Effect of Shot Duration on the Firing Accuracy when Burst Fire of Unguided Rockets

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***Abstract*— The paper introduces an analysis of multiple rocket launcher oscillation during fire of an unguided rocket set. It contains built mathematic model of a launcher including oscillation as well as model of unguided rocket motion. The effect of a variable time delay between two consequent launches and its impact on a launcher oscillation is analysed. The BM-21 (Russia) multiple rocket launcher system with corresponding 9M22U unguided rockets have been used for the model simulation and experimental verification. The results are used for assessment of launcher stability and oscillation during fire. The model simulation results are very close to the experimental results.**

Keywords—multiple rocket launcher system; firing stability; the wheeled vehicle; multibody system dynamics; rate of fire.

I. INTRODUCTION

Multiple rocket launcher belongs among rocket artillery. It is used to fire unguided rockets. This type of artillery has a simple structure, fast manoeuvrability, convenience in exploitation, high operational reliability, and strong power. Therefore, it is one of the important artillery systems in the army of countries around the world. The recent conflicts between Israel and Lebanon, Russia and Georgia, etc. proved it.

Along with the change of fighting form, the role of the multiple rocket launcher system is more and more enhanced in the artillery fire structure of countries. It motivated the researchers in the new designs of the modern multiple rocket launcher systems, meeting the high requirements of combat and technology in military and army combat.

The time delay between two consequent rocket launches influences the oscillation of the launcher. The motion of unguided rocket is also influenced by the stirred-up gas exhaust from the previous rocket. These are factors that significantly affect the unguided rocket firing accuracy. Therefore, the task of the optimal time delay determination (rate of fire) for the launcher is essential and must be considered.

In this paper, the dynamic model of the multiple rocket launcher system mounted on the vehicle and the model of unguided rocket motion in the air is developed. The models are arranged for the multiple rocket launcher system BM-21 (Fig 1) using unguided rockets 9M22U. The results of simulation were compared with the corresponding experimental data to verify the reliability of the model. These results may be utilized in the design process that will help to optimize the structure of combat vehicles - combine weapons.

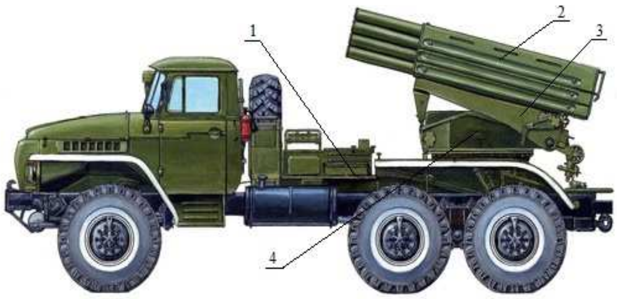

Fig. 1. Multiple rocket launcher system BM-21.

1. Vehicle body Ural-375, 2. Launcher, 3. Elevation parts, 4. Traverser parts.

II. BUILDING SYSTEM OF EQUATIONS DESCRIBING THE MOTION OF UNGUIDED - ROCKETS

A. The Problem of Oscillation of the Launcher

Based on the structure of the real body and the links between the parts of the combat vehicle and the simplifying assumptions, the model of the BM-21 combat vehicle was established from the viewpoint of the multi-objects' mechanics, see Fig. 2. Overall system status survey: the elevation angle is zero, the traverser angle is zero and the combat vehicle is placed on horizontal flat ground.

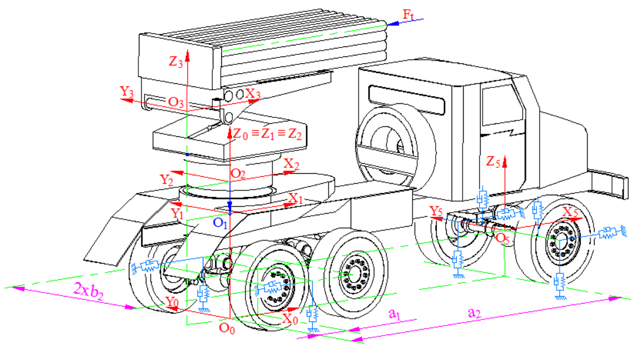

Fig. 2. The model of multiple launch rocket system BM-21.

