УПРАВЛІННЯ У ТЕХНІЧНИХ СИСТЕМАХ

CONTROL IN TECHNICAL SYSTEMS

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AN IMPROVED MATHEMATICAL MODEL OF THE METHOD OF FULLY PREPARING THE DETERMINATION OF FIRING UNITS FOR HITTING THE INFORMATION AND CALCULATION COMPONENT OF THE AUTOMATED FIRE CONTROL SYSTEM OF COMBAT VEHICLES OF REACTIVE ARTILLERY

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ABSTRACT

Context. As part of the automation of the fire control system of rocket artillery combat vehicles, in relation to the preparation of data for firing and fire control, the information and computing process of this system has been improved, namely, the mathematical model of the method of fully preparing the determination of installations for firing projectiles used in rocket salvo fire systems has been improved. In the system of differential equations of the mathematical model of the information and computing process of the component of the automated fire control system of combat vehicles of jet artillery, weighting functions for air temperature, wind influence for the active and passive sections of the projectile flight trajectory and the section of the opening of combat elements have been introduced, which allows determining the weighting coefficients for them for each projectile type.

Objective. To improve the information and calculation component of the automated fire control system of combat vehicles of reactive artillery, by improving the mathematical model of the method of full preparation of the determination of installations for firing on damage. Having proposed a system of differential equations that will take into account the weighting functions of air temperature, wind influence for active and passive sections of the projectile flight path and the section of the opening of combat elements, and will also give the opportunity to determine weighting coefficients for each type of projectile based on them, which in turn will lead to an increase the accuracy of determining firing settings.

Method. The proposed analytical method allows: to calculate the weighting coefficients for each type of rocket, characterizing the process of the approach of the rocket flight to the tabular trajectory and to set the initial conditions necessary for solving the differential equations of the mathematical model of the information-computing process of the component of the automated fire control system of combat vehicles of rocket artillery; to increase the accuracy of determining firing positions when performing firing tasks, which makes it possible to quickly respond to a change in the combat situation by means of changes in the software-mathematical process of the automated fire control system; effectively and efficiently ensure the development or clarification of textual and graphic administrative and combat documents based on the results obtained using differential equations of the mathematical model of the information-computational process of the component of the automated fire control system.

Results. The improved information and calculation component of the automated fire control system of combat vehicles of jet artillery was tested during the conduct of hostilities. The system of differential equations of the mathematical model of the information-computing process of the component of the automated fire control system of combat vehicles of reactive artillery ensures a timely response to a change in the situation in the information-computational process of the component of the automated fire control system of combat vehicles of reactive artillery during firing and fire control. Provides an opportunity to efficiently and

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quickly ensure the development or clarification of textual and graphic administrative and combat documents based on the information received during the execution of fire missions.

Conclusions. The calculations based on the proposed system of differential equations confirm the improvement of the information-calculation component of the automated fire control system of jet artillery combat vehicles and allow timely response to changes in tasks in the information-calculation process during firing and fire control, as well as effectively and quickly ensure the formation of formalized messages and documents based on the information received during the execution of a fire mission by units of reactive artillery. Prospects for further research are the creation of agreed mathematical methods, models, algorithms and programs for the implementation of the goals and tasks of firing and fire control when compiling Firing Tables for prospective or received combat vehicles of reactive artillery from partners.

KEYWORDS: automated control system, information and calculation component, mathematical model, system of differential equations, approximation of the functions of the real distribution law, weight functions for air temperature, wind influence.

ABBREVIATIONS

AFCSRSFS is an automated fire control system of reactive salvo fire systems;

AMS is an automated management system;

ICC is an information and calculation component;

M is a mathematical model;

TAS is a trajectory active section;

TPS is a trajectory passive section;

WFTS is a warhead flight trajectory section;

FP is a full preparation.

NOMENCLATURE

a_p is a rocket projectile jet acceleration;

a_r is an azimuth of the rocket projectile launch;

a_x is an acceleration of the air drag force of a rocket projectile by TAS;

B is a width of the starting position;

$C_x\left(\frac{V_{r\tau}}{a}\right)$ is an aerodynamic coefficient of the respective projectile;

$C_{X_{ET}}\left(\frac{V_{r\tau}}{a}\right)$ is an aerodynamic coefficient of the reference projectile;

d is a charge caliber;

$E_{X_{ft}^{1}}$ is a total errors of full preparation by range for the existing method without taking into account the geophysical conditions of firing, combined influence of air temperature, ground atmospheric pressure, wind influence, with entered wind coefficients of direct and cross wind for 9M21HE rockets separately for the indicated sections of the trajectory;

$E_{X_{ft}^{2}}$ is a total errors of full preparation by range for the existing method without taking into account the geophysical conditions of firing, combined influence of air temperature, ground atmospheric pressure, wind influence, with entered wind coefficients of direct and cross wind for 9M27HE rockets separately for the indicated sections of the trajectory;

$E_{X_{ft}^{3}}$ is a total errors of full preparation by range for the existing method without taking into account the geophysical conditions of firing, combined influence of air temperature, ground atmospheric pressure, wind influence, with entered wind coefficients of direct and cross wind for 9M55C rockets separately for the indicated sections of the trajectory;

$E'_{X_{ft}^{1}}$ is a total errors of full preparation by range for the existing method, taking into account the geophysical conditions of firing, the combined effect of air temperature and ground atmospheric pressure, the effect of wind, with the entered wind coefficients of direct and cross wind effect on 9M21HE rockets separately for the indicated sections of the trajectory;

$E'_{X_{ft}^{2}}$ is a total errors of full preparation by range for the existing method, taking into account the geophysical conditions of firing, the combined effect of air temperature and ground atmospheric pressure, the effect of wind, with the entered wind coefficients of direct and cross wind effect on 9M27HE rockets separately for the indicated sections of the trajectory;

$E'_{X_{ft}^{3}}$ is a total errors of full preparation by range for the existing method, taking into account the geophysical conditions of firing, the combined effect of air temperature and ground atmospheric pressure, the effect of wind, with the entered wind coefficients of direct and cross wind effect on 9M55C rockets separately for the indicated sections of the trajectory;

$E_{Z_{ft}^{1}}$ is a total errors of full preparation by direction for the existing method without taking into account the geophysical conditions of firing, the combined influence of air temperature and ground atmospheric pressure, wind influence, with the entered wind coefficients of direct and cross wind influence on 9M21HE rockets separately for the indicated sections of the trajectory;

$E_{Z_{ft}^{2}}$ is a total errors of full preparation by direction for the existing method without taking into account the geophysical conditions of firing, the combined influence of air temperature and ground atmospheric pressure, wind influence, with the entered wind coefficients of direct and cross wind influence on 9M27HE rockets separately for the indicated sections of the trajectory;

$E_{Z_{ft}^{3}}$ is a total errors of full preparation by direction for the existing method without taking into account the geophysical conditions of firing, the combined influence of air temperature and ground atmospheric pressure, wind

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influence, with the entered wind coefficients of direct and cross wind influence on 9M55C rockets separately for the indicated sections of the trajectory;

