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A STUDY ON MULTI-BODY MODELING AND VIBRATION ANALYSIS FOR TWIN-BARREL GUN WHILE FIRING ON ELASTIC GROUND

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Abstract:
In this paper, we propose a new twin-barrel gun model for calculating firing on the elastic ground to study the effects of structural parameters on the weapon's performance. This paper intends to provide a theoretical basis and establish a specific model of twin-barrel gun, to build a system of differential equations of vibration, and to determine the rules of vibration of the gun when firing on the elastic ground. The method is used to establish a model of two sets of automatic firing systems by dynamics of a multi-body system. The results of the calculation revealed the instructional significance for improving the vibration performance and increasing the firing accuracy. Experiments were tested out on a 37 mm twin anti-aircraft gun, type 65. The results of the theoretical mathematic model provide a good correlation to experimental data. The maximum amplitude deviation on the horizontal plane does not exceed 8.1%, while in the vertical plane does not exceed 6.4%. The outputs can be used for validation of a dynamic model of a weapon system while firing on the elastic ground, and the procedure can be used as an example of a practical technique and methodology for other weapon systems.

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Multi-body modeling, vibration, twin-barrel gun, elastic ground, the stability of firing, automatic firing systems

1. INTRODUCTION

Firing stability is one of the most important key factors of weapons. It determines the firing accuracy and affects the firing efficiency of automatic guns, [1,2]. However, guns can be moved and vibrated while firing, which makes the firing angle of guns deflected after the projectile has left the barrel muzzle and reduced the probability of destroying the target, [3-9]. The larger the deflection of firing, the smaller finding the probability of destroying the target, [3,5]. So, reducing the muzzle vibration can provide the gun with a fine initial ballistic condition and improve firing accuracy.

It shows that the cycle of operation and the mathematical model are selected according to the important role in the research process, designing, manufacturing, and improving weapons. Due to this reason, there were documents and research about establishing the model and investigating the influence of the basic factors on the stability of the gun while firing as can be found in research [10-20]. However, documents and research that have comprehensive, systematic, and in-depth analyses on the dynamic of twin-barrel guns still have many limitations and are rarely published, [16-18]. The twin-barrel gun is a complicated mechanism, in which the process of movement often takes place at high speed. The model traditionally used for modeling due to symmetry is often viewed as an object with mass to satisfy the demand for vibration analysis for twin-barrel guns [19,20]. However, in fact, the movement of barrels sometimes isnot simultaneous because of the structure of the automatic firing system.

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Therefore, describing the structure and motion of a twin-barrel gun can be presented with explicit physical significance.

In this paper, we propose a new method to find out the dynamical properties of multi-barrel weapons firing on elastic ground.

2. MATERIALS AND METHODS

The research content has focused on setting up a mathematical model by using dynamics of a multi-body system, establishing a system of differential equations and solving it by numerical methods. The authors build a calculation program to solve these equations by MATLAB software. In the experimental part, non-contact measurement techniques are used to determine some dynamic parameters of the weapon system. These experimental results are used to verify the established mathematical model reliability. Calculations and experiments were carried out on a 37mm twin-barrel anti-aircraft gun type 65, Fig. 1 [21].

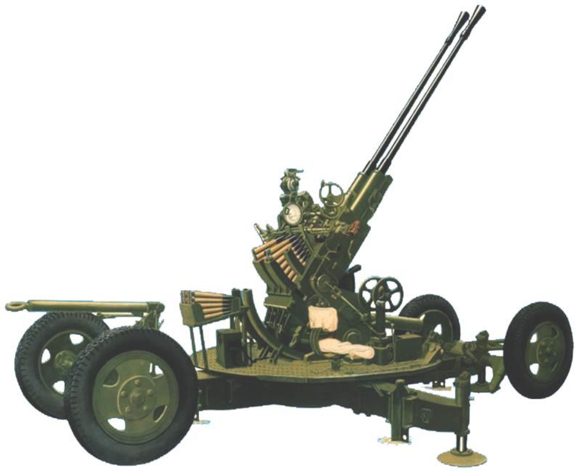

Fig. 1. Overview of 37mm K65 twin-barrel [21]

3. PROBLEM FORMULATION

3.1. Multi-body system model of twin-barrel gun description

The dynamic model has been made up by using the following assumptions:

- Deformation of the leveling jack is smaller than soil deformation, thus the effect of the lower carriage on the gun is considered as soil deformation which is located on four leveling jacks. Thus, it is modeled by spring k_i and dumper c_i on three axes of the fixed coordinate system.