The combat vehicle system consists of five rigid bodies:

- body 1 - vehicle body and the whole rear axle of mass m_1,
- body 2 - traverser parts of mass m_2,
- body 3 - elevation parts of mass m_3,
- body 4 - the rockets have not been fired of mass m_4,
- body 5 - the whole front axle of mass m_5.

The masses, the positions of the centre of gravity, and the moments of inertia of all bodies are determined through SolidWorks software.

For investigation of the system of rigid body dynamics, the bodies of the system are attached to a Cartesian coordinate system (Fig. 2), where:

- $R_0 = (O_0X_0Y_0Z_0)$ represents the stationary coordinate system fixed to the ground.
- $R_i = (O_iX_iY_iZ_i)$: represents the local coordinate system established at the i-th rigid body, for $i = 1 \div 5$.

where the coordinate system of the body 4 coincides with the coordinate system of the body 3.

From the assumptions and layout of objects, the BM-21 multiple rocket launcher system has 6 independently generalized coordinates: $[q_j]= [q_1, q_2, q_3, q_4, q_5, q_6]$, where:

q_1 – longitudinal displacement of body 1 along X_0-axis,

q_2 – longitudinal displacement of body 1 along Z_0-axis,

q_3 – angular displacement of body 1 about X_0-axis,

q_4 – angular displacement of body 1 about Y_0-axis,

q_5 – longitudinal displacement of body 5 along Z_1-axis,

q_6 – angular displacement of body 5 about X_1-axis.

In this article, we choose the Lagrange's method. The Lagrange's differential equations system describes the motion of the mechanical system as follows, [1].

$$\frac{\mathrm{d}}{\mathrm{d}t}\left[\frac{\partial T}{\partial \dot{q}_j}\right]-\frac{\partial T}{\partial q_j}=Q_j\,, \tag{1}$$

where: T - total kinetic energy of the whole mechanical system; q_j - independent generalized coordinate; Q_j - generalized force corresponding to the generalized coordinates q_j.

In terms of structure, it can be completely determined: the centre of mass vector, transfer matrix, the moment of inertia of solid objects. Then, we can determine the total kinetic energy T from equation:

$$T_k=\frac{1}{2}\left(\dot{R}_k^T M_k \dot{R}_k+\bar{\omega}_k^T A_0^k I_k A_0^{kT}\bar{\omega}_k\right), \tag{2}$$

where, R_k is the centre of mass vector of body k in the fixed coordinate system O_0; M_k is mass matrix of body k; $\bar{\omega}_k$ is the angular velocity vector of the body k represented on the fixed coordinate O_0; A_0^k is transfer matrix from system O_k to system O_0; I_k is matrix of the inertia tensor of the body k to the axis system O_k. A detailed explanation of these values can be found in [2], [3], [4].

The components of the generalized force vector Q_j is determined from equation, as follows:

$$Q_j=\frac{\partial(\delta W_{F_t})}{\partial(\delta q_j)}=F_t\frac{\partial r_F}{\partial q_j}\,. \tag{3}$$

Where F_t is the firing force – the force of the rocket action on the combat vehicle system. This force can be divided into three phases: the braking phase, the phase of rocket motion in a launcher tube, and the exhaust phase, [2], [3], [4].

The value of the firing force is a function of time. It depends on rocket function only and does not depend on the vibrating state of the system. The firing force is determined as follows:

1) Phase of braking

When the braking force reaches the limit value F_k (about 6 kN to 8 kN) the rocket will be released. This phase is very fast in the range from 0 to $t_k = 0.025$s. Therefore, we assume that the braking force increases linearly from 0 to F_k in the time interval $\left(0 \le t \le t_k\right)$:

$$F_t = F_k\frac{t}{t_k} - Q\sin\varphi \quad (0 \le t \le t_k) \tag{4}$$

where: Q – is the weight of the rocket, F_k – is the limit value of the braking force.

