UDC 623.4

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THE CONDITION OF THE VEHICLE'S STABILITY TO OVERTURNING ON A SURFACE WITH A LATERAL SLOPE WHEN FIRING FROM THE WEAPON

The issue of evaluating vehicle stability on a side-sloped surface during weapon firing has been considered. A mathematical expression for determining the condition of vehicle stability on a side-sloped surface while firing weapons has been improved. Unlike known expressions, it takes into account the impact of the recoil force of weapons and the overturning and stabilizing moments it generates. A stability coefficient and a relative stability coefficient are proposed, enabling the assessment of the stability margin against overturning of a combat vehicle during weapon firing, as well as decision-making regarding its operational feasibility under various conditions or the use of more powerful weapons with correspondingly greater recoil forces.

Keywords: *combat vehicle, resistance to overturning, recoil of weapons, state of vehicle stability, stability coefficient, overturning moment.*

Statement of the problem. The experience of military conflicts in recent decades shows the ever-increasing role of combat vehicles (CVs). In recent years, a significant number of combat vehicles for various purposes have been developed and adopted by the Ukrainian security forces: armoured personnel carriers; carriers of anti-tank weapons, anti-aircraft weapons, mortars; electronic intelligence and electronic warfare vehicles; medical evacuation vehicles, etc. One particular category of CVs worth noting is unmanned ground systems equipped with various firearms such as automatic rifles, light machine guns, general-purpose machine guns and heavy machine guns, automatic grenade launchers, and automatic cannons.

Unmanned vehicles, unlike traditional ones, usually have smaller weight and dimensions (Table 1) [1, 2, 3].

This positively impacts their stealth, combat survivability, and cost-effectiveness, overall enhancing the efficiency of such vehicles. However, the relatively small track width and wheelbase cause challenges with static and dynamic stability when overcoming obstacles. This is due to the unfavorable ratio of the geometric dimensions of obstacles to the dimensions of unmanned CVs, necessitating an increase in the relative wheel diameter and ground clearance. As a result, the relative position of the center of mass shifts upward, adversely affecting stability indicator's, particularly the lateral stability coefficient, which is defined as the ratio of the vehicle's track width to twice the height of its center of mass [4].

Another significant factor worsening the stability of unmanned CVs is the recoil force of firearms, which generates an overturning moment. Compared to traditional CVs, the recoil force has a greater impact on unmanned CVs with smaller mass and dimensional characteristics. This is due to the ratio of the overturning moment caused by the recoil force to the stabilizing moment, which is proportional to the vehicle's mass.

This ratio for traditional CVs, depending on the vehicle's mass and weapon type, ranges from approximately $2\cdot10^{-4}\ldots1.5\cdot10^{-5}$. For significantly lighter unmanned CVs, the ratio of the overturning moment caused by the recoil force to the stabilizing moment is substantially higher, ranging from 0.8 to 0.12. This has a negative impact on static stability during weapon use. The calculations of these ratios were conducted in accordance with [4]. The effective recoil force values for the 7.62-mm PKT machine gun, 12.7-mm NSVT machine gun, 14.5-mm KPVT machine gun, and 30-mm ZTM-2 cannon were determined based on [5, 6, 7].

Additionally, when performing tasks in rugged terrain or in areas covered with vegetation, the height of the firing line must exceed the vegetation height to ensure unobstructed movement of bullets (projectiles or grenades) through space. Raising the firing line, however, increases the overturning moment arm and the overall destabilizing moment.

Table 1 – Weight and Dimensional Characteristics of Selected Unmanned Modules (Platforms)

No.	Name	Length, mm	Width, mm	Height, mm	Mass, kg	Centre of mass height, mm
1	Unmanned robotic module "Scorpion"	1320	860	500	370	360
2	Unmanned logistics platform "Turan"	1600	1400	800	470	540
3	Robotic platform "Laska 2.0"	2270	1300	950	670	680
4	Unmanned robotic platform "Gnome"	600	570	380	50	270
5	Unmanned robotic six-wheeled platform "Gnome"	710	615	380	85	255
6	Ground robotic fire support platform "Gnome-VP"	1050	747	1057	88	400
7	Logistics and evacuation platform "Taira"	1200	800	500	120	340

Thus, the significant impact of firearm recoil on the stability of combat vehicles necessitates its consideration when modeling the process of stability loss under various operational conditions of CVs.

