Investigating the effect of the gap between the throttling ring and the control rod in the hydraulic braking mechanism on the stability of the cannon during firing

Lai Thanh Tuan[1], Bui Xuan Tung[2], Do Ngoc Tien[2*]

[1]Faculty of Weapons, Le Quy Don Technical University, 236 Hoang Quoc Viet, Nghia Do, Hanoi, Viet Nam;

[2]University of Transport Technology, 54 Trieu Khuc, Thanh Liet, Hanoi, Viet Nam.

[*]Corresponding author: tiendn@utt.edu.vn

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ABSTRACT

In this paper, a mathematical model is developed to describe the dynamics of the recoiling part of the cannon during both the recoil and counter-recoil (push-up) phases. Based on the analysis of the forces acting on the cannon during these phases, expressions are derived to evaluate the stability conditions - specifically, preventing the cannon from overturning upward during recoil and downward during counter-recoil. The influence of the gap between the throttling ring and the control rod of the recoil braking mechanism on the stability of the 85mm D44 cannon is investigated. The results show that a change in the gap to 1 mm does not cause instability (either upward or downward overturning) but does significantly affect the recoil velocity, recoil distance, and final impact speed during the counter-recoil process. These changes can potentially reduce the durability of the components or even cause structural failure of the cannon mechanisms. Therefore, it is essential to consider the tolerances of these parts during technical inspections, maintenance, and repair. This research can contribute to improving the reliability and maintenance effectiveness of field artillery systems under actual combat conditions.

Keywords: Gap between the throttling ring and the control rod; Stability condition; Recoil braking machine; Cannon.

1. INTRODUCTION

Nowadays, all types of cannons are elastic-supported, using a hydraulic recoil braking mechanism. The recoil braking mechanism of modern artillery guns allows for a significantly reduction in the force acting on the support, thereby ensuring good stability for the entire cannon when firing as well as increasing the rate of fire. In addition, it also ensures the ability to minimize the gun support as well as the entire gun in general while still maintaining the durability and life of the parts. From the energy perspective, the recoil braking mechanism converts the kinetic energy of the recoil mass received from the shot into heat energy (mainly in the recoil braking machine) and potential energy (in the recuperator), thereby causing the recoil mass to stop at a certain recoil distance and then returning the recoil mass to its original position before firing.

The recoil and thrust braking machine in modern artillery guns usually uses the hydraulic recoil principle. In the hydraulic braking principle, the kinetic energy of the recoiling mass is converted into heat energy and is dissipated when radiating heat to the outside environment through the pipe wall. The recuperator can use springs or compressed air as the working element, in which the kinetic energy of the recoiling mass is converted into the potential energy of the working element and then becomes the kinetic energy of the thruster.

During the working process, the hydraulic recoil braking mechanism is often affected by some basic parameters. When calculating the design, these parameters are often brought to the standard state and considered unchanged. However, when studying in depth, the design problem of the hydraulic recoil mechanism, to have a more accurate and reliable result, we must evaluate the influence of these parameters in practice.

The combat properties of artillery, such as firing accuracy, rate of fire and durability of artillery structures, to a large extent depend on the stability of the artillery when firing. The stability of the artillery when firing includes immobility (no straight movement) and stability (no angular movement). Stability is the property of the components of a gun to maintain the position occupied when subjected to forces that tend to cause its angular displacement. This means the ability of the gun to maintain the initial firing angle when fired within certain permissible limits under natural firing conditions.

In the paper [1], a typical naval gun's recoil mechanism with a control rod is selected as the research object, and a two-dimensional model of the flow field in the recoil mechanism is established. The finite element calculation software ANSYS Fluent was used to numerically simulate the internal flow field model before and after considering the cavitation effect, and the physical parameters such as the pressure, flow velocity and composition change of the internal flow field in the recoil mechanism were determined. The simulation results before and after considering the cavitation effect were compared. The recoil resistance test indirectly verifies the correctness of the simulation results. Through experimental observation of the internal parts of the recoil mechanism, the hazard of the internal cavitation effect of the hydraulic components was verified. The paper [2] presents combining the liquid cavitation theory with ultrasonic test and pressure test of a non-working chamber of a recoil mechanism, the recoil oil cavitation and its influence on the actual performance of a gun recoil mechanism were investigated.