2) Phase of rocket motion in launcher tube

This phase lasts about 0.095 s, i.e., from 0.026 s till the moment $t_c = 0.121$s. The actual F_t value is not large compared to other phases; it is derived linearly from the value F_{c1} to F_{c2}. The value of F_t force is determined by the formula, see [2].

$$F_t=\frac{\dfrac{1}{m_d}\left(P'-F_k\right)+\dfrac{d_c.M_0}{2.I_{dx}.tg\gamma}}{\dfrac{d_c^2}{4.I_{dx}.tg\gamma}(\cos\gamma-f.\sin\gamma)+\dfrac{1}{m_d}(\sin\gamma+f.\cos\gamma)} \tag{5}$$

where: P' - the thrust of the engine that includes friction losses, m_d - mass of rocket, M_0 - initial drag torque, d_c - diameter of the rocket, I_{dx} - moment of inertia of rocket around the longitudinal axis, f - friction coefficient, γ - slope of the rifle.

3) Phase of exhaust gas acting on the launcher

When the rocket engine works, the exhaust gas flow is formed and acts on the front of the launcher. This phase lasts from the time the rocket comes out of the muzzle of launching tube until the exhaust gas flow stops an acting on the launcher (Fig. 7). The exhaust force is determined by the following formula, see [3].

$$F_t=-\int_{(S)}\xi.p(\rho,\tau)\,\mathrm{d}s \tag{6}$$

where: S - the surface area of the launcher; ds - differential of area; $p(\rho, \tau)$ - gas pressure at the review point and ξ - coefficient of surface coverage.

The diagram of the firing force acting on the launcher surface with respect to time is shown in Fig. 3.

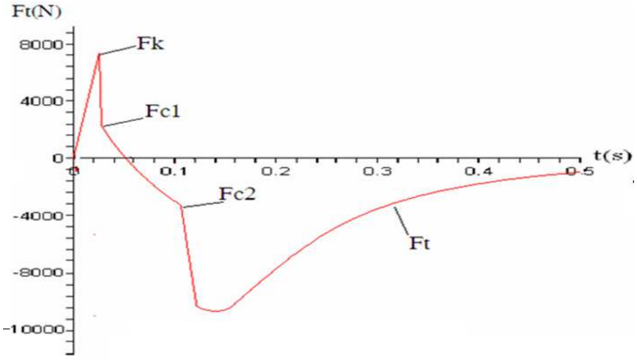

Fig. 3. Time course of of firing force.

After determination of the kinetic energy, the potential work, and the generalized force of the mechanical system and substituting it into Lagrange's Equation (1) we have a system of 6 second-order differential equations. This is the system of equations that describes the oscillation of the multiple rocket launcher system in space when firing.

B. Mathematical Model of Unguided Rocket Motion in the Air

To study the rocket motion in the air, the article uses the following coordinate systems, see [4], [5]:

- normal earth coordinate system, $O_gX_gY_gZ_g$ is a coordinate system fixed to the ground. Where: O_g coincides with the rocket's centre of gravity at a moment the rocket leaves the launcher; the axis, O_gX_g is the intersection of the firing plane with the horizontal plane across the origin, the direction of the launch is positive; the axis, O_gZ_g, is perpendicular to O_gX_g, and downward; the axis, O_gY_g, is determined according to right rotation rule.
- earth coordinate system attached to the rocket, $Ox_gy_gz_g$, where: O is in the rocket's centre of gravity; its axes are always parallel with the axes of the normal earth coordinate system.
- aerodynamic coordinate system, $OX_aY_aZ_a$ is the coordinate system attached to the velocity vector of the rocket's centre of gravity, OX_a coincides with rocket velocity vector ***V***; OZ_a is perpendicular to OX in a vertical plane passing through ***V*** and downward; OY_a is perpendicular to the plane OX_aZ_a in a right rotation rule. The position angles between the aerodynamic coordinate system and normal earth coordinates system are: χ_a – aerodynamic azimuth, γ_a – aerodynamic pitch.
- body coordinate system, OXYZ determines the position of the rocket axes. Where: O coincides with the rocket's centre of gravity; OX is parallel to the rocket's symmetry axis; OZ is in the vertical plane and downward; OY is determined according to the right rotation rule. The rocket's spin motion is determined by the spin angle, ν around the axis, OX. The position angles between the body coordinate system and the velocity coordinate system: α – the angle of attack, β – sideslip angle.

Fig. 4. shows the geometrical relationship between coordinate systems $Ox_gy_gz_g$; $OX_aY_aZ_a$ and OXYZ.