$E'_{Z_{ft}^{1}}$ is a total errors of full preparation by direction for the existing method, taking into account the geophysical conditions of firing, the combined influence of air temperature and ground atmospheric pressure, wind influence, with the entered wind coefficients of direct and cross wind influence on 9M21HE rockets separately for the indicated sections of the trajectory;

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$E'_{Z_{ft}^{3}}$ is a total errors of full preparation by direction for the existing method, taking into account the geophysical conditions of firing, the combined influence of air temperature and ground atmospheric pressure, wind influence, with the entered wind coefficients of direct and cross wind influence on 9M55C rockets separately for the indicated sections of the trajectory;

$F\left(t, \bar{x}\right)$ is a right part of the system;

∂_e is an estimated turn on the target from the main direction of fire of the respective firing range, considering meteorological firing conditions;

∂_t is a turn to the target not considering meteorological conditions;

$F_{58}\left(V_\tau\right)$ is an air resistance law;

g_0 is an acceleration of gravity;

ΔH is a deviation of ground pressure from the table value at the height of the starting position;

ΔH_0 is a ground air pressure at the height of the firing position;

i_a is a rocket projectile shape coefficient by TAS;

i_n is a coefficient of the shape of the rocket projectile by the TPS;

I_{1N} is a table value of a single traction pulse;

i_{CU} is a coefficient of the rocket projectile shape by the WFTS;

K_1 is a coefficient that takes into account the effect of the temperature of the reactive charge on a single thrust pulse;

K_2 is a coefficient that takes into account the effect of the jet engine's operating time;

m_0 is a mass of the rocket projectile;

q_0 is a total weight of the projectile;

q_a is a rocket projectile weight by the TAS;

q_{CU} is a rocket projectile weight by TPS;

q_n is a rocket projectile weight by the TPS;

Δq is a deviation of the projectile weight from the table value;

R_E is an Earth's radius;

S is a sight of the appropriate firing range taken from the firing tables;

S_e is an estimated sight of the appropriate range of firing rocket projectiles considering meteorological firing conditions;

ΔS_{gc} is a correction factors of the sight for deviations of geophysical conditions from the table value;

ΔS_H is a sight correction coefficient for the deviation of the ground atmospheric pressure from the table value at the height of the firing position;

ΔS_{H_t} is a sight correction coefficient for the deviation of the ground atmospheric pressure from the table value at the height of the target;

ΔS_h is a sight correction factors for the target exceeding the starting position;

ΔS_{T_a} is a sight correction factors for ballistic deviation of air temperature from the table value;

$\Delta S_{T_{ah}}$ is a sight correction factors for the combined effect of deviations of air temperature and ground air pressure from the table value;

$\Delta S_{T_{pc}}$ is a sight correction sight correction coefficient for the temperature deviation of powder charges of the main engine;

$\Delta S_{T_{pc_a}}$ is a sight correction coefficient of the sight for the deviation of the temperature of the powder charges of the engine, which corrects the projectile on the trajectory, from the table value;

$\Delta S_{W_{ax}}$ is a correction coefficient of the sight according to the longitudinal component of the ballistic wind within the TAS;

$\Delta S_{W_{nx}}$ is a correction coefficient of the sight according to the longitudinal component of the ballistic wind within the TPS;

$\Delta S_{W_{ex}}$ is a correction coefficient of the sight according to the longitudinal component of the ballistic wind within the WFTS;

t' is a rocket projectile flight time;

t_a is an estimated time of opening of the projectile warhead of the respective firing range, considering the meteorological conditions of firing;

t_H is a jet engine start-up time;

Δt_H is a projectile warhead opening time correction factors for deviation of the ground atmospheric pressure from the table value at the height of the starting position;

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Δt_{gc} is a projectile warhead opening time correction factors for geophysical conditions deviation from the table value;

Δt_h is a projectile warhead opening time correction factors for for exceeding the target over the starting position;

Δt_{T_a} is a projectile warhead opening time correction factors for ballistic deviation of air temperature from the table value within the entire trajectory of the projectile;

$\Delta t_{T_{aH}}$ is a projectile warhead opening time correction factors for the combined effect in air temperature and ground air pressure deviations;

$\Delta t_{T_{pc}}$ is a projectile warhead opening time correction factors for deviation of the temperature of main engine powder charges;

$\Delta t_{W_{ax}}$ is a correction coefficient of the opening time of the main part of the projectile according to the longitudinal component of the ballistic wind within the limits TAS;

$\Delta t_{W_{nx}}$ is a correction coefficient of the opening time of the main part of the projectile according to the longitudinal component of the ballistic wind within the limits TPS;

$\Delta t_{W_{ex}}$ is a correction coefficient of the opening time of the main part of the projectile according to the longitudinal component of the ballistic wind within the limits WFTS;

ΔT is a ballistic air temperature deviation within the full trajectory;

ΔT_a is a ballistic air temperature deviation;

$\Delta T_a'$ is a ballistic deviation of air temperature from the table value within the entire trajectory of the projectile;

ΔT_{pc} is a deviation of the temperature of the main engine charges from the table value;

ΔT_{pc_a} is a deviation of the temperature of the engine charges, which corrects the projectile on the trajectory, from the table value;

T_{pc} is a charge temperature;

V is a rocket projectile flight speed;

$\dot{V}$ is a rocket projectile acceleration;

V_r is a relative speed of rotation of the rocket projectile;

$V_{r\tau}$ is a relative velocity of the projectile, considering the air temperature;

W_a is an average wind speed value by TAS;

W_{ax} is a longitudinal component of the ballistic wind by TAS;

W_{az} is a lateral component of the ballistic wind by TAS;

W_{CU} is an average wind speed by WFTS;

W_{CU_X} is a longitudinal component of the ballistic wind by WFTS;

W_{CU_z} is a lateral component of the ballistic wind by WFTS;

W_n is a wind speed average value by TPS;

W_{nx} is a longitudinal and lateral wind components by TPS;

W_x is a longitudinal component of the ballistic wind;

W_z is a lateral component of the ballistic wind;

W_{ex} is a longitudinal component of the ballistic wind by WFTS;

X_a is a rocket active section projectile flight trajectory length;

X_n is a rocket projectile passive section flight trajectory length;

X_{ce} is a rocket projectile warhead flight trajectory length;

$\dot{x}, \dot{y}, \dot{z}$ is a current value of the velocity changes of the projectile coordinates;

Y_a is a rocket projectile active section flight trajectory final point;

Y_n is a rocket projectile passive section flight trajectory final point;

Y_s is a height of the rocket projectile flight trajectory;

y is a geometrical height;

ΔZ_{gc} is a correction in the direction of deviation of geophysical conditions from the table value;

$\Delta Z_{W_{az}}$ is a correction factor in the direction of the lateral component of the ballistic wind within the limits TAS;

$\Delta Z_{W_{nz}}$ is a correction factor in the direction of the lateral component of the ballistic wind within the limits TPS;

$\Delta Z_{W_{ez}}$ is a correction factor in the direction of the lateral component of the ballistic wind within the limits WFTS;

αW_a is an average value of the wind directional angle by TAS;

αW_{CU} is an average value of the wind directional angle by WFTS;