- Vibration of elevating and traversing mechanisms is based on elastic moments.

- The two automatic firing systems are considered as two bodies that have mass. They are moved on the vertical of the gun-tube axis.

- The mass distribution of the gun is replaced with mass centralization and moments of inertia of objects are located in the center of parts of the body.

- The lower carriage is mounted on the top carriage by a ball holder ring, so its link is considered absolutely hard.

- The weapon system is at rest before firing, the elevation angle and traverse angle are constant, i.e. the target is not tracked.

The computational model of the twin-barrel gun system is given in Fig. 2, and Fig. 3. When surveying the overall 37mm K65 cannon in a combat state, the gun firing process is stable with 4 jacks, elevating rotation angle is φ, traversing rotation angle is α.

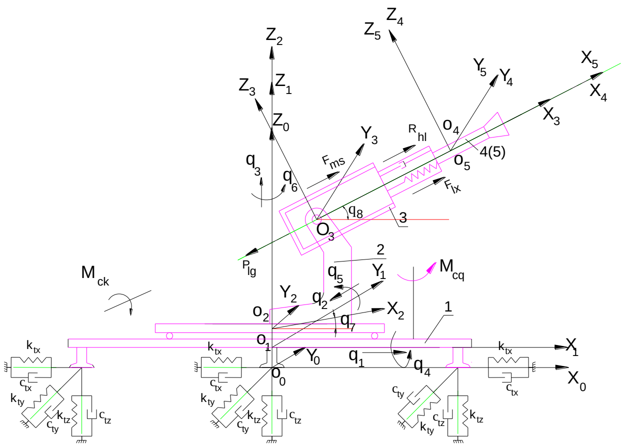

Fig. 2. The Multi-body system model of twin-barrel gun (side view)

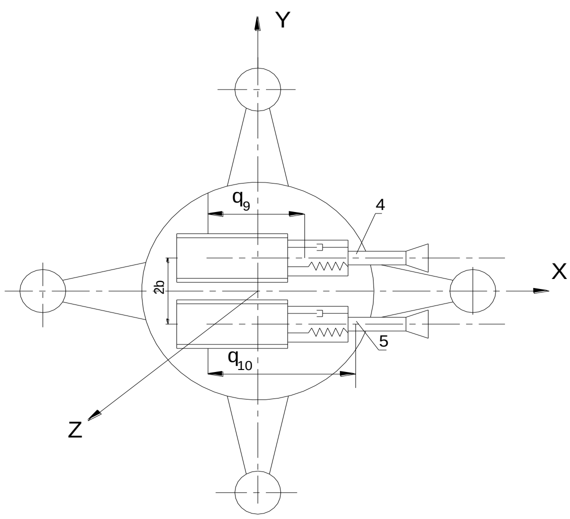

Fig. 3. The Multi-body system model of twin-barrel gun (overhead view)

As shown in Fig. 2, and Fig. 3, the weapon system is considered as a chain configuration, which contains six rigid bodies O_i (i= 0, 1, 2, 3, 4, 5). Where: The first body O_0 is an immovable platform, which contains no freedom. The second body O_1 is lower carriage, it contains four levelling jacks put on the elastic ground while firing and six degrees of freedom denoted by generalized coordinate from q_1 to q_6. The third body O_2 is the top carriage, it turns about the gyration axis to enable the tube traversing, which contains one degree of freedom denoted by generalized coordinate q_7. The fourth body O_3 is the cradle, which supports the tube and gives an elevating motion denoted by generalized coordinate q_8. The barrel recoils on the left of the cradle are the fifth body O_4, which possesses one freedom of slide denoted by generalized coordinate q_9. Finally, the barrel recoils on the right of the cradle are the sixth body O_5, which possesses one freedom of slide denoted by generalized coordinate q_{10}.