Analysis of recent research and publications. At present, the issue of vehicle stability has been extensively studied and covered in numerous literary sources. For instance, in [8], the evaluation indicators of vehicle stability are considered, including the conditions for maintaining lateral and longitudinal stability, the impact of operational factors on stability, and vehicle stability testing.

The scientific article [9] presents methods for evaluating vehicle stability in various driving modes, addressing the rationale behind stability and controllability, and the impact of driving modes on stability. In publication [10], significant attention is devoted to the theory of vehicle operational properties, focusing on evaluation indicators of vehicle stability and conditions for maintaining it. In [11], the movement of vehicles and tractors on lateral slopes is analyzed, including questions of their controllability and stability. The monograph [12] focuses on the lateral stability of road trains, examining the criteria for evaluating lateral stability indicators and ways to improve these metrics. In [13], the topic of technical system testing is explored, detailing the main evaluation indicators of lateral stability and the procedure for testing vehicle lateral stability. The author of a scientific article [14] examines a method for evaluating lateral stability during obstacle traversal, considering wheel adhesion, as well as models of lateral stability in straight-line motion at a constant speed, particularly over rough terrain. The work [15], concerning the theory of vehicle operational properties, also addresses the topic of lateral vehicle stability.

However, none of the analyzed sources, including those examining military equipment, consider the impact of weapon recoil force on a vehicle's lateral stability. Thus, a problematic situation arises, characterized by the contradiction between the need to predict stability indicators of vehicles, particularly combat vehicles, taking into account weapon recoil force, and the lack of corresponding mathematical and empirical models.

The purpose of the article is to determine the condition for vehicle stability against overturning on a surface with a lateral slope during the use of weapon fire.

Sammary of the main material. To evaluate the lateral stability of a vehicle, several indicators are commonly used, including critical speed for skidding, critical speed for overturning, critical lateral slope angle for skidding, critical lateral slope angle for overturning, the lateral stability coefficient, and others [4, 16, 17].

Given that unmanned combat vehicles (UAVs) are predominantly operated in off-road conditions at relatively low speeds and lack weapon stabilization mechanisms, allowing effective fire only from a stationary position, the most important lateral stability indicator for such vehicles is considered to be the critical lateral slope angle for overturning.

The critical lateral slope angle for overturning, denoted as β, is the threshold angle at which straight-line movement of the vehicle on a slope is still possible without overturning [4].

To determine the critical lateral slope angle, it is necessary to assess the ratio of the overturning moment O_m to the stabilizing moment S_m. During straight-line movement on a laterally inclined road, the vehicle may begin to overturn when the overturning moment caused by the lateral force is balanced by the stabilizing moment generated by the normal component of the vehicle's weight [4]:

$$O_m = S_m. \quad (1)$$

To determine these moments, a common approach involves using the diagram in Figure 1 [4], which illustrates the action of the vehicle's weight G_a, applied at the center of mass (CM) and decomposed into its projections $G_a \sin\beta$ та $G_a \cos\beta$.

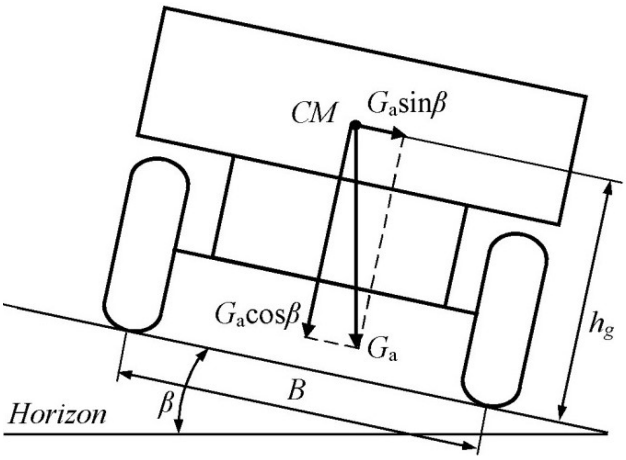

Figure 1 – Diagram of forces and moments acting on the centre of mass of a vehicle, located on a surface with a lateral slope