In the work [3], by means of fluent software, a two-phase flow model based on liquid-solid coupling is established, and the motion trajectory and erosion velocity of solid particles are calculated by numerical simulation, and the influence of different parameters on particle erosion velocity is studied, which provides reference data for the simulation of controlled ring erosion and the study of wear law. In the paper [4], firstly, the recoil and counter-recoil dynamics model of the artillery recoil system is established, and then, the fifth-order Runge-Kutta numerical integration method is employed to calculate the displacement, velocity and acceleration of the recoil system during the recoil and counter-recoil movement. Finally, these results are compared with the experimental results.

Huang and Liu, in their research work [5], explicitly examined the effect of structural clearances within hydraulic recoil devices. They demonstrated that the gap between the throttling ring and the control rod directly influences fluid resistance and energy dissipation, which are critical to ensuring smooth recoil and restoring barrel alignment. In the paper [6], a mathematical model is established to determine the working parameters of a hydraulic recoil mechanism, considering the characteristic parameters of the oil. However, the parameters considered in this study are oil compression and oil temperature. Paper [7] presents a survey of the influence of the clearance between the piston and the recoil braking cylinder on the operation of the hydraulic recoil braking mechanism.

In this paper, based on the hydraulic recoil brake model and the study of the stability condition of the cannon when firing, the author builds a mathematical model for the problem. From there, the expression of the recoil force resistance of the recoil braking mechanism when pushing back and the total recuperating force when pushing up of the 85mm D44 cannon is determined. Using the system of differential equations describing the motion of the recoiling part when pushing back and when pushing up, the influence of the gap between the throttling ring and the control rod on the stability of the cannon is investigated.

2. PROBLEM

2.1. Research methods

The article provides a comprehensive and detailed analysis of the operating parameters of the hydraulic reverse brake machine on the artillery. A mathematical model describing the operation of the artillery body was built. Based on the analysis of the forces acting on the receding block when firing, the stability conditions of the cannon when the recoiling mass moves backward and when pushed up are established. In the mathematical model, the gap between the throttling ring and the control rod is considered. The results of the study aim to evaluate the stability of the cannon when firing, when the recoiling mass is pushed back, and when the recoiling mass is pushed up. Modern computer tools and software are used to accurately simulate and represent a problem model that closely resembles reality. Numerical methods are used to provide simulation results.

2.2. Formulations

2.2.1. Stability condition of the cannon when the recoiling part is pushed back

To simplify the investigation, a general diagram is used for the types of artillery and the following assumptions are made:

- The recoiling part and the cannon support are absolutely rigid objects; the recoiling part is connected to the support by elastic connections.

- The cannon is placed on a horizontal hard base (orientation angle $\psi = 0°$) and the shot is fired with a range angle $\varphi > 0°$.

- The cannon is symmetrical to the firing plane; all forces acting on the cannon are in the cannon's symmetry plane, not taking into account the loads acting on the barrel from the bullet's muzzle.

- The cannon is in a balanced state when fired, meaning there is no displacement relative to the firing platform.

The diagram of the forces acting on the cannon when the recoiling part moves backward and pushes up is shown in figures 1 and 2.

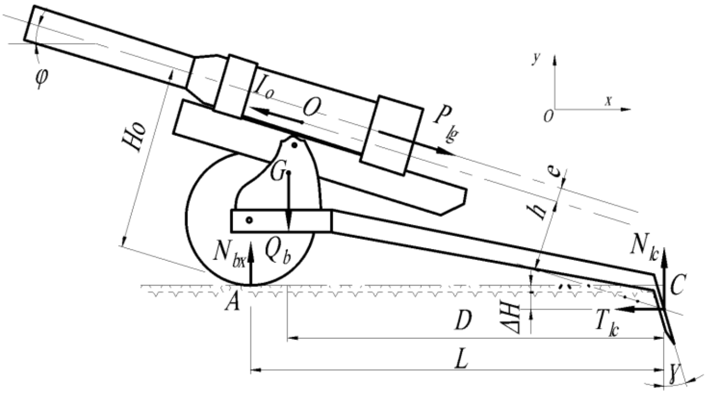

Figure 1. *Diagram of forces acting on the cannon when the recoiling part moves backward.*