To investigate the system of rigid body dynamics, Cartesian coordinate systems have been established for each body and the whole system as shown in Fig. 2, where:

- Fixed coordinate system R_0={$O_0X_0Y_0Z_0$}

Where: O_0 is the center of the chassis frame that has a vertical projection on the background as shown in Fig. 2; the X_0-axis is oriented towards the barrel muzzle, it is the intersection of the plane of symmetry of the lower carriage; the Z_0-axis is parallel to the direction of the spin axis and oriented vertically upwards; Y_0-axis is perpendicular to the X_0-axis and Z_0-axis.

- **Coordinate system R_1={$O_1X_1Y_1Z_1$}**

Where O_1 is the center of the chassis frame of the lower carriage, X_1-axis is parallel and has the same direction with X_0-axis, Z_1-axis is parallel and has the same direction with Z_0-axis, and Y_1-axis is parallel and has the same direction with Y_0-axis.

- **Coordinate system R_2={$O_2X_2Y_2Z_2$}:** is the coordinate system of the body 2, in the current state of the model, R_2 coincides with R_1.

- **Coordinate system R_3={$O_3X_3Y_3Z_3$}:** is the coordinate system of the body 3. X_3-axis is parallel with the barrel axis and oriented towards the muzzle of the barrel. Y_3-axis, Z_3-axis are shown as in Fig. 2.

- **Coordinate system R_4={$O_4X_4Y_4Z_4$}:** is the coordinate system of the body 4. O_4 coincides with the center of gravity and located on the axis of the barrel. The X_4-axis, Y_4-axis, Z_4-axis are shown as in Fig. 2.

- **Coordinate system R_5={$O_5X_5Y_5Z_5$}:** is the coordinate system of the body 5. O_5 coincides with the center of gravity and located on the axis of the barrel. The X_5-axis, Y_5-axis, Z_5-axis are shown as in Fig. 2.

From the assumptions and kinetic constraints between objects, the system has 10 independently generalized coordinates: $[q_j]=[q_1, q_2, q_3, q_4, q_5, q_6, q_7, q_8, q_9, q_{10}]$, in which: q_1 - longitudinal displacement of body 1 along X_0-axis; q_2 - longitudinal displacement of body 1 about Y_0-axis; q_3 - longitudinal displacement of body 1 about Z_0-axis; q_4 - angular displacement of body 1 about X_0-axis; q_5 - angular dis-placement of body 1 about Y_0-axis; q_6 - angular displacement of body 1 about Z_0-axis; q_7 - angular displacement of body 2 about Z_2-axis; q_8 - angular displacement of body 3 about Y_3-axis; q_9 - longitudinal displacement of body 4 along X_4-axis; q_{10} - longitudinal displacement of body 5 along X_5-axis.

3.2. Kinetic energy of the weapon system

The kinetic energy of the weapon system is equal to the sum of the particular kinetic energy of the bodies, of which the system consists.

$$T = \sum_{k=1}^{5} T_k = T_1 + T_2 + T_3 + T_4 + T_5 . \qquad (1)$$

The kinetic energy of body k is determined by the following formula, [22]:

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

where R_k is the center of the mass vector of body k in the fixed coordinate system O_0; M_k is the 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 transferring 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.

3.3. Virtual Work - Generalized Force

The dynamical weapon system constructed from 5 rigid bodies has its configuration defined in terms of 10 degrees of freedom. Then, the virtual work for the weapon system is given by [22]:

Consider virtual work of generalized force F_k and torque M_k:

$$\delta WF_k = \sum_{k=1}^{5}\sum_{j=1}^{10} F_k^T \frac{\partial R_k}{\partial q_j} = \sum_{j=1}^{10}\left[\sum_{k=1}^{5} F_k^T \frac{\partial R_k}{\partial q_j}\right]\delta q_j . \qquad (3)$$

$$\delta WM_k = \sum_{k=1}^{5}\sum_{j=1}^{10} M_k^T \frac{\partial \theta_k}{\partial q_j} = \sum_{j=1}^{10}\left[\sum_{k=1}^{5} M_k^T \frac{\partial \theta_k}{\partial q_j}\right]\delta q_j . \quad (4)$$

If the link is considered the ideal link, ignore friction, and then the potential work of the link force (or the link reaction) is zero. So that, Q_j may be written:

$$Q_j = \sum_{k=1}^{5} F_k^T \frac{\partial R_k}{\partial q_j} . \quad (5)$$

$$Q_j = \sum_{k=1}^{5} M_k^T \frac{\partial \theta_k}{\partial q_j} . \quad (6)$$

where F_k and M_k are forces and moments acting on the object k-th respectively. These include: the gravity of the bodies (P_k), the propellant gases pressure force (P_{lg}), the force of elastic ground (P_{nen}), the deformation moment (M_{cq}, M_{ck}), the recoil braking force (R_{hl}), and total drag force while counter-recoil (R). In which, the definition and analysis of the forces: the propellant gases pressure force, the recoil braking force, and total drag force while counter-recoil is described in detail in [23,24]. This paper will analyze the remaining forces.