The magnitudes of these weight components (projections) depend on the value of the slope angle β. The weight component $G_a\sin\beta$ acts relative to the road surface at the shoulder h_g, which corresponds to the height of the center of mass (CM), forming an overturning moment $h_g G_a \sin\beta$. The component $G_a\cos\beta$ acts on an shoulders equal to half the vehicle's track width B and forms a stabilizing moment $B/2\ G_a\cos\beta$. In this case, equation (1) takes the following form [4]:

$$h_g G_a \sin\beta = B/2\ G_a \cos\beta. \qquad (2)$$

Considering that in this case β equals the critical overturning angle β_o, the critical lateral slope angle for overturning can be determined [4]:

$$\beta_o = \operatorname{arctg}\frac{B}{2h_g}. \qquad (3)$$

When a firearm is mounted on a vehicle, additional forces and moments arise during firing, as illustrated in Figure 2.

The recoil force of the weapon $F_в$ is applied at the point where the barrel axis intersects the symmetry axis of the mounting element (such as a turret, pintle, or stand). The vector of the recoil force forms an angle Θ_0 with the horizontal, determined by the elevation angle of the target and its distance. Relative to the vehicle's horizontal plane, the recoil force vector forms an angle $(\Theta_0 - \beta)$ so the recoil force can be decomposed into the projections $\cos(\Theta_0 - \beta)$ and $F_в \sin(\Theta_0 - \beta)$.

The component of the recoil force $F_в \cos(\Theta_0 - \beta)$ acts relative to the road surface on the shoulder $h_в$, which corresponds to the height of the weapon barrel and forms the overturning moment $h_в F_в \cos(\Theta_0 - \beta)$. The component $F_в \sin(\Theta_0 - \beta)$ acts on the shoulder equal to half the track of the vehicle B and forms the setting moment $B/2\ F_в \sin(\Theta_0 - \beta)$.

In this case, expression (1) takes the form (4):

$$h_g G_a \sin\beta + h_в F_в \cos(\Theta_0 - \beta) = \frac{B}{2}\big(G_a\cos\beta + F_в \sin(\Theta_0 - \beta)\big). \qquad (4)$$

Expression (4) represents an improved condition for vehicle rollover stability on a surface with a lateral slope during weapon firing. Unlike known formulas, this expression accounts for the recoil force of the weapon and the resulting tipping and stabilizing moments it generates.

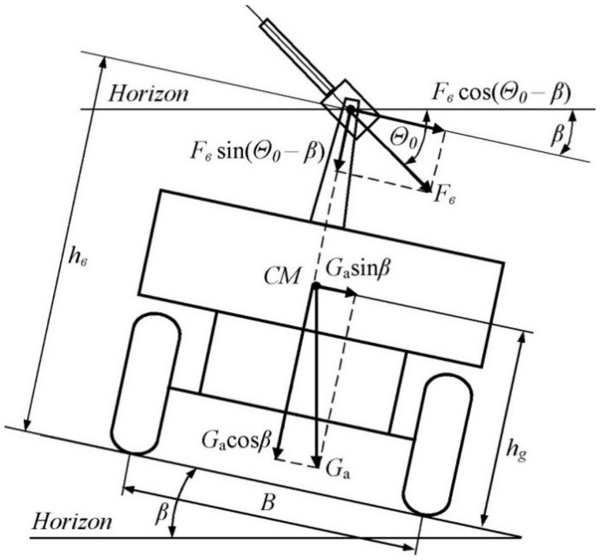

Figure 2 – Diagram of the forces and moments acting on the centre of mass of the vehicle, located on a surface with a lateral slope, when firing a weapon

The presence of trigonometric functions with different arguments in formula (4) significantly complicates the analytical determination of the rollover angle β_o. However, determining β_o using numerical methods does not pose any difficulty.

Table 2 provides calculated values of the rollover angle for certain combinations of unmanned modules (platforms) and types of firearms. The calculations were performed for a weapon barrel height of 1.3 meters above ground level and an angle $\Theta_0 = \beta$, which corresponds to the most unfavorable conditions for ensuring the stability of the combat vehicle. Indeed, when Θ_0 equals β, the stabilizing moment due to the recoil force becomes zero, while the tipping moment reaches its maximum value. This is explained by the respective values of the trigonometric functions at a zero argument.