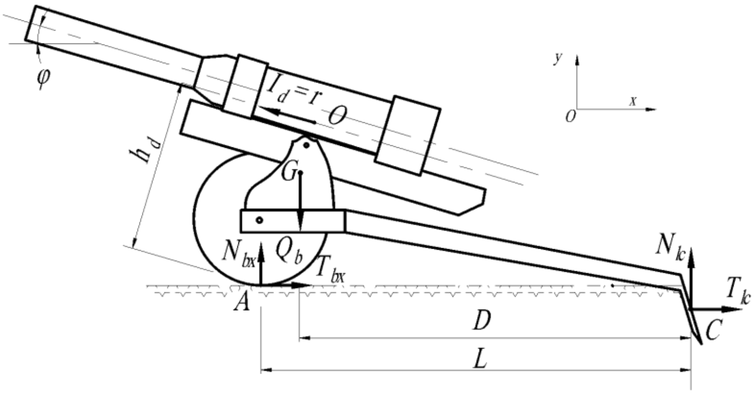

Figure 2. *Diagram of forces acting on the cannon when pushed up.*

In figure 1, P_{lg} - The resultant gas force appears in the barrel when firing during the period of action of the gas; Q_b - Combat weight of cannon; N_{bx}- Reaction force of the foundation on the wheel (each wheel bears $1/2N_{bx}$); N_{lc} and T_{lc} - Vertical and horizontal reactions of the foundation on the plow blade (each plow blade bears $1/2N_{lc}$ and $1/2T_{lc}$); I_0 - Inertial force of the recoiling mass; L - Distance from the center of gravity of the plow blade C (center of resistance) to the fulcrum of the wheel; D - Distance from the center of gravity of the plow blade C to the center of gravity of the cannon G; h - Distance from the center of gravity of the plow blade C to the orbit of the center of gravity of the recoiling part O; e - Distance between the orbit of the center of gravity of the recoiling mass O and the axis of the barrel, often called the dynamic moment arm; ΔH- Distance from the center of the plow blade C to the shooting base.

The equation of motion of the recoiling part when pushed back is written in the following form [8]:

$$M_o J_o = P_{\lg} - R = I \tag{1}$$

where

$$R = \Pi + \Phi_L + R_f - Q_o sin\varphi \tag{2}$$

is the recoil force resistance acting on the recoiling part when pushing backward; Π - Force of recuperator; Φ_L - Hydraulic resistance of the recoil braking mechanism; R_f - friction resistance of the cannon support and in the sealing parts of the recoil braking mechanism.

Applying the Dalambe principle, if we apply external forces and inertial forces to the system under consideration, the system will be in a state of equilibrium. We get the following system of equations:

$$\begin{cases} \sum F_X = R\cos\varphi - T_{lc} = 0; \ \sum F_Y = -R\sin\varphi - Q_b + N_{bx} + N_{lc} = 0 \\ \sum M_C = P_{\lg} e + Rh - Q_b D + N_{bx} L = 0 \end{cases} \tag{3}$$

From the system of equations (3), we find:

$$T_{lc} = R\ cos\varphi;\ N_{bx} = \frac{Q_o D - Rh - P_{\lg} e}{L};\ N_{lc} = Q_b + Rsin\varphi - N_{bx} \tag{4}$$

To ensure stability, when firing the artillery wheel must not leave the base on which the artillery is placed, that is:

$$Q_0 D \geq Rh + P_{lg} e \tag{5}$$

2.2.2. Stability condition of the cannon when the recoiling part is pushed up

The diagram of the forces acting on the cannon when pushed up is shown in figure 2.

Differential equation of motion of the recoiling part when pushed up [8]:

$$M_0 \frac{du}{dt} = r = I_d \tag{6}$$

Here: u - Push up speed; r - Resultant force acting on the recoiling part when pushing up.