- **Gravity of the bodies (P_k)**

The force of gravity in body k-th is pointed at the center, is perpendicular to the horizontal plane OXY and the direction is vertically downwards.

$$P_k = m_k \cdot g . \quad (7)$$

where m_k - the mass of k-th solid object, g - acceleration of gravity.

- **The force of elastic ground (P_{nen})**

The force of elastic ground acts on the system at the location on 4 levelling jacks. In the fixed coordinate system:

$$P_{\text{nenj}} = (k_j \cdot \Delta r_j + c_j \cdot \dot{r}_j) . \quad (8)$$

where Δr_j is the initial displacement vector at position on leveling jacks j-th and $\dot{r}_j$ is the velocity of points which put on leveling jacks in a fixed coordinate system; k_j and c_j are the drag coefficient matrix of rigidity and viscosity of the background respectively.

In order to determine k_j and c_j by using the test data in [21], soil samples are used for testing corresponding to soil samples when firing guns. The kinetic results of the elastic ground are measured by Tritech 100 machine, manufactured by Controls-Wykeham France, Fig. 4.

- **Deformation moment (M_{cq}, M_{ck})**

Deformation moment acting on elevating and traversing mechanisms is determined as follows:

$$\begin{aligned} M_{cq} &= c_{eq} \cdot q_7(\mathrm{t}) \\ M_{ck} &= c_{ek} \cdot q_8(\mathrm{t}) \end{aligned} . \quad (9)$$

in which c_{eq}, c_{ek} are stiffness of traversing and elevating mechanisms, respectively. Their values can be found in [21].

Fig. 4. Tritech 100 machine

3.4. Establishing the system of differential equations for mechanical system

After calculating the total kinetic energy of the whole mechanical system T and generalizing force Q_j, Lagrange equation (10) is used to establish differential equations for the dynamic system [22]. Equations conclude in 10 differential equations making the description of the movements of 5 objects of the mechanical system. We apply the Lagrange equation (10) for twin-barrel gun while firing.

$$\frac{d}{dt}\left[\frac{\partial T}{\partial \dot{q}}\right] - \left[\frac{\partial T}{\partial q}\right] = Q \qquad (j = 1 \div 10) . \quad (10)$$

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.

4. RESULTS AND DISCUSSION

4.1. Problem solution

To solve equations (10), first we need to determine input parameters of the system:

parameters of internal ballistics, parameters of the structure, parameter of the boundary link at the locations of 4 levelling jacks, circulation diagram, and dynamical link characteristics of the automatic firing system. Parameters of dimension and mass are determined by measuring directly on the gun or were obtained from the technical specification when direct measurements were not possible. Parameters such as the moment of inertia, the centre of mass coordinates are determined by Solidworks software.

The above mathematical model describing oscillation gun when firing is validated by the 37mm twin anti-aircraft gun. Input parameters of the system are determined in [21,23], and the motion equations system (10) has been solved by numerical integration method. Due to the very large number of inputs, only the most important parameters are mentioned in Table 1 and 2.

Table 1. Mass and Moment of inertia of the objects

Body	Mass (kg)	J_x (kg·m²)	J_y (kg·m²)	J_z (kg·m²)
Lower carriage	451.22	2818.2	13479.9	15784.8
Top carriage	69.94	267.9	258.1	310.8
Cradle	40.75	447.7	435.6	106.4
Left barrel	25.2	622	525.8	102.4
Right barrel	25.2	622	525.8	102.4