αW_n is an average value of the directional wind angle by TPS;

$C_x\left(V_\tau\right)$ is an aerodynamic coefficient of force of frontal air resistance;

θ is a projectile throwing;

$\dot{\theta}$ is a rate of change of the throwing angle;

ψ is a speed of change of direction of the projectile;

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γ_{aw} is a wind coefficient of direct effect of wind on TAS;

γ_{aM} is a wind coefficients of the cross effect of the wind on TAS;

γ_{CU_W} is a wind coefficient of direct effect of wind on WFTS;

γ_{CU_M} is a wind coefficients of the cross effect of the wind on WFTS;

μ_y is a jet engine of a rocket projectile fuel consumption coefficient;

$\pi(y)$ is an atmospheric pressure with height distribution function;

σ_1 is an interval on the abscissa axis, on which is defined TAS;

σ_2 is an interval on the abscissa axis, on which is defined TPS;

σ_3 is an interval on the abscissa axis, on which is defined WFTS;

τ_{aN} is a table operating time of the rocket projectile jet engine;

$\Delta\tau$ is a deviation of the virtual air temperature by TAS, TPS, WFTS from table value;

τ_y is a distribution of virtual temperature with change of height;

τ_{ON} is a table value of the virtual air temperature on Earth;

Ψ is a rocket projectile angle of penetration;

Ω_E is an angular velocity of the Earth's rotation;

ω_0 is a rocket projectile weight.

INTRODUCTION

The analysis of the liberation struggle in Ukraine from the мuscovites points to the imperfection of the existing MM of the method of fully preparing the determination of firing units of the ICC of the automated fire control system of combat vehicles of reactive artillery. In real conditions, the calculation using the existing MM of the method of fully preparing the determination of firing units of the ICC of the automated control system will be accompanied by a large number of stages of calculation of weighting factors taking into account ballistic deviations of air temperature and ballistic wind, which will increase the time for the formation of formalized reports and documents on the basis of the received information and will lead to the non-fulfillment of the combat mission due to the irrelevance of the goal. And will also cause a decrease in the accuracy of the projectile falling from the target to 1.6–1.9% in the range and 0–05 – 0–13 divisions of the protractor in the direction [15].

The existing MM of the method of complete preparation of the determination of firing settings of the ICC of the automated control system shows that corrections for the deviation of meteorological, ballistic and geophysical conditions from tabular values are taken into account separately for each section of the projectile flight path, and when calculating corrections for range and direction approximately, correction coefficients are taken into account that characterize the deviation of the projectile in terms of range and direction from the tabular point of fall at all heights of the trajectories (Table 1).

Table 1 – Correction coefficients for calculating corrections in sight and direction

R_{km}	Correction factors for calculating deviations in							
	sight					direction		
	$\Delta S_{wax}, m$ $1 m/s$	$\Delta S_{wnx}, m$ $1 m/s$	$\Delta S_{wex}, m$ $1 m/s$	$\Delta S_H, m$ $1\ mm.\ m.\ c$	$\Delta S_{T_a}, m$ $10^0\ C$	$\Delta Z_{wax}, m$ $1 m/s$	$\Delta Z_{wnx}, m$ $1 m/s$	$\Delta Z_{wex}, m$ $1 m/s$
30	76	22	70	49	60	15	11	56
40	46	16	41	45	34	22	26	42
50	49	48	35	62	14	30	36	37
60	59	56	42	78	16	39	42	40
70	68	55	52	90	53	47	43	45

Analyzing the data presented in Table 1, it can be concluded that the effect of the longitudinal wind on the movement of the projectile in the active section of the trajectory (TAS), the passive section of the trajectory (TPS) and the section of the flight trajectory of combat elements (WFTS) is approximately the same, with the exception of distances from 30 up to 40 km, where the influence of the bucket on the PDT is 2–2.5 times less compared to its influence within the ADT and on the DTPBE, and the effect of the side wind within the ADT and PDT is identical at all firing ranges, except for the DTPBE in 2–3 times higher than the impact on ADT and PDT at distances of 30–40 km.

1 PROBLEM STATEMENT

The main shortcomings of the MM of the method for the complete preparation of determination of settings for firing the ICC of the automated control system during the calculation of the values of the settings for defeating individual and lightly armored targets are: the accuracy of determining the median deviations in range and direction; failure to take into account the weighting factors for accounting for ballistic deviations of air temperature and ballistic wind on the active and passive sections of the trajectory, as well as on the flight section of combat elements. And also the imperfection of: mathematical (numerical) methods of solving problems in the ICC of the automated control system regarding the approximation

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of the functions of the real law of distribution [2, 7, 12]; differential equations of the MM of the method of full preparation for determining the installations for shooting, the information-calculating component of the automated control system for determining the meteorological, ballistic, topographic and geophysical conditions of shooting [1, 6]. An important direction of the accuracy of the calculation of the correction values for the deviation of the meteorological conditions of shooting from the tabular values, using a MM of the method of full preparation of the determination of the settings for shooting information-calculation component of the automated system management, there is an approach based on the approximation of the functions of the real distribution law of the deviations of meteorological factors from tabular values, which can be described by the corresponding distribution ratios expressed by the algebra of intervals [18, 20].

The existing approaches to the approximation of the functions of the real law of the distribution of deviations of meteorological factors from tabular values in the system of differential equations of the MM of the information-computing process of the component of the automated fire control system of combat vehicles of reactive artillery have a number of significant shortcomings.

The main ones are: replacing real distribution laws with linear ones, which leads to significant errors in the calculation of meteorological corrections and is approximate; increased efficiency of calculating the values of corrections for the deviation of meteorological shooting conditions from tabular values, which significantly affects the calculation time, and, accordingly, the efficiency and speed of forming formalized messages and documents based on the received information; separate accounting of meteorological conditions on the sections of the trajectory, which significantly complicates and reduces the accuracy of calculations of weighting factors to take into account ballistic deviations of air temperature and ballistic wind [6, 9, 10].

The existing MM of the method for the complete preparation of the determination of firing positions of the ICC of the automated fire control system of jet artillery combat vehicles, namely, the system of differential equations does not take into account the weighting factors on the active, passive sections of the trajectory and the section of the flight of combat elements, which leads to errors during calculation of firing settings and, as a result, affects the deviation of the projectile from the target in terms of range and direction by up to 5–7%. And this significantly reduces the efficiency and speed of forming formalized messages and documents on the basis of the received information and, accordingly, defeating the target (Table 2).

Table 2 – Deviation of projectiles by range and direction at the values of the determined meteorological conditions

R_{km}	in sight, m					in direction, m		
	$W_{a_x} = 15\ m/s$	$W_{n_x} = 20\ m/s$	$W_{e_x} = 15\ m/s$	$\Delta H_0 = 20\ mm.m..c$	$T_a = 20^0\ C$	$W_{a_z} = 15\ m/s$	$W_{n_z} = 20\ m/s$	$W_{e_z} = 15\ m/s$
30	1140	440	1050	980	1200	225	220	840
40	690	320	615	900	680	330	520	630
50	735	960	525	1240	280	450	720	555
60	885	1120	630	1560	320	585	840	500
70	1020	1100	780	1800	1060	705	860	675

Let's consider one of the components of the information and calculation process of the AMS. The component is related to the determination of the settings for shooting, the calculation of the values of corrections for the deviation of meteorological conditions from the tabular conditions by evaluating the proposed method of their determination.