To establish the stability condition of the cannon when pushed up, we use the following force balance equation system:

$$\begin{cases} \sum F_X = T_{lc} + T_{bx} - rcos\varphi = 0; \quad \sum F_Y = rsin\varphi - Q_b + N_{lc} + N_{bx} = 0 \\ \sum M_A = Q_b(L-D) - N_{lc} L - r h_d = 0 \end{cases} \tag{7}$$

To prevent the cannon from collapsing, the plow must not be lifted off the ground. Then, we get the condition for the cannon not to collapse when pushed up as follows:

$$Q_b(L - D) \ge rh_d \tag{8}$$

2.2.3. Determine the recoil braking force of the cannon when pushed back

To establish an expression to calculate the hydraulic braking force Φ_L for a hydraulic recoil braking machine with a control rod, we use the calculation diagram as shown in figure 3.

In figure 3, we use the symbols: D - Outer diameter of piston; d - Outer diameter of recoil piston rod; d_1 - Inner diameter of recoil piston rod; δ - Diameter of control rod (varies with length); d_V - Diameter of throttling ring; X - Displacement of the recoil part; V - Velocity of motion of the recoil part; W_1 - The speed of oil flow from chamber I into the piston inner chamber; W_2 - The velocity of the oil flow through the flow hole between the throttling ring and the control rod a_x (main stream); W_3 - The velocity of oil flow through gap Ω_1 into chamber III (sub-flow); p_1 - Oil pressure in chamber I and chamber inside piston; p_2 - Oil pressure in chamber II; p_3 - Oil pressure in chamber III.

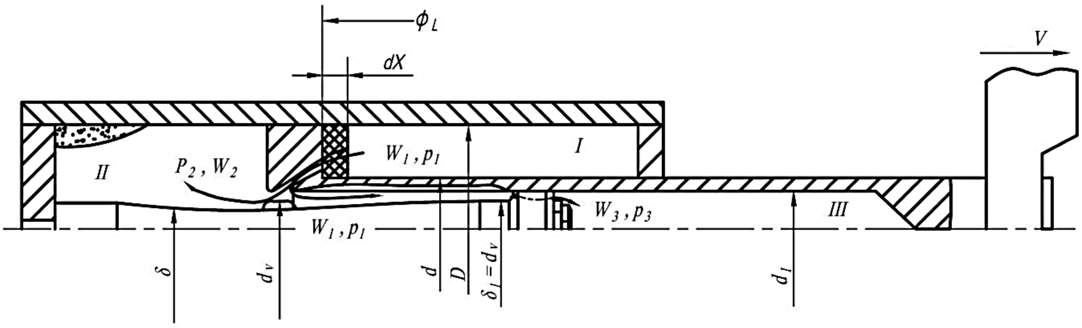

Figure 3. *Schematic diagram of a hydraulic braking mechanism with a control rod.*

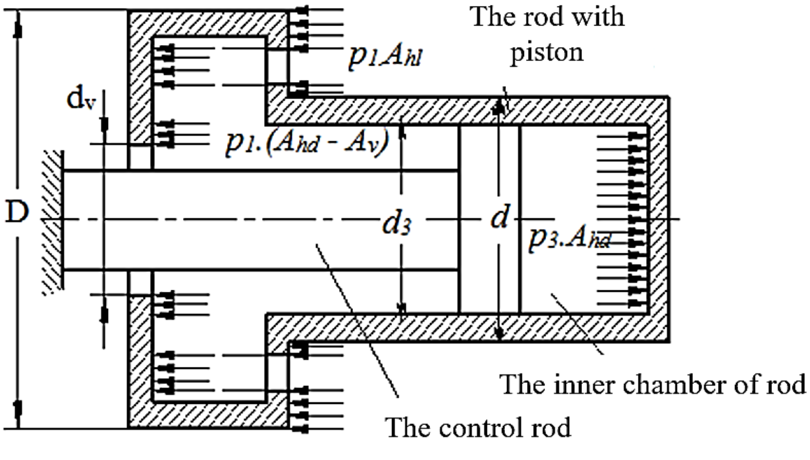

Figure 4. *Diagram to determine hydraulic braking force Φ_L.*

Based on the structural diagram (figure 4), we can write the general formula of hydraulic braking force as follows:

$$\Phi_L = p_1\left(A_{hl} - A_V\right) + \left(p_1 - p_3\right)A_{hd} \tag{9}$$

Where: A_{hl} - Working surface area of the piston when the block is pushed back; A_V - Area of the throttling ring; A_{hd} - Working surface area of the chamber of the recoil piston rod.