Table 2. The parameters of elasticity and viscous resistance

Body	Symbol	Value
Coefficient elastic of the background in the x-direction	k_{tx}	(250 ÷ 350) N/m
Coefficient elastic of the background in the y-direction	k_{ty}	(250 ÷ 350) N/m
Coefficient elastic of the background in the z-direction	k_{tz}	(450 ÷ 520) N/m
Drag coefficient viscous of the background in the x-direction	c_{tx}	(1 ÷ 1.5) N·s/m
Drag coefficient viscous of the background in the y-direction	c_{ty}	(1 ÷ 1.5) N·s/m
Drag coefficient viscous of the background in the z-direction	c_{tz}	(2 ÷ 3) N·s/m
Stiffness of elevating mechanisms	c_{ek}	$1.03\cdot10^4$ N·m/rad
Stiffness of traversing mechanisms	c_{eq}	$2.8\cdot10^3$ N·m/rad

Solve the motion equations system (10) in the case of two barrels working simultaneously, the same forces acting on the two barrels, and the result of the gun's oscillation when firing 5 shots as from Fig. 5 to Fig. 8.

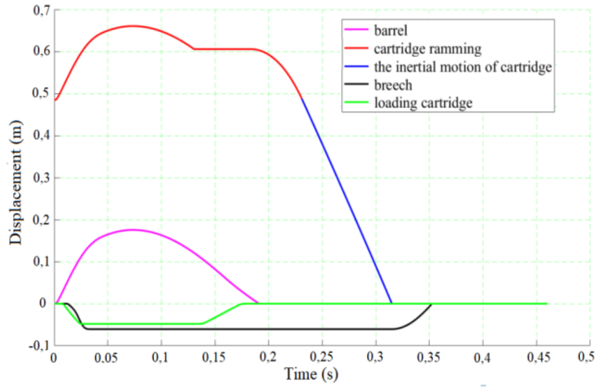

Fig. 5. The cycle of operation on automatic firing system 37mm [16]

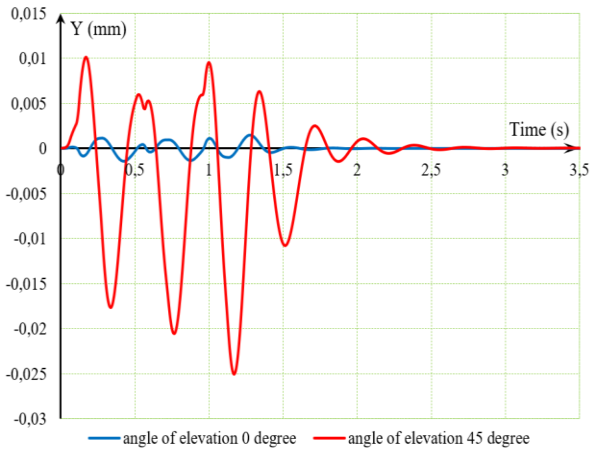

Fig. 6. Vibration curve of 37mm gun along Y-axis

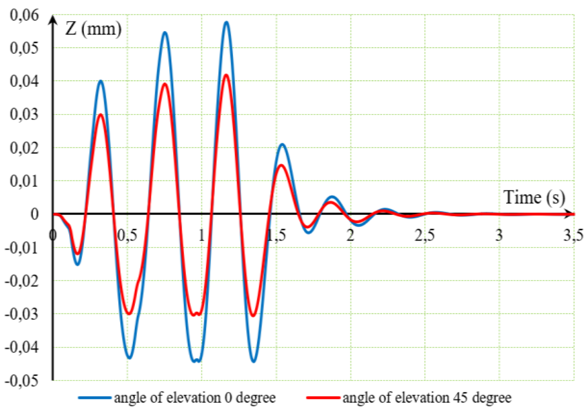

Fig. 7. Vibration curve of 37mm gun along Z-axis

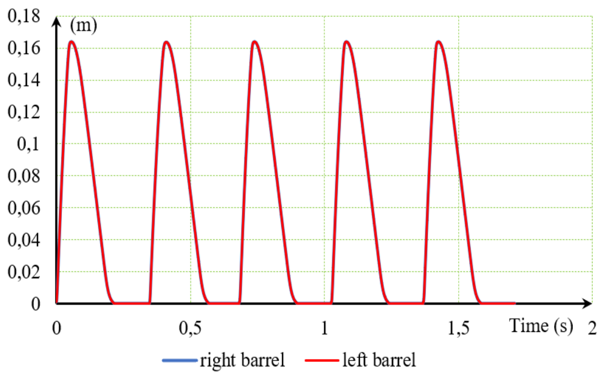

Fig. 8. Movement laws of the barrel

One of the parameters used as a basis for evaluating the indicators to ensure the accuracy, ability to work safely and reliably of the gun is the oscillation of the muzzle of the barrel when firing at different firing angles in the vertical plane and horizontal plane [3,4,6,25]. Another way, to ensure safety during testing, the gun is fired at elevating rotation angle is zero. Due to that reason, this paper selects the oscillation of the muzzle in the vertical plane and horizontal plane when firing at elevating rotation angle of zero to compare and validate the established model with measurement results by experiment.