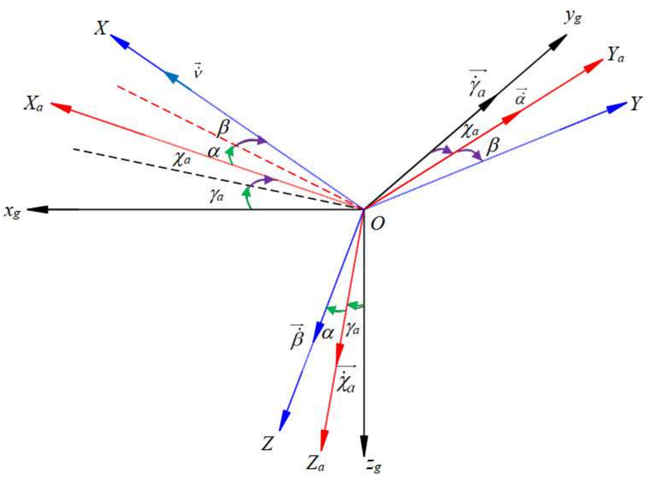

Fig. 4. Geometric relationship between coordinate systems.

Transformation matrices between the coordinate systems:

$$\begin{bmatrix} x_g \\ y_g \\ z_g \end{bmatrix} = \begin{bmatrix} \cos\gamma_a \cos\chi_a & -\cos\gamma_a \sin\chi_a & \sin\gamma_a \\ \sin\chi_a & \cos\chi_a & 0 \\ -\sin\gamma_a \cos\chi_a & \sin\gamma_a \sin\chi_a & \cos\gamma_a \end{bmatrix} \begin{bmatrix} x_a \\ y_a \\ z_a \end{bmatrix}$$
$$\begin{bmatrix} x_a \\ y_a \\ z_a \end{bmatrix} = \begin{bmatrix} \cos\alpha\cos\beta & -\cos\alpha\sin\beta & \sin\alpha \\ \sin\beta & \cos\beta & 0 \\ -\sin\alpha\cos\beta & \sin\alpha\sin\beta & \cos\alpha \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} \qquad (7)$$

The set of equations of the unguided rocket motion is derived from the momentum theorem and moment of momentum theorem combined with the transformations (7). After arrangement we get the following set of differential equations [4], [5]:

$$\begin{cases} \dot{V} = \dfrac{\sum F_x}{m} \\ \dot{\gamma}_a = \dfrac{\sum F_y}{m \cdot V} \\ \dot{\chi}_a = -\dfrac{\sum F_z}{m \cdot V \cdot \cos\gamma_a} \\ \dot{\alpha} = \dfrac{1}{\cos\beta}\left(\omega_y \cos\nu - \omega_z \sin\nu\right) \\ \dot{\beta} = \omega_y \sin\nu + \omega_z \cos\nu \\ \dot{\nu} = \omega_x - tg\beta\left(\omega_y \cos\nu - \omega_z \sin\nu\right) \\ \dot{\omega}_x = \dfrac{1}{I_x}\left\{\sum M_x + \left(I_y - I_z\right)\omega_y\omega_z\right\} \\ \dot{\omega}_y = \dfrac{1}{I_y}\left\{\sum M_y + \left(I_z - I_x\right)\omega_x\omega_z\right\} \\ \dot{\omega}_z = \dfrac{1}{I_z}\left\{\sum M_z + \left(I_x - I_y\right)\omega_x\omega_y\right\} \\ \dot{X}_g = V\cos\gamma_a \cos\chi_a \\ \dot{Y}_g = V\cos\gamma_a \sin\chi_a \\ \dot{Z}_g = -V\sin\gamma_a \end{cases} \qquad (8)$$

where: $\sum F$ is the sum of all the forces acting on the rocket in flight. It includes: The thrust of the rocket engine P, weight Q, aerodynamic force R, Coriolis force F_{cl} and Magnus force F_{mag}. For unguided jet bullet, Coriolis force and Magnus force have a very small value compared to the other forces.

$$\sum \vec{F} = \vec{P} + \vec{Q} + \vec{R} + \vec{F}_{cl} + \vec{F}_{mag} \;;\; \vec{P} + \vec{Q} + \vec{R} \qquad (9)$$

M_x, M_y, M_z are the total projections of the aerodynamic and external moments acting on the rocket in flight on the coordinate axes OXYZ, respectively.