Using Bernoulli's equation for oil flow from chamber I to chamber II, we get:

$$p_1 = \frac{K\rho}{2}\left(\frac{A_{hl} - A_\delta}{a_x}\right)^2 V^2 \tag{10}$$

Here: K - Main stream resistance coefficient; A_δ - Cross-sectional area of the control rod at the throttling ring position; a_x - Clearance area between the control rod and the throttling ring.

Using Bernoulli's equation for the auxiliary oil flow from chamber I to chamber III in applied form, when considering the pressure and flow rate of oil flowing through the holes on the one-way valve body at the end of the control rod without loss, we get:

$$p_1 - p_3 = \frac{K_3\rho}{2}\frac{A_{hd}^2}{\Omega_1^2} V^2 \tag{11}$$

Here: K_3 - Secondary resistance coefficient; Ω_1 - Clearance area between the end of the control rod and the inner chamber of the recoil piston rod.

Substitute p_1 according to (10) and (p_1–p_3) according to (11) into formula (9) to get:

$$\Phi_L = \frac{\rho}{2}\left[K\left(\frac{A_{hl} - A_\delta}{a_x}\right)^2 \left(A_{hl} - A_V\right) + K_3\frac{A_{hd}^3}{\Omega_1^2}\right] V^2 \tag{12}$$

Formula (11) shows that the hydraulic back braking force is proportional to the square of the back speed and depends on the structural parameters of the back braking machine, the flow resistance coefficient and the density of the working oil.

For convenience of use, formula (12) is transformed into the following form:

$$\Phi_L = \frac{k_1\rho}{2}\left[\left(\frac{A_{tg}}{a} + 1\right)^2 A_{tg} + \frac{k_3}{k_1}\frac{A_{hd}^3}{\Omega^2}\right] V^2 \tag{13}$$

where $A_1 - A_V = A_{tg}$ - Compact area of piston.

2.2.4. Determine the condition for the stability of the cannon when pushing back

From formula (2), we get the expression of the recoil force resistance acting on the recoiling part in the following form:

$$R = \frac{k\gamma}{2g}\left[\left(\frac{A_1 - A_v}{a_x} + 1\right)^2 \left(A_1 - A_v\right) + \frac{k_3}{k}\frac{A_d^3}{\Omega^2}\right] v^2 + \Pi_0\left(\frac{S_o}{S_0 - X}\right)^k + R_f - Q_o sin\varphi \tag{14}$$

Using condition (5) and formula (13), we get the expression for the stability condition of the cannon when pushing back:

$$Q_0 D \geq \left[\frac{k\gamma}{2g}\left[\left(\frac{A_1 - A_v}{a_x} + 1\right)^2 \left(A_1 - A_v\right) + \frac{k_3}{k}\frac{A_d^3}{\Omega^2}\right] v^2 + \Pi_0\left(\frac{S_o}{S_0 - X}\right)^k + R_f - Q_o sin\varphi\right] h + P_{lg} e \tag{15}$$

Based on expression (15), we see that the stability of the cannon when pushing back depends on the cross-section of the throttling ring, the control rod and the gap between the throttling ring and the control rod. Thereby, we will find the law of dependence of the stability of the cannon when pushing back on dv, δ, ax.