4.2. Assessing the reliability of the established model

To assess the reliability of the established model, the authors conducted an experimental measurement on twin 37mm anti-aircraft guns, then the calculated results were compared to the experimental results. To ensure the validity of the model, the authors created a phase difference between the left barrel and right barrel (the left and the right of automatic firing doesn't operate simultaneously, the forces exerted on two barrels are different) by keeping the amount of oil inside the left of automatic firing according to the design, proceeding to oil the right of automatic firing by an amount equal to 0.02 liters. At this time, the recoil resistance acting on the two automatic firings is completely different, Fig. 9. The blue curve shows the recoil resistance acting on the left barrel, the black curve shows the recoil resistance acting on the right barrel.

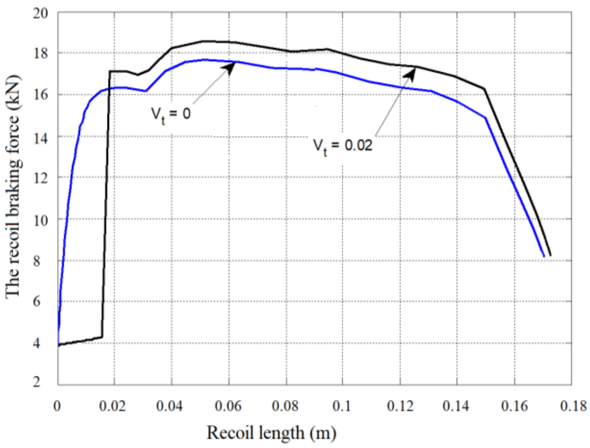

Fig. 9. Relationship between R and X of 37mm gun

During the experimental part of the research, we have used the contactless measurement techniques of the weapon barrel displacement, two high-speed cameras, in positions 2 and 3 in Fig. 10.

Two high-speed cameras Fast-cam SA1.1 were used as Fig. 10, model 675K - C1 with the maximum frame rate 675000 (frames per second), [26]. The used frequency of imaging 5400 (frames per second) made it possible to obtain the record with the resolution pixels. The first camera (No. 2) is to record the horizontal displacement, Fig. 11. The other one (No. 3) is located on the site to record the barrel vertical displacement, Fig. 12. The experiment was performed under the temperature of 30°C and humidity of 61%.

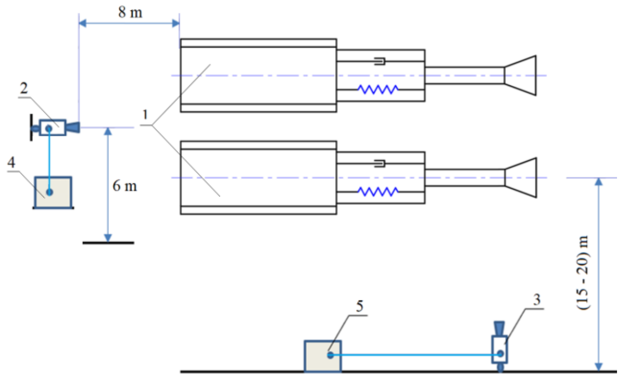

Fig. 10. Schematic of the experimental setup
1. The object (37mm twin anti-aircraft gun); 2, 3. High-speed camera; 4,5. Computer