I_x, I_y, I_z are the rocket's principal moments of inertia for the axes of the coordinate system OXYZ, respectively.

$\omega_x, \omega_y, \omega_z, \dot{\omega}_x, \dot{\omega}_y, \dot{\omega}_z$ are the angular velocities and angular accelerations of the rocket's absolute rotation on the coordinate system OXYZ, respectively.

The system of equations (8) includes 12 variables: V, γ_a, χ_a, α, β, ν, ω_x, ω_y, ω_z, X_g, Y_g, Z_g. The system is often solved by numerical methods. The initial condition for system solution is the set of the motion parameters at the time the rocket leaves the launching tube.

Combining the system of equations (1) and (8), we obtain a general system of equations of unguided rocket launch and flight. The input parameters were determined from the multiple rocket launcher system BM-21 construction parameters, structural parameters, and parameters of internal ballistics of 9M22U unguided rocket, see [2], [3] and [4].

III. Effect of Time Delay Between Consequent Rocket Launches on the Firing Accuracy

A. Calculation according to Theoretical Model

The effect of the time delay between consequent unguided rocket launches on accuracy has been investigated. The time delay has been changed and the displacement of the tip of the launcher in the vertical plane, the bounce angle in the vertical plane at the time the rocket leaves the launcher tube muzzle were evaluated. The change of the time delay affects the firing range and lateral deviation of the rockets.

Based on the models and initial conditions, input parameters were defined. The authors build a calculation program on MATLAB software and proceed to solve. In this article, the authors only evaluate the case of fire series of 5 rockets with time delay, T_b, changing from 0.46s to 0.6s (step equals 0.02s). The elevation angle is $\varphi = 25^0$ and the traverser angle is $\beta = 30^0$. In this paper, the mean square deviation as the judgment is used to reflect the quality of the series shot, see [6]:

$$\bar{x} = (x_2 + \ldots + x_n)/n - 1 = \sum_{i=2}^{n} \frac{x_i}{n-1} \tag{10}$$

$$\begin{cases} \sigma_x = \sqrt{\dfrac{\sum_{i=2}^{n}(x_i - \bar{x})^2}{(n-2)}} \quad when\ n < 30 \\ \sigma_x = \sqrt{\dfrac{\sum_{i=2}^{n}(x_i - \bar{x})^2}{(n-1)}} \quad when\ n \geq 30 \end{cases} \tag{11}$$

where: x_i – is sample data set (the bounce angle values θ in the vertical plane or displacement of the tip of the launcher Z_0 in the vertical plane); n - sample size.

Results of the calculation of the launch oscillation at the time the rocket leaves the launcher tube muzzle (at $t = 0.121$s) are presented in Fig. 5, Fig. 6, the firing range, and lateral deviation of rockets are presented in Tab. I.

Some comments:

- The first launch has a bounce angle (θ) and oscillating the tip of the launcher (Z_0) unchanged with every time delay. Therefore, the firing range and lateral deviation of rockets are the same for every time delay.

- The value of the bounce angle is a random quantity. For its assessment, the whole series of fire must be evaluated. Minimum average deviation in time delay T_b = 0,46 s ($\bar{\theta}$ = 0,318×10^{-3} rad), but minimum mean square deviation in time delay T_b = 0,50 s (σ_θ = 0,4571×10^{-3} rad) and T_b = 0,52 s (σ_θ = 0,4158×10^{-3} rad).

- The deviation in firing range and lateral deviation is the smallest in case of time delay T_b = 0,50 s. The mean square deviation of the firing range is 5,85 m, the average lateral deviation is 95,56 m, the mean square deviation of lateral deviation is 6,42 m (Tab. I).

- Bounce angle is stable at the time delay T_b = 0.50 s and converges according to with period t = 0.1 s, which means that they will stabilize at the time delay T_b = 0.60 s, T_b = 0.70 s, etc. But to ensure firepower focus, need to increase the firing rate of the launcher, so T_b = 0.5 s is the best time delay. This explains why the multiple rocket launcher system BM-21 has the time delay T_b = 0.5s (rate of fire = 2 rounds/s).