Calculation of settings for firing is carried out using mathematical dependencies, taking into account the tabular deviation values: ground atmospheric pressure at the height of the firing position (ΔH_0), ballistic air temperature deviation within the full trajectory (ΔT), ballistic air temperature deviation (ΔT_a), longitudinal and lateral components of the ballistic wind (W_x, W_z).

In the MM of the method of complete preparation of the determination of firing units for hitting the ICC of the automated fire control system of combat vehicles of jet artillery, during the calculation of the values of corrections for the deviation of meteorological conditions from the tabular ones, the flight path of the jet projectile is divided into three sections: trajectory active section; trajectory passive section; warhead flight trajectory section (Fig. 1).

Therefore, it is necessary to calculate the values of the calculated corrections, by range and direction, for the deviation of meteorological conditions from tabular values, taking into account geophysical conditions: the deviation of the temperature of charges on the trajectory, the combined effect of air temperature and ground atmospheric pressure, as well as the effect of wind to be determined by dependences (1, 2, 3), for each section of the trajectory [2, 12, 15].

2 REVIEW OF THE LITERATURE

At present, during the experiments of projectile flight research using a MM of the method of fully preparing the determination of firing units of the ICC of the automated fire control system of jet artillery combat vehicles, it is very relevant to study the consideration of corrections for the deviation of meteorological, ballistic and geophysical

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firing conditions from the tabular values separately for each section of the flight path of this projectile. In general, during calculations, with the help of a MM of the method of full preparation of the determination of firing units of the ICC of the automated fire control system of combat vehicles of jet artillery, the values of corrections for range and direction, taking into account the correction coefficients characterizing the deviation of the projectile in terms of range and direction from the table the drop points at all heights of the projectile flight path are approximate, which affects the accuracy of hitting targets and is 1.6–1.9% in range and 0–05 – 0–13 protractor divisions in direction [3, 11, 19].

$$\begin{aligned} S_e &= S + \Delta S_{W_{ax}} W_{ax} + \Delta S_{W_{nx}} W_{nx} + \Delta S_{W_{ex}} W_{ex} + \Delta S_H \Delta H + \Delta S_{H_\tau} \Delta H^2 + \Delta S_{T_a} + \\ &+ \Delta T_a + \Delta S_{T_{pc}} T_{pc} + \Delta S_{T_{pc_e}} \Delta T_{pc_e} + \Delta S_{gc} + \Delta S_{T_{ah}} + \Delta T_a^2 + \Delta S_h + \Delta S_{T_H} \Delta T' \Delta H \end{aligned}, \tag{1}$$

$$t_a = t + \Delta t_{W_{ax}} W_{ax} + \Delta t_{W_{nx}} W_{nx} + \Delta t_{W_{ex}} W_{ex} + \Delta t_H \Delta H + \Delta S_{T_a} \Delta T_a + \Delta t_{T_{pc}} T_{pc} + \Delta t_{gc} + \Delta t_h + \Delta t_{T_{aH}} \Delta T_a \Delta H \ , \tag{2}$$

$$\partial_e = \partial_t + \Delta Z_{W_{az}} W_{az} + \Delta Z_{W_{nz}} W_{nz} + \Delta Z_{W_{ez}} W_{ez} + \Delta Z_{gc} \tag{3}$$

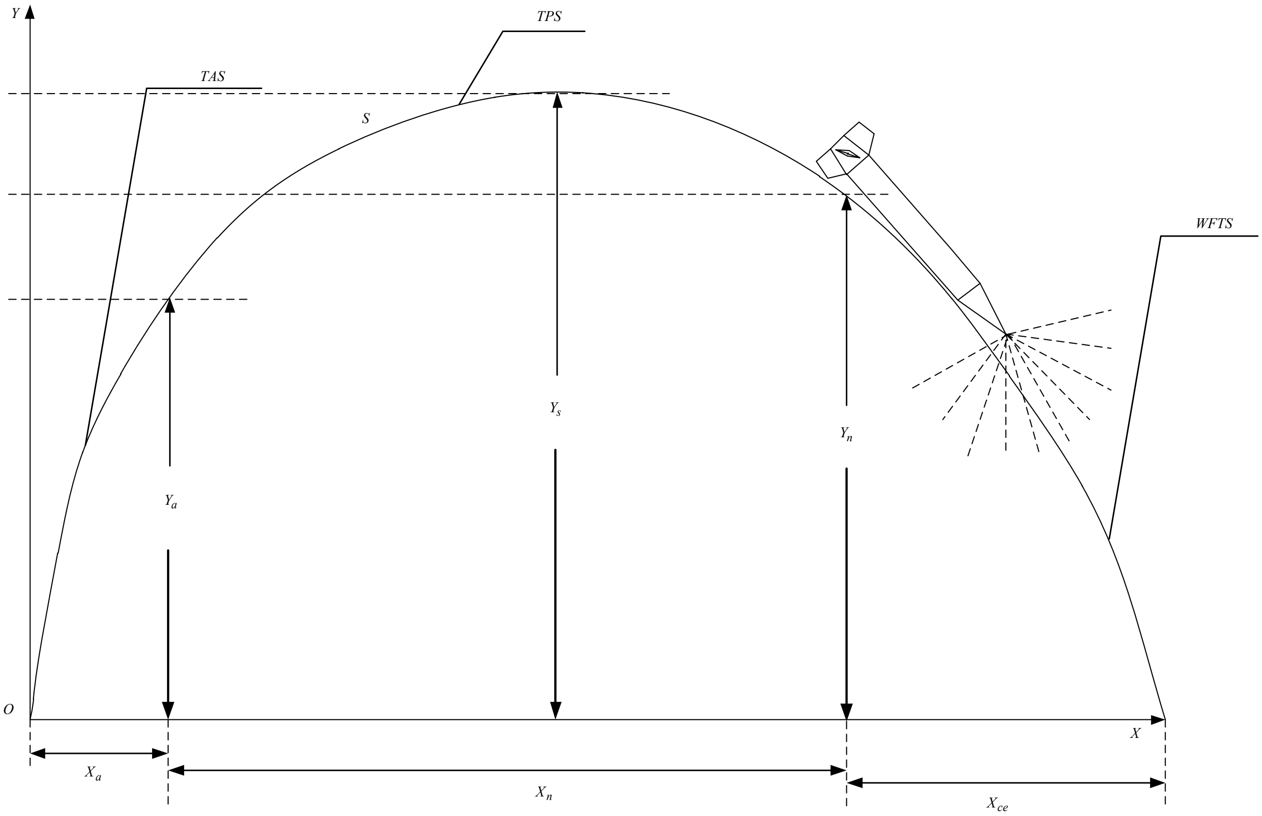

Figure 1 – Rocket projectile flight trajectory

In modern ballistics literature, there are no MM of the method of fully preparing the determination of firing settings of the ICC of the automated fire control system of combat vehicles of reactive artillery [1–3, 16–18] which would make it possible to calculate firing installations taking into account corrections for the deviation of meteorological firing conditions from tabular conditions separately for each section of the missile flight path.