2.2.5. Determine the condition for the stability of the cannon when pushing up

The total recuperating force is determined by the formula:

$$r = \Pi - R'_f - \Phi_d - Q_0 sin\varphi \tag{16}$$

Where:

$\Pi = \Pi_0 \left(\frac{H_0}{H_0 - X} \right)^k$ - The force of the mechanism pushes up pneumatically;

$R_f = Q_0 (f \cos\varphi + v)$ - Total friction force;

$G = M_0 g$ - Weight of the recoil part;

φ - Range angle;

Π_0 - The initial force of the mechanism pushes up;

H_0 - Initial volume conversion length of the push-up mechanism;

k - Adiabatic exponent;

v - Proportionality coefficient of the frictional force compared to the weight of the recoil part;

$\Phi_d = \Phi_{ld} + \Phi_{hd} + \Phi_V$ - Counter-recoil braking force, where: $\Phi_{ld} = \frac{C_{ld}}{a^2} U^2 = f_1(a) U^2$ - hydraulic braking force of the recoil braking machine when pushing up;

$\Phi_{hd} = \frac{C_{hd}}{a_{hd}^2} U^2 = f_2(a_{hd}) U^2$ - Hydraulic braking force of the counter-recoil brake;

$\Phi_V = f(a_V) U^2$ - Anti-recoil force.

From the stability condition (8) and the expression for calculating the total recuperating force (16), we get the stability condition of the cannon when pushing upward in the following form:

$$Q_{CĐ}\left(L - D_0\right) + Q_0(\lambda - \xi) \geq \left[\Pi' - \frac{k\gamma\left(A_0 - A_v\right)^3 / 2g}{a^2} U^2 - \frac{k_3' \gamma A^3_{hd} / 2g}{a^2_{hd}} U \right] h_d \tag{17}$$

3. RESULTS AND DISCUSSION

3.1. Input data

To accurately assess the reliability of the theoretical basis established in item 3, the hydraulic recoil mechanism on the 85mm anti-tank artillery was selected as a model to evaluate the influence of the gap between the throttling ring and the control rod of the hydraulic braking mechanism on the stability of the cannon when firing. The main components of the hydraulic recoil mechanism are shown in figure 5.

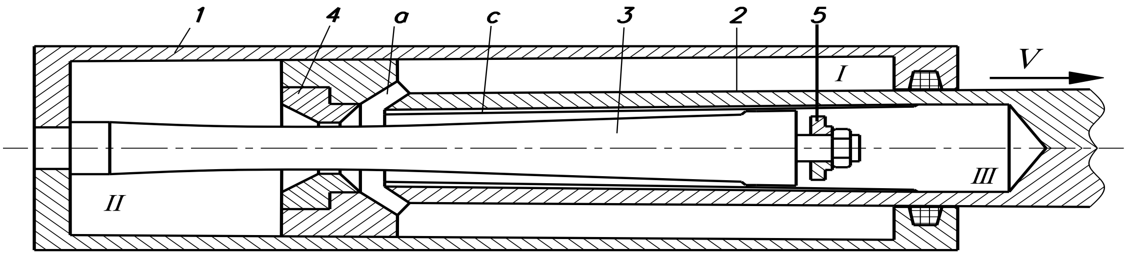

Figure 5. Schematic diagram of the 85mm D44 artillery hydraulic brake.
1 - Recoil cylinder; 2 - Recoil piston; 3 - Control rod; 4 - Piston; 5 - Valve.

The launch parameters of the 85mm D44 gun are as follows [6, 7]:

Table 1. *The launch parameters of the 85mm D44.*

№	Parameter	Symbol	Value	Unit
1	Combustion chamber volume	W_0	3,94	dm^3
2	Cross-sectional area of the barrel	S	0,582	dm^2
3	Distance movement of the bullet	l_d	35,92	dm
4	Warhead weight	q	9,54	kG
5	Bullet ejection pressure	p_0	3.10^4	kG/dm^2
6	Propellant weight	ω	2,48	kG
7	Propellant force	f	98.10^4	$kG.dm/kG$
8	Additive quantity	α	1	dm^3/kG
9	Propellant density	δ	1,6	kG/dm^3
10	Pulse pressure of the gas	I_k	1270	$kG.s/dm^3$
11	Power factor	K	1,06	
12	Propellant shape characteristics	χ	1,06	
		$\chi\lambda$	-0,06	
		θ	0,2	

Basic parameters of the hydraulic recoil mechanism are as follows:

Table 2. *Basic parameters of the hydraulic recoil mechanism.*

№	Parameter	Symbol	Value	Unit
1	Diameter of the throttling ring	d_V	38	mm
2	Inner diameter of the recoil cylinder	D	102	mm
3	Inside diameter of the recoil piston rod	d_1	38	mm
4	Outer diameter of the recoil piston rod	d	48	mm
5	Back length	λ	580 ÷ 660	mm
6	Limited back length	λ_{lm}	675	mm
7	Maximum oil pressure	$p_{\max}$	118	kG/cm^2
8	Maximum recoil braking force	$R_{\max}$	7474	kG
9	Maximum hydraulic braking force	$\Phi_{l\max}$	6075	kG
10	Maximum recoil velocity	$W_{\max}$	10,46	m/s

3.2. Investigation of the effect of the gap between the throttling ring and the control rod on the stability of the cannon when pushing back

Figure 6 shows the recoil force resistance, and figure 7 shows the cannon stability when changing the gap between the throttling ring and control rod in the following cases:

1 - Overturning up moment when the parts are at their original size;

2 - Overturning up moment when the throttling ring is worn by 0,5 mm;

3 - Overturning up moment when the throttling ring and control rod are both worn by 0,5 mm;

4 - Stabilizing moment of the cannon when pushing back.

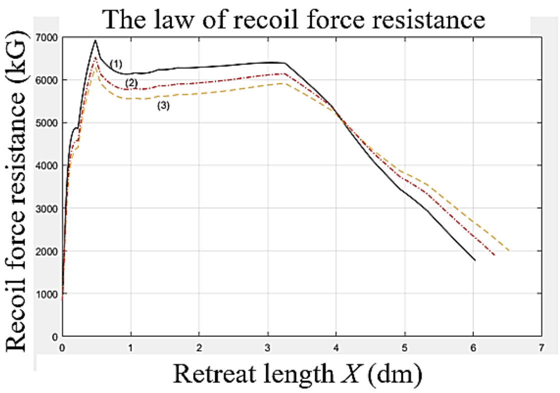

Figure 6. *Graph of recoil force resistance when changing the gap between the throttling ring and control rod.*

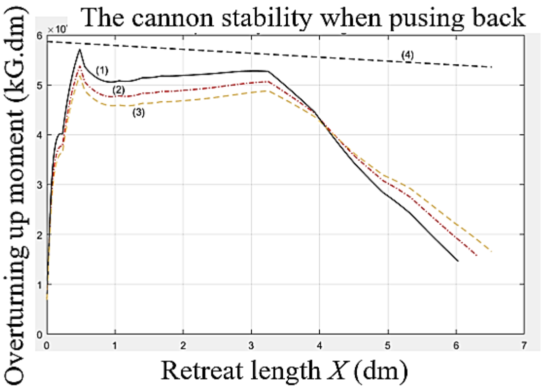

Figure 7. *Graph of cannon stability when changing the gap between the throttling ring and control rod.*

Table 3 shows the change in values according to the increase in the gap between the throttle ring and the control rod Δd (mm).

Table 3. *The change of Rmax, Vmax and retreat length.*

Change in value (mm)	$R_{\max}$ (kG)	$V_{\max}$ (m/s)	**Retreat length** (mm)
$\Delta d = 0$	6926,8	10,351	603,14
$\Delta d = 0{,}5$	6520,9	10,377	630,94
$\Delta d = 1{,}0$	6286,3	10,394	651,93

From the results, we see that when changing the gap between the throttling ring and the control rod, the recoil force resistance R and the overturning moment change. When increasing the gap between the throttling ring and the control rod, the value Rmax decreases, increasing the stability of the cannon, but also increasing the maximum recoil velocity and recoil length.

This means that during the recoil process, we do not have to care about the influence of the gap of the throttling ring and the control rod on stability, but only need to care about their influence on the recoil length to see if it affects the quality of the shooting process or not.

3.3. Investigation of the effect of the gap between the throttling ring and the control rod on the stability of the cannon when pushing up

Figure 8 shows a graph of the overturning moment of the cannon and the cannon stability when changing the gap between the throttling ring and the control rod when pushing up in the following cases:

1 - The overturning down moment when the parts are at their original size;

2 - Overturning down moment when the throttling ring is worn by 0,5 mm;

3 - Overturning down moment when the throttling ring and control rod are both worn by 0,5 mm;

4 - Stabilizing moment of the cannon when pushing up.