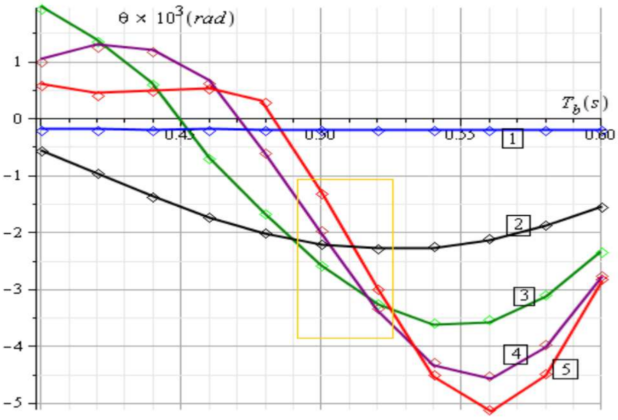

Fig. 5. The bounce angle values θ in the vertical plane corresponding to different time delay of the first 5 launches.

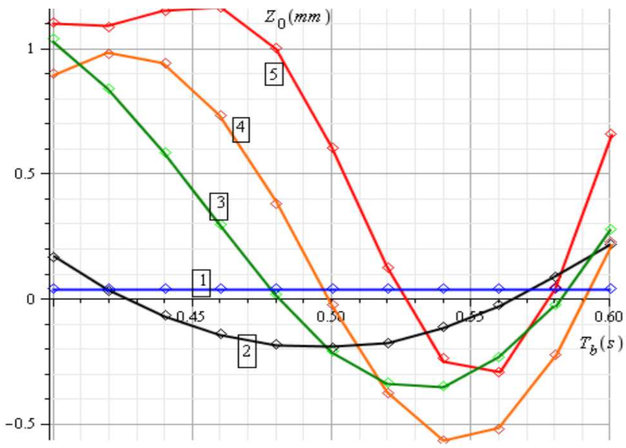

Fig. 6. Displacement of the tip of the launcher Z_0 in the vertical plane corresponding to different time delays of the first 5 shots.

TABLE I. Firing Range and Lateral Deviation of Rockets

Shot duration T_b [s]		First firing	Second firing	Third firing	Fourth firing	Fifth firing	Average	MSD
0,46	FR [m]	15338	15258	15267	15373	15372	15317,5	55,09
	LD [m]	-86,78	-92,07	-98,84	-123,64	-116,80	-107,84	12,84
0,48	FR [m]	15338	15255	15259	15329	15368	15302,75	47,80
	LD [m]	-86,78	-94,13	-103,73	-122,95	-122,29	-110,78	12,32
0,50	FR [m]	15338	15308	15303	15312	15319	***15310,5***	***5,85***
	LD [m]	-86,78	-92,98	-103,55	-99,18	-86,55	***-95,56***	***6,42***
0,52	FR [m]	15338	15306	15293	15186	15290	15268,75	48,15

	LD [m]	-86,78	-94,41	-102,83	-127,70	-101,04	-106,49	12,64
0,54	FR [m]	15338	15310	15289	15113	15110	15205,5	94,30
	LD [m]	-86,78	-96,46	-110,18	-126,06	-82,25	-103,74	16,24
0,56	FR [m]	15338	15311	15289	15110	15097	15201,75	98,67
	LD [m]	-86,78	-99,40	-110,03	-128,14	-80,75	-104,58	17,17
0,58	FR [m]	15338	15314	15291	15116	15098	15204,75	98,29
	LD [m]	-86,78	-106,77	-117,36	-113,73	-82,06	-104,98	13,77
0,60	FR [m]	15338	15319	15303	15262	15261	15286,25	25,39
	LD [m]	-86,78	-105,34	-109,67	-112,05	-89,00	-104,015	8,99

(FR - firing range; LD - lateral deviation; "-" represents left deflection; MSD – the mean square deviation).

B. *Experimental Assessment of the Model's reliability*

To evaluate the reliability of the established model and the results of the calculation, the authors have carried out experimental measurements on the multiple rocket launcher system BM-21. A diagram depicting the experimental equipment system is shown in Fig. 7.