The paper [8] describes a new multidisciplinary computational study conducted to simulate the flight trajectories and free-flight aerodynamics of both a finned projectile at supersonic speeds and a rotating projectile at subsonic speeds with and without aerodynamic flow control. The method of effective formation of a complete aerodynamic description for dynamic simulation of projectile flight is described in [16].

The textbook [13] contains basic information about the motion of an aerodynamic body, and gives the equations of motion of aircraft for the active and passive sections of the trajectory. In works [16, 17], a model of a mobile solid-fueled aircraft is proposed, taking into account the rotation and curvature of the Earth, the influence of wind and other aerodynamic parameters; the study of the impact of ramjet operation parameters on the

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range and accuracy of rockets was carried out in [14]. A realistic nonlinear model of flight dynamics was developed to perform simulations to confirm the accuracy of the presented algorithms [4, 5]. The analysis of projectile flight dynamics with full six degrees of freedom is considered in [1, 17]. The article [14] presents a new approach to controlling the external ballistic properties of spin-stabilized bullets by optimizing their internal mass distribution. Currently, MM for the study of external ballistics are cumbersome. This work aims to define and expand the theoretical procedure for determining the complex of indicators that accompany the movement of the projectile, as well as the MM of the method of fully preparing the determination of firing units for the ICC of the automated fire control system of combat vehicles of reactive artillery, which is presented in the work and can be used for calculating the values of corrections for the deviation of the meteorological conditions of firing from the tabular conditions in the firing units separately for each section of the missile flight path.

3 MATERIALS AND METHODS

To determine the correction factors for TAS, TPS and WFTS considering the geophysical conditions of firing, the combined effect of air temperature and ground pressure of the atmosphere, as well as the wind effect, we will use the known system of differential equations of the MM of the method of complete preparation of the determination of firing units of the ICC of the automated fire control system of combat vehicles of reactive artillery [5], but when calculating the relative velocity of the projectile and the acceleration of the air drag force, we will introduce wind coefficients of range and cross wind effects on projectiles separately for the specified sections of the trajectory (4).

$$\begin{cases} \dot{x} = V\cos\theta\cos\psi \Big/ \left(1-\dfrac{2y}{R_E}\right); \\ \dot{y} = V\sin\theta; \\ \dot{z} = V\cos\theta\sin\psi; \\ \dot{V} = a_p - a_x\cos\gamma - g_0\sin\theta\left(1-\dfrac{2y}{R_E}\right); \\ \dot{\theta} = \dfrac{\cos\theta g_0\left(1-2y/R_E\right)}{V} - \dfrac{a_x\cos\gamma W_x\sin\theta}{VV_r} + \dfrac{V\cos\theta}{R_E+y} - \\ -\Omega_E\cos B\sin\left(a_{r-\psi}\right); \\ \dot{\psi} = -\dfrac{a_x\cos\gamma W_z}{\cos\theta VV_r} + \Omega_E\left(\sin B_l - \cos B_l\cos\left(a_{r-\psi}\right)tg\theta\right); \\ \dot{\pi}(y) = -\dfrac{\pi(y)\dot{y}}{R\left[\tau_y+\Delta\tau\right]} \end{cases}, \quad (4)$$

where, $a_p = \dfrac{\omega_0\left(I_{1N}+K_1\Delta T_{pc}\right)}{m_0\left[\tau_{aN}-K_2\Delta T_{pc}\right]\left(1-\mu_y\right)}$,

$\Delta T_{pc} = T_{pc} - 15$, $m_0 = {q_0}\big/{g_0}$,

$$\mu_y = \frac{\omega_0\left(t'-t_H\right)}{g_0 m_0\left(\tau_{aN}+K_2\Delta T_{pc}\right)},$$

$$a_x = 0.474\frac{i_a d^2}{q_0}10^3\frac{\tau_{ON}}{\tau_y+\Delta\tau}\frac{\pi(y)F_{58}\left(V_{r\tau}\right)}{1-\mu_y},$$

$$i_a = {C_x\left(\frac{V_{r\tau}}{a}\right)}\Bigg/{C_{X_{ET}}\left(\frac{V_{r\tau}}{a}\right)}, \qquad V_{r\tau} = V_r\sqrt{\frac{\tau_{ON}}{\tau_y+\Delta\tau}}$$

$$V_r = V\sqrt{\begin{aligned}&1-\frac{2W_{ax}\left(\cos\theta\cos\psi+\gamma_{aw}W_{ax}\sin\psi-\gamma_{aM}W_{az}\sin\theta\cos\psi-\gamma_{aw}\gamma_{aM}W_{ax}W_{az}tg\theta\cos\psi\right)}{V}-\\&-\frac{2W_{ax}\left(\cos\theta\sin\psi-\gamma_{aw}W_{ax}\cos\psi-\gamma_{aM}W_{az}\sin\theta\sin\psi+\gamma_{aw}\gamma_{aM}W_{ax}W_{az}tg\theta\cos\psi\right)}{V}+\frac{W_a^2}{V^2}\end{aligned}}$$

at $\theta \to \theta_0 + \delta\theta, \psi = \psi_0 + \Delta\psi$, $W_a^2 = W_{ax}^2 + W_{az}^2$, $W_{ax} = W_a\cos\alpha W_a$, $W_{az} = W_a\sin\alpha W_a$;

$$V_r = V\sqrt{\begin{aligned}&1-\frac{2W_{ax}\left(\cos\theta\cos\psi+\gamma_{aw}W_{ax}\sin\psi-\gamma_{aM}W_{az}\sin\theta\cos\psi+\gamma_{aw}\gamma_{aM}W_{ax}W_{az}tg\theta\sin\psi\right)}{V}-\\&-\frac{2W_{ax}\left(\cos\theta\sin\psi+\gamma_{aw}W_{ax}\cos\psi-\gamma_{aM}W_{az}\sin\theta\sin\psi-\gamma_{aw}\gamma_{aM}W_{ax}W_{az}tg\theta\cos\psi\right)}{V}+\frac{W_a^2}{V^2}\end{aligned}}$$

if $\theta \to \theta_0 + \delta\theta, \psi = \psi_0 - \Delta\psi$;

$$V_r = V\sqrt{\begin{aligned}&1-\frac{2W_{ax}\left(\cos\theta\cos\psi-\gamma_{aw}W_{ax}\sin\psi+\gamma_{aM}W_{az}\sin\theta\cos\psi-\gamma_{aw}\gamma_{aM}W_{ax}W_{az}tg\theta\sin\psi\right)}{V}-\\&-\frac{2W_{ax}\left(\cos\theta\sin\psi+\gamma_{aw}W_{ax}\cos\psi+\gamma_{aM}W_{az}\sin\theta\sin\psi+\gamma_{aw}\gamma_{aM}W_{ax}W_{az}tg\theta\cos\psi\right)}{V}+\frac{W_a^2}{V^2}\end{aligned}}$$

