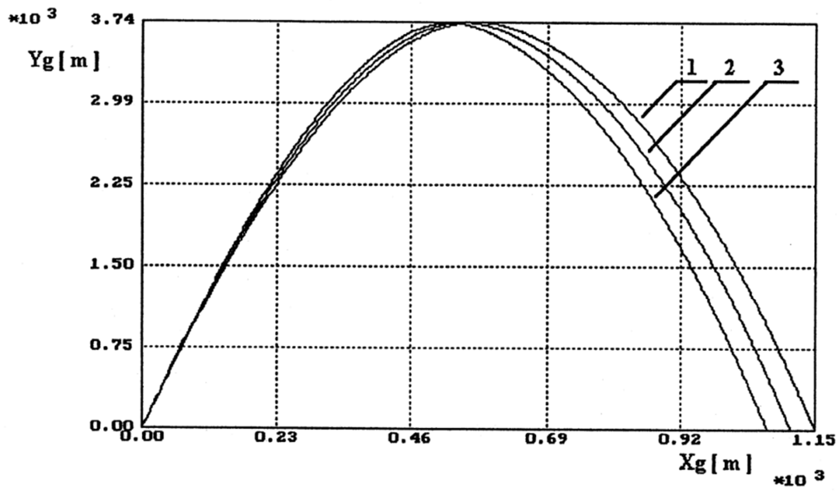

Fig. 8. Relationship $Y_g = f(X_g)$ for angle of elevation $\Theta_0 = 85$ [°] at the moment of firing, the initial projectile velocity $V_0 = 320$ [m/s] and the head wind: 1 – $W_x = 0$ [m/s]; 2 – $W_x = -5$ [m/s]; 3 – $W_x = -10$ [m/s]

Table 2. Values of the essential projectile trajectory factors from live firing range testing of a cal. 120 mm mortar

Curve no. in chart	**Angle of elevation Θ_0 [°]**	**Initial projectile velocity V_0 [m/s]**	**Range X_g [m]**	**Maximum ordinate Y_g [m]**	**Head wind velocity W_x [m/s]**
1	85	320	1147	3742	0
2	85	320	1106	3739	-5
3	85	320	1065	3735	-10

The results of the live firing range tests shown in Table 2 were selected from a set of several dozen shots at an angle of elevation $\Theta_0 = 85$ [°]. These shots were taken in various meteorological conditions (including various longitudinal wind velocities).

A comparative analysis was carried out on the results of the projectile trajectory factors, tested by simulation and live firing (according to a proprietary methodology). The comparative analysis proved compliance between the simulated and live-testing results at $\delta < 4.5\%$, which is an accuracy level satisfactory in artillery practice.

4. SUMMARY AND FINAL CONCLUSIONS

Development of firing tables exclusively on the basis of the results of live firing range testing is very time-consuming and requires considerable financial outlays. Due to the high onerousness inherent to this type of research (e.g. restricted accessibility of artillery ranges, the necessity of testing at various times of day and year, adverse weather conditions, etc.), computer-aided simulation has been established as the basic type of research in the development process of firing control system algorithms and firing tables. The results obtained by computer simulations must always be verified with properly designed and performed live firing tests with the number of shots sufficient for a statistical analysis of results. This approach was applied by the authors hereof. The results of live firing range tests were produced with the use of state-of-the-art instrumentation (typical of NATO countries) to measure the ballistic parameters of projectiles along their trajectories. The instrumentation has allowed to accurately capture the changes in the projectile trajectory factors under variable firing conditions. The results produced with the proprietary methodology of the authors were used to validate the developed computer algorithms; the algorithms were then used to determine the primary indicators (i.e. projectile trajectory factors) with standard (calculated or tabulated) and variable firing conditions, which included the following: propelling charge temperature, projectile weight, mortar barrel wear (from the change in the initial projectile velocity) and the changing values of atmospheric parameters.

The achieved compliance (δ < 4.5%) of the results of the projectile trajectory factors obtained from theoretical testing and live firing range tests, and carried out according to the proprietary methodology of ballistic firing, features a level of accuracy sufficient for practical artillery applications.

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Badania teoretyczno-eksperymentalne czynników toru pocisków moździerzowych na użytek nowo opracowywanego systemu kierowania ogniem

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Streszczenie. W pracy przedstawiono wyniki badań teoretycznych i doświadczalnych ukierunkowanych na opracowanie zbiorów danych niezbędnych do zestawienia tabel strzelniczych oraz opracowania algorytmu funkcjonowania przelicznika balistycznego systemu kierowania ogniem przeznaczonego zarówno dla aktualnie występującego na uzbrojeniu Wojska Polskiego, jak i nowo opracowywanego zestawu moździerzowego. Względy ekonomiczne, oszczędność czasu oraz rozwój metod numerycznych uzasadniają wykorzystanie symulacji komputerowych w procesie tworzenia oprogramowania systemów kierowania ogniem. Warunkiem koniecznym, umożliwiającym zastosowanie w tym celu wyników badań teoretycznych, jest uzyskanie akceptowalnego poziomu ich zgodności z wynikami strzelań poligonowych.

Słowa kluczowe: mechanika, balistyka zewnętrzna, teoria strzelania, broń artyleryjska