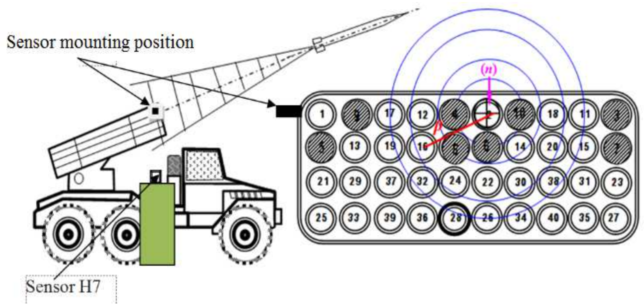

Fig. 7. Diagram depicts the experimental system.

Test plan:

- 5 rockets are installed onto the vehicle in the launcher positions: 1, 2, 3, 4, 5.
- Series with time delay: $T_b = 0.5$ s are launched.
- five rounds with the elevation angle $\varphi = 25°$ and traverse angle $\alpha = 30°$ are fired in burst.
- Because the bounce angle of the launcher is very difficult to guarantee during the test, the authors measured the displacement of the tip of launcher No.1 and measured the falling point of rockets to determine the firing range and lateral deviation.
- Device for determining the displacement of the tip of the launcher is used: Displacement measuring Sensor H7.

Experimental results are obtained as follows:

Maximum amplitudes of oscillation at the tip of the launching tube No. 1 in the vertical direction are shown in Tab. II. Firing range and lateral deviation are shown in Tab. III.

Some comments:

The comparisons show a very good agreement between the results of calculation and experimental results: amplitude of oscillation at the tip of the launcher vertically has the greatest error 5,5% (Tab. II).

The theoretical calculation results are close to the results of the firing table and with direct experimental measurements: The firing range error between computation and measurement is 0,3%; between computation and lookup firing table is 0,6%. The error of lateral deviation between calculation and measurement is 6,4 %; between computation and lookup firing table is 8,6 % (Tab. III).

The results of analysis show that the mathematical model ensures the required accuracy. This model can be used for evaluation of the structural parameters of the launchers to firing accuracy as well as for evaluation of the quality of the launchers after repairs and improvements.

TABLE II. MAXIMUM AMPLITUDE OF VARIATION (MM)

	Measurement results	Calculated value	Error (%)
First firing	-2,10 +2,21	-2,17 +2,28	3,23 3,07
Second firing	-1,55 +2,16	-1,64 +2,18	5,50 0,92
Third firing	-1,29 +2,73	-1,28 +2,88	0,78 5,21
Fourth firing	-1,38 +2,60	-1,39 +2,75	0,72 5,45
Fifth firing	-1,35 +2,41	-1,37 +2,55	0,72 5,45

TABLE III. FIRING RANGE AND LATERAL DEVIATION OF ROCKETS

		First firing	Second firing	Third firing	Fourth firing	Fifth firing	Average	Error
C	FR [m]	15338	15308	15303	15312	15319	15310,5	
	LD [m]	-86,78	-92,98	-103,55	-99,18	-86,55	-95,56	
V	FR [m]	15400	15400	15400	15400	15400	15400	0,6%
	LD [m]	88	88	88	88	88	88	8,6%
M	FR [m]	15242	15272	15295	15285	15270	15272,8	0,3%
	LD [m]	-96,28	-99,89	-116,5	-102,5	-95,1	-102,06	6,4%

(C - calculated value; V - value in firing table; M - measurement result; FR - firing range; LD - lateral deviation; "-" represents left deflection).

IV. CONCLUSION

The paper presents a method to establish the oscillation model of multiple rocket launcher systems mounted on the wheeled vehicle and the mathematical model of unguided-rockets' motion in the air. The model is built for multiple rocket launcher system BM-21 (of Russia) with 6 degrees of freedom and motion of 9M22U unguided-rocket in the air with 12 degrees of freedom. The comparison of theoretical with experimental results and values in the firing table shows very good accuracy and reasonableness of the model. The dependence of the firing accuracy on the rate of fire was investigated, has determined the optimal rate of fire for each launcher. This model is applicable to all guns, artillery as well as launchers mounted on the wheeled vehicle. These results may be utilized in the design process to help optimize the structure of combat vehicles - combine weapons.

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