if $\theta \to \theta_0 - \delta\theta,\ \psi = \psi_0 - \Delta\psi$;

$$V_r = V\sqrt{1-\frac{2\left(W_{nx}\cos\theta\cos\psi+W_{nx}\cos\theta\sin\psi\right)}{V}+\frac{W_n^2}{V^2}},\quad W_n^2 = W_{nx}^2 + W_{nz}^2,\quad W_{nx} = W_n\cos\alpha W_n,\ W_{nz} = W_n\sin\alpha W_n;$$

$$V_r = V\sqrt{\begin{aligned}&1-\frac{2W_{CU_x}\left(\cos\theta\cos\psi+\gamma_{CU_w}W_{CU_x}\sin\psi-\gamma_{CU_M}W_{CU_z}\sin\theta\cos\psi-\gamma_{CU_w}\gamma_{CU_M}W_{CU_x}W_{CU_z}tg\theta\sin\psi\right)}{V}-\\&-\frac{2W_{CU_x}\left(\cos\theta\sin\psi-\gamma_{CU_w}W_{CU_x}\cos\psi-\gamma_{CU_M}W_{CU_z}\sin\theta\sin\psi+\gamma_{CU_w}\gamma_{CU_M}W_{CU_x}W_{CU_z}tg\theta\cos\psi\right)}{V}+\frac{W_{CU}^2}{V^2}\end{aligned}}$$

where $W_{CU}^2 = W_{CU_x}^2 + W_{CU_z}^2$, $W_{CU_x} = W_{CU}\cos\alpha W_{CU}$, $W_{CU_z} = W_{CU}\sin\alpha W_{CU}$,

$$\tau_y = \begin{cases}289.0 - 0.006328Y \text{ } if \text{ } 0 \le Y \le 9324,\\ 230 - 0.006328(Y-9324) + 0.000001172\times\\ \times(Y-9324)^2 \text{ } if \text{ } 9324 \le Y \le 12000,\\ 221.5 \text{ } if \text{ } Y\rangle 12000.\end{cases}$$

Accordingly, in the system of differential equations (4), the acceleration of the air drag force by the TPS will be determined by the formula

$$a_x = 0.474\frac{i_n d^2}{q_n}10^3\frac{\tau_{ON}}{\tau_y+\Delta\tau}F_{58}\left(V_{r\tau}\right), \tag{5}$$

where $q_n = q_a - \omega_0$, and the acceleration of the air drag force by the WFTS will be determined by equation

$$a_x = 0.474\frac{i_{CU} d^2}{q_{CU}}10^3\frac{\tau_{ON}}{\tau_y+\Delta\tau}F_{58}\left(V_{r\tau}\right). \tag{6}$$

4 EXPERIMENTS

We will give the system (4) in a kind

$$\frac{d\overline{x}}{dt} = F\left(t,\overline{x}\right). \tag{7}$$

We consider that system of nonlinear differential equalizations of external ballistics of kind (5) relatively variables $\overline{x} \in \Re^n$, $t \in I = [0,\infty)$, thus $\overline{x}\left(x,y,z,V,\theta,\psi,\pi(y)\right)$ is vector-line of variables $(n=6)$, fulfills conditions of existence, uniqueness and continuous dependence on the initial conditions of decisions in a region [20] $\left(t\overline{x}\right) \subset G_H = IB_h$; $B_h = \left\{\overline{x} \in \Re^n : \|\overline{x}\|\langle H\right\}$.

Then taking into consideration essence of the use of procedure, which consists in that in the process of calculation of relative speed of reactive to the shell and we will enter acceleration of force of head-resistance of air winds coefficients of the direct and cross influencing of force wind on jet-projectiles separately for the indicated areas of trajectory as a result providing of exactness of implementation of this procedure is possible by bringing in of principle of Borel-Lebeg [20], in obedience to which it is possible with a confidence to consider that in the case of reserved to the segment on an axis OX it is always possible to select a complete subsystem which fully will cover this segment; hereupon complete trajectory of flight to the shell, certain on some complete interval, will be covered by the complete set of intervals, each of which will answer the separate areas of complete trajectory of motion of shell.

Consequently, reserved interval $\left\lfloor 0; X_a + X_p + X_{fe}\right\rfloor$, which a curve, that is associated with flight to shell, is certain on, always will be covered by some system of segments $\sum = \{\sigma\}$ of the opened intervals which a complete subsystem is selected from

$$\sum{}^{*} = \{\sigma_1, \sigma_2, \sigma_3\}, \tag{7}$$

where $\sigma_1 = T_{TAS} = \left[0; X_a\right], \sigma_2 = T_{TPS} = \left[X_a; X_a + X_p\right]$, $\sigma_3 = T_{WFTS} = \left[X_a + X_p; X_a + X_p + X_{fe}\right]$ – segments of line on abscises axis, on which certainly active, passive and opening of battle elements accordingly.

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5 RESULTS

The results of calculations of the values of the total average errors by range and direction using a system of differential equations (4) of the MM of the method of complete preparation of the determination of firing units of the information-calculation component of the automated fire control system of combat vehicles of jet artillery, considering the geophysical conditions of firing, the combined effect of air temperature and ground pressure, as well as the effect of wind, with the introduction of wind coefficients of direct and cross wind effects on rockets separately for the specified trajectory sections for 122-mm combat vehicle BM-21 –9M21HE projectile, 220-mm combat vehicle 9P140 – 9M27HE projectile and 300-mm 9A52 9M55C fragmentation projectile are given in Table 3.

From the data presented in the table, it can be concluded that the calculations of the total average errors by range and direction when determining firing settings by the FP method, using the proposed system of differential equations for 122-mm combat vehicle FM-21 – 9M21HE projectile, 220-mm combat vehicle 9P140 – 9M27HE projectile and 300-mm 9A52 9M55C fragmentation projectile are reduced by half during firing.by range and direction when determining firing.
Calculations of the total FP errors according to the system (4) in the range for 122-mm combat vehicle FM-21 – 9M21HE projectile, 220-mm combat vehicle 9P140 – 9M27HE projectile and 300-mm 9A52 9M55C fragmentation projectile are given on the Fig. 2.