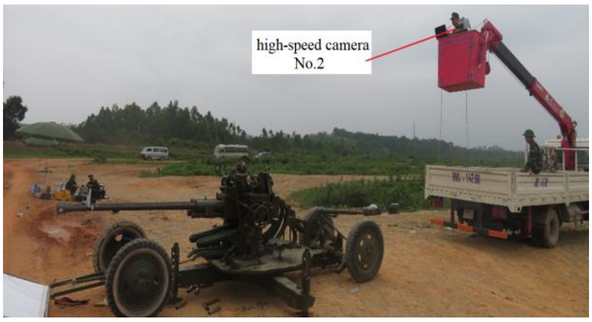

Fig. 11. Position of camera SA1.1 measures horizontal displacement

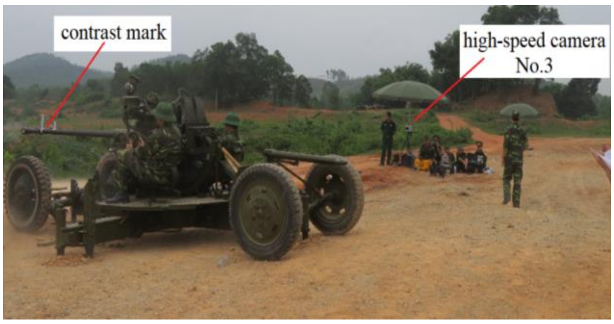

Fig. 12. Position of camera SA1.1 measures vertical displacement [16]

The measured data were processed using DASYLab motion analyzing system. This result was compared with the theoretical model by selecting the survey points in muzzle which coincided with the measurement points while firing. The firing method in experiment coincides with the theoretical calculations: the elevation and traverse angle of gun on 3 shots is 0 degree. The deviation between calculation results and experimental results are shown in Fig. 13, and Fig. 14.

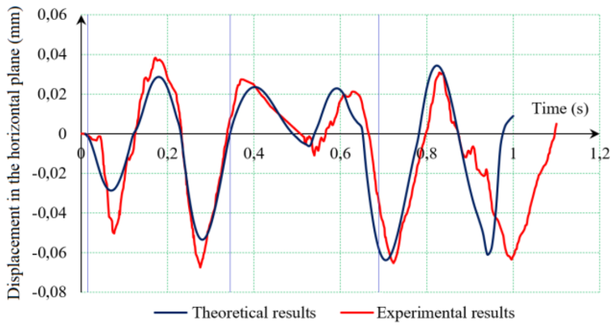

Fig. 13. Firing vibration curves of muzzle on displacement in the horizontal plane

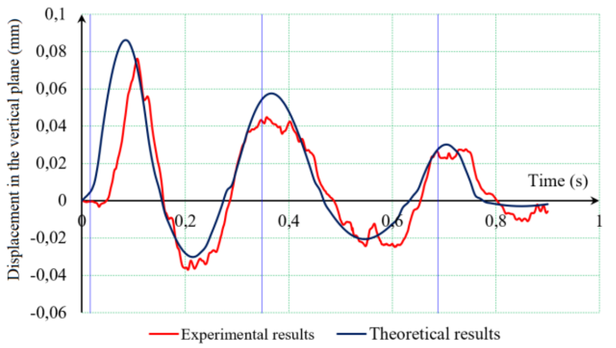

Fig. 14. Firing vibration curves of muzzle on displacement in the vertical plane

4.3. Discussions

The comparisons show a very good correlation between the results of the calculation and experimental results. The amplitude of vibration is calculated according to the model and the experimental results are relatively similar. The maximum amplitude deviation on the horizontal plane does not exceed 8.1% (Fig. 13), while in the vertical plane does not exceed 6.4% (Fig. 14). The reason for the discrepancy is due to the theoretical calculation model which has used several assumptions to simplify the calculation process and while firing, the jacks have a displacement.

From the analysis, results show that the mathematical model is reasonably representative of real-world phenomena. This model can be used to survey, evaluate the structural parameters of the guns, to approximate firing accuracy, as well as to evaluate the quality of the guns after repairs and improvements.

5. CONCLUSION

The multi-body model of the gun system was built on the theory of the machine dynamics. The calculated results are close to the experimental ones. The system vibration amplitude was estimated, which corresponded well with the experimental results. Through the simulation analysis, the factors dominating the firing accuracy were determined. This means that guns firing well on elastic ground may fire better on the land with low mechanical structure. The multi-body modeling method adopted in this paper also can be applied to analyze other weapons, such as twin-barrel guns, Gatling guns, rocket launchers, etc. The next work for authors is to research the dynamics behaviour of guns considering barrel's flexibility, and the influence of projectile-barrel coupling on muzzle vibration excited by accelerating projectile.

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