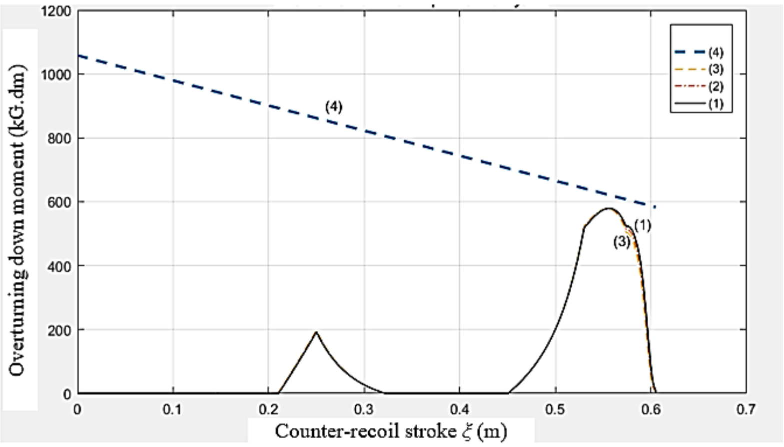

Figure 8. *Graph of overturning moment of the cannon and the cannon's stability.*

From the graph, the gap between the throttling ring and the control rod changes (wears out during operation), the overturning down also changes in the direction of decreasing by a small amount. Thus, when the gap between the throttling ring and the control rod increases, the stability of the cannon increases. However, due to the decrease in Φld, the counter-recoil velocity of the recoiling mass will increase, it is necessary to pay attention to its influence on the operation of the mechanisms and the durability of the details during the firing process.

4. CONCLUSIONS

From the research results, we see that the parameters and structure of the recoil braking mechanism are important factors affecting the operation of the recoil braking machine and specifically the hydraulic braking force during the pushing back and pushing up of the cannon. In the surveyed cases, when the magnitude of the gap between the throttling ring and the control rod changes, although it does not lead to instability (overturning or collapsing) of the cannon, it significantly changes the velocity and distance of reversing or the final impact speed during the pushing-up process. This can completely lead to a reduction in the durability of the details or worse, the structural destruction of the mechanisms on the cannon. Therefore, we need to pay attention to the tolerances of these details during the technical inspection, maintenance and repair process to ensure the normal operation of the cannon.

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TÓM TẮT

Nghiên cứu ảnh hưởng của khe hở giữa vòng điều tiết và cán điều tiết trong máy hãm lùi thủy lực đến độ ổn định của pháo khi bắn

Trong bài báo này mô hình toán học được xây dựng để mô tả động lực học máy hãm lùi thủy lực của pháo trong cả hai giai đoạn lùi và đẩy lên. Dựa trên việc phân tích các lực tác động lên pháo trong các giai đoạn này, các biểu thức được rút ra để đánh giá các điều kiện ổn định - cụ thể là ngăn pháo bị lật lên khi lùi và bị gục trong quá trình đẩy lên. Ảnh hưởng của khe hở giữa vòng điều tiết và cán điều tiết của máy hãm lùi đối với độ ổn định của pháo 85mm Đ-44 được nghiên cứu. Kết quả cho thấy việc thay đổi khe hở 1 mm không gây mất ổn định (lật hoặc gục pháo) nhưng ảnh hưởng đáng kể đến vận tốc lùi, chiều dài lùi và tốc độ va chạm cuối cùng trong quá trình đẩy lên. Những thay đổi này có khả năng làm giảm độ bền của các bộ phận hoặc thậm chí gây ra hư hỏng kết cấu các cơ cấu của pháo. Do đó, việc xem xét dung sai của các bộ phận này trong quá trình kiểm tra kỹ thuật, bảo dưỡng và sửa chữa là rất cần thiết. Nghiên cứu này có thể góp phần nâng cao độ tin cậy và hiệu quả bảo dưỡng của các hệ thống pháo binh dã chiến trong điều kiện chiến đấu thực tế.

Từ khoá: Khe hở giữa vòng điều tiết và cán điều tiết; Điều kiện ổn định; Máy hãm lùi; Pháo.