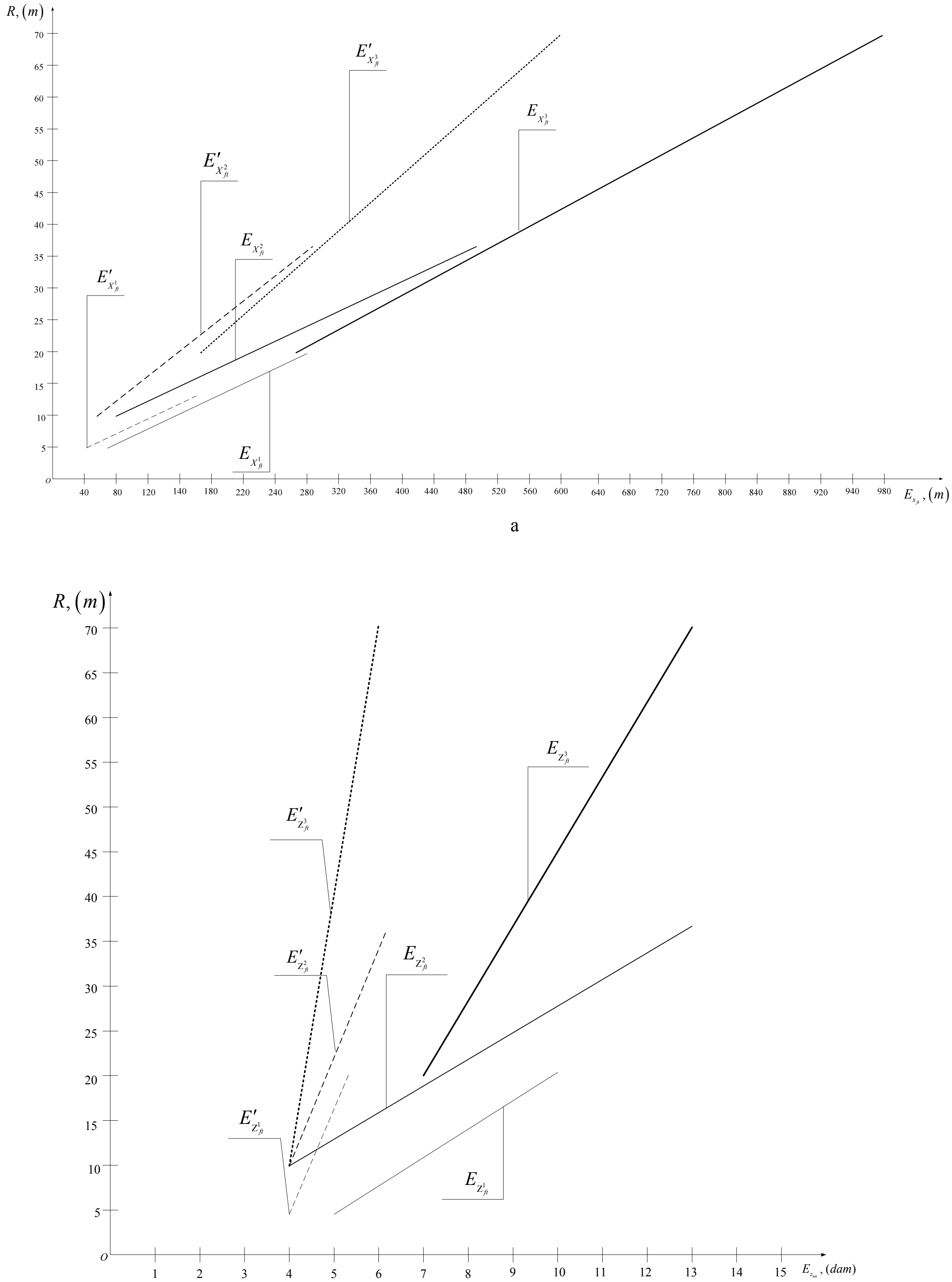
The following conclusions can be drawn from the given data: direction when determining the firing settings by FP method for accuracy depends on the firing range and the multiple launch rocket system; when firing at medium and long ranges, the value of the total average range errors is reduced by 1.5 times, taking into account the geophysical conditions of firing, the combined effect of air temperature and ground pressure, as well as the effect of wind, with the wind coefficients of direct and cross wind effects on rockets separately introduced for the specified trajectory sections; taking into account the geophysical conditions of firing, the combined effect of air temperature and ground pressure, as well as the effect of wind, with the introduced wind coefficients of direct and cross wind effects on rocket projectiles separately for the specified trajectory sections, the total average directional errors at the minimum firing ranges almost do not change and make up a difference of 0–01 for 122-mm combat vehicle BM-21 – 9M21HE projectile, 220-mm combat vehicle 9P140 – 9M27HE projectile, and for 300-mm 9A52 projectile 9M55C is halved; taking into account the geophysical conditions of firing, the combined effect of air temperature and ground pressure, as well as the effect of wind, with the introduced wind coefficients of direct and cross wind effects on rockets separately for the specified trajectory sections, the total average errors in the direction at maximum firing ranges for 122-mm combat vehicle BM-21 – 9M21HE projectile, 220-mm combat vehicle 9P140 – 9M27HE projectile, and for 300-mm 9A52 projectile 9M55C is halved.

6 DISCUSSION

Determination of correction coefficients on the active and passive sections of the trajectory and on the section of the flight trajectory of combat elements, taking into account the geophysical conditions of firing, the combined effect of air temperature and ground atmospheric pressure, as well as the effect of wind, is carried out using a system of differential equations of the mathematical model of the method of complete preparation of the determination of firing installations of the information and calculation component of the automated fire control system of combat vehicles of reactive artillery [2, 13, 17], or by the Dmitrievsky method [21].

Table 3 – Total average errors in range and direction when determining the firing settings by the full preparation method, using a system of differential equations with and without coefficients

Artillery system	Range, km	Median errors, м			
		with coefficients		without coefficients	
		$E_{X_{fp}}$	$E_{Z_{fp}}$	$E_{X_{fp}}$	$E_{Z_{fp}}$
122-mm BM-21	5	73	0–05	43	0–04
	10	141	0–06	85	0–04
	15	215	0–08	121	0–05
	20	283	0–10	165	0–05
220-mm 9P140	10	81	0–04	67	0–04
	20	262	0–07	167	0–05
	30	425	0–11	251	0–06
	36	505	0–13	308	0–06
300-mm 9A52	20	276	0–07	158	0–04
	30	433	0–08	249	0–04
	40	564	0–09	335	0–05
	50	717	0–10	425	0–05
	60	904	0–11	509	0–06
	70	980	0–13	595	0–06



b

Figure 2 – Total errors of the full preparation

a – by range for: 122-mm combat vehicle FM-21 –9M21HE projectile, 220-mm combat vehicle 9P140 – 9M27HE projectile and 300-mm 9A52 9M55C fragmentation projectile

b – by direction for: 122-mm combat vehicle FM-21 –9M21HE projectile, 220-mm combat vehicle 9P140 – 9M27HE projectile and 300-mm 9A52 9M55C fragmentation projectile

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The system of equations (4) can be used for accurate calculation of the trajectory elements taking into account the wind coefficients of direct and cross wind effects on rockets separately for the active and passive sections of the trajectory and for the section of the flight trajectory of combat elements in the mathematical model of the method of complete preparation of the determination of firing units of the information-calculating component of the automated fire control system of combat vehicles of reactive artillery.

The dependencies of the calculation of the trajectory elements using a system of differential equations of the mathematical model of the method of full preparation of the determination of firing units of the information-calculation component of the automated fire control system of combat vehicles of jet artillery allow solving the problems of external ballistics with a perspective optimization of the trajectory of the projectile, which is used in reactive systems of salvo fire, as well as to determine a set of indicators that characterize the process of projectile flight approaching the tabular trajectory [5] and specify the initial conditions that are necessary to solve the system of equations of motion of the projectile on the active and passive sections of the trajectory and on the section of the flight trajectory of combat elements, which are considered as independent trajectories.

As the calculations showed, with the help of differential equations of the mathematical model of the method of complete preparation of the determination of firing installations of the information and calculation component of the automated fire control system of combat vehicles of reactive artillery (4), the accuracy of firing and the overall effectiveness of artillery fire depend on how successfully the task of ensuring the calculated movement of projectiles will be solved under the conditions of the influence of direct and cross, constant and variable wind on the trajectory.

CONCLUSIONS

The improved mathematical model of the method of complete preparation of the determination of firing units of the information-calculation component of the automated fire control system of combat vehicles of reactive artillery allows to significantly speed up the process of preparing information for firing, and as a result ensures the promptness of response to changes in – a tribute to the software-mathematical complex of shooting and fire control.

It also increases the accuracy of their calculation at the same time.

The results of the calculated values show that the influence of various sources of error on the accuracy of the full training depended on the firing range, the artillery system, and the charge number.

The proposed system of differential equations of the mathematical model of the method of complete preparation of the determination of firing units of the information and calculation component of the automated system allows to take into account the weight functions of the air temperature, the influence of the wind for the active and passive sections of the trajectory of the projectile and the section of the detection of combat elements, to determine according to them, the weighting coefficients for each type of projectile, which makes it possible to quickly respond to changes in the tasks in the information-calculation process.

The system of differential equations of the mathematical model of the method for the complete preparation of the determination of firing units of the information and calculation component of the automated fire control system of combat vehicles of jet artillery can be used to calculate the values of corrections for the deviation of meteorological conditions of firing from the tabular conditions in fire divisions separately for each section of the missile's flight path, both existing and prospective.

Information of numerical calculations is resulted ground to assert:

1. Compared with the existing mathematical model of the method of full preparation for determining the settings for firing, the information-calculation component of the automated fire control system of combat vehicles of jet artillery will allow to shorten the equation when calculating the weighting coefficients for accounting for ballistic deviations of the subjects – air and ballistic wind conditions on active and passive sections of the trajectory and flight section of combat elements.
2. It will also ensure that when approximating the functions of the real distribution law, it is not replaced by a linear law, which will significantly increase efficiency and reduce the errors of calculating meteorological corrections by range and direction to 1.5–2%, will allow timely response to changing tasks in the information-calculation process during shooting and fire control, as well as effectively and quickly ensure the formation of formalized messages and documents based on the received information.
3. The improved mathematical model of the method of complete preparation of the determination of firing units of the information and calculation component of the automated fire control system of combat vehicles of jet artillery by solving the system of differential equations of motion of 9M21XE, 9M27XE and 9M55C projectiles allows hitting the specified targets with an accuracy of 0.5 – 0.9% in distance and 0–02 – 0–05 divisions of the protractor in direction and reduce the time for the preparation of installations.

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УДОСКОНАЛЕНА МАТЕМАТИЧНА МОДЕЛЬ СПОСОБУ ПОВНОЇ ПІДГОТОВКИ ВИЗНАЧЕННЯ УСТАНОВОК ДЛЯ СТРІЛЬБИ НА УРАЖЕННЯ ІНФОРМАЦІЙНО-РОЗРАХУНКОВОЇ СКЛАДОВОЇ АВТОМАТИЗОВАНОЇ СИСТЕМИ УПРАВЛІННЯ ВОГНЕМ БОЙОВИХ МАШИН РЕАКТИВНОЇ АРТИЛЕРІЇ

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АНОТАЦІЯ

Актуальність. У рамках автоматизації системи управління вогнем бойових машин реактивної артилерії, щодо підготовки даних для стрільби та управління вогнем, удосконалено інформаційно-обчислювальний процес цієї системи, а саме удосконалено математичну модель способу повної підготовки визначення установок для стрільби снарядами які застосовуються в реактивних системах залпового вогню. В систему диференційних рівнянь математичної моделі інформаційно-обчислювального процесу складової автоматизованої системи управління вогнем бойових машин реактивної артилерії, введено вагові функції по температурі повітря, впливу вітру для активної, пасивної ділянок траєкторії польоту снаряду та ділянки розкриття бойових елементів, що дозволяє визначати по ним вагові коефіцієнти для кожного типу снаряду.

Мета роботи. Удосконалити інформаційно-розрахункову складову автоматизованої системи управління вогнем бойових машин реактивної артилерії, шляхом покращення математичної моделі способу повної підготовки визначення установок для стрільби на ураження. Запропонувавши систему диференційних рівнянь яка буде враховувати вагові функції по температурі повітря, впливу вітру для активної, пасивної ділянок траєкторії польоту снаряду та ділянки розкриття бойових елементів, а також дасть можливість визначати по ним вагові коефіцієнти для кожного типу снаряду, що в свою чергу призведе до підвищення точності визначення установок для стрільби.

Метод. Запропонований аналітичний метод дозволяє: провести розрахунок вагових коефіцієнтів для кожного типу реактивного снаряду, що характеризують процес наближення польоту реактивного снаряду до табличної траєкторії та задати початкові умови необхідні для вирішення диференціальних рівнянь математичної моделі інформаційно-обчислювального процесу складової автоматизованої системи управління вогнем бойових машин реактивної артилерії; підвищити точності визначення установок для стрільби при виконанні вогневих завдань, що надає змогу оперативно реагувати на зміну бойової обстановки шляхом змін у програмно-математичному процесі автоматизованої системи управління вогнем; ефективно та оперативно забезпечити розробку або уточнення текстуальних і графічних розпорядчих та бойових документів на основі отриманих результатів за допомогою диференціальних рівнянь математичної моделі інформаційно-обчислювального процесу складової автоматизованої системи управління вогнем.

Результати. Система диференціальних рівнянь математичної моделі інформаційно-обчислювального процесу складової автоматизованої системи управління вогнем бойових машин реактивної артилерії забезпечує своєчасне реагування на зміну обстановки в інформаційно-обчислювальному процесі складової автоматизованої системи управління вогнем бойових машин реактивної артилерії під час стрільби та управління вогнем. Надає можливість ефективно та оперативно забезпечити розроблення або уточнення текстуальних і графічних розпорядчих та бойових документів за інформацією, отриманою під час виконання вогневих завдань.

Висновки. Проведені розрахунки на основі запропонованої системи диференційних рівнянь підтверджують покращення інформаційно-розрахункової складової автоматизованої системи управління вогнем бойових машин реактивної артилерії та дозволяють своєчасно реагувати на зміну завдань в інформаційно-розрахунковому процесі під час стрільби і управління вогнем, а також ефективно і швидко забезпечують формування формалізованих повідомлень і документів на основі отриманої інформації під час виконання вогневого завдання підрозділами реактивної артилерії. Перспективами подальших досліджень є створення узгоджених математичних методів, моделей, алгоритмів і програм для реалізації цілей і завдань стрільби і управління вогнем при складанні Таблиць стрільби для перспективних або отриманих бойових машин реактивної артилерії від партнерів.

КЛЮЧОВІ СЛОВА: автоматизована система управління, інформаційно-розрахункова складова, математична модель, система диференційних рівнянь, апроксимація функцій реального закону розподілу, вагові функції по температурі повітря, впливу вітру.

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