For relatively light platforms like "Gnome" (50 kg) and "Gnome-VP" (88 kg), the weapon recoil during firing in a lateral direction (90° relative to the vehicle's longitudinal axis) leads to rollover. A similar situation occurs with the logistics-evacuation platform "Taira" when equipped with a 12.7-mm NSVT machine gun. The calculations correspond to a value of $h_в = 1.3$ m and are illustrative in nature. By reducing $h_в$ by a certain amount, the stability condition can be met. For instance, the "Gnome-VP" system with a 7.62-mm PKT machine gun becomes stable at $h_в \leq 0.965$ m.

To evaluate the stability margin of combat vehicles under conditions of weapon fire, it is proposed to use a stability coefficient SC, defined as the difference between the stabilizing and tipping moments due to the weight of the combat vehicle and the weapon's recoil force, according to the following formula:

$$SC = \frac{B}{2}\left(G_a\cos\beta + F_в\sin(\Theta_0 - \beta)\right)h_g G_a \sin\beta - h_в F_в. \quad (5)$$

The dependencies of the stability coefficient on the incline angle for various combinations of unmanned platforms and firearm models are shown in Figure 3. The calculations were performed for a weapon barrel height of 1.3 meters above ground level and an angle $\Theta_0 = \beta$.

As shown in Figure 3, higher values of the stability coefficient are observed for unmanned modules (platforms) with greater mass and track width. At the same time, for the same type of module (platform), the value of the stability coefficient depends on the weapon used: for the 7.62 mm PKT machine gun, the value of SC is higher than for the 12.7 mm NSVT machine gun, which is explained by the difference in the recoil force of the NSVT compared to the PKT by more than three times. The intersection of the curves with the abscissa axis corresponds to the value of the rollover angle β_O.

Another method of assessing the stability margin of combat vehicles under weapon firing conditions is the relative stability coefficient, defined as the ratio of the sum of stabilizing moments to the sum of tipping moments:

$$RSC = \frac{0{,}5B\left(G_a\cos\beta + F_в\sin(\Theta_0 - \beta)\right)}{h_g G_a \sin\beta + h_в F_в}. \quad (6)$$

The dependencies of the relative stability coefficient on the incline angle for various combinations of unmanned platforms and firearm models are shown in Figure 4.

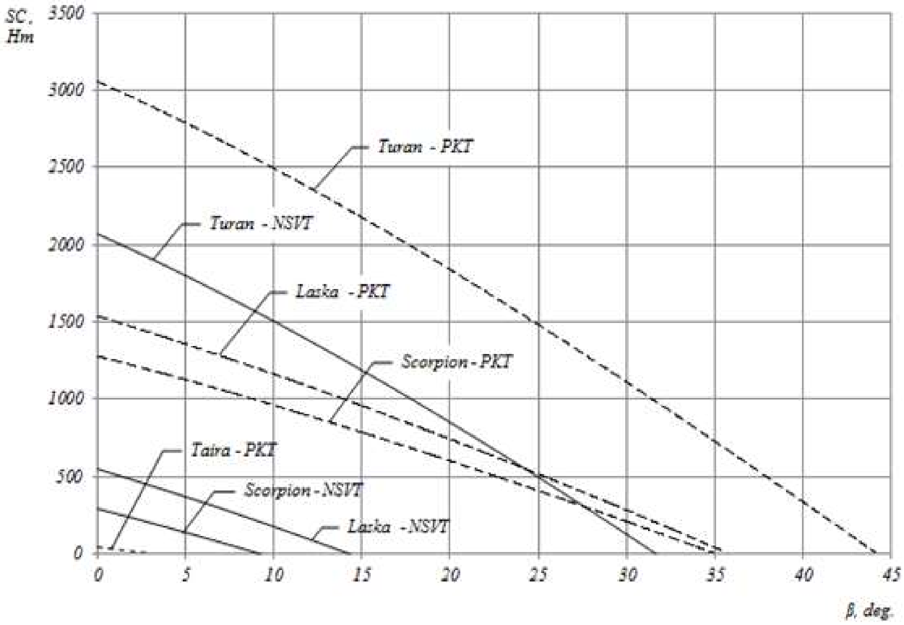

Figure 3 – Dependence of the stability coefficient on the angle of inclination for some combinations of unmanned platforms with small samples at $h_в = 1.3$ m, $\Theta_0 = \beta$

Table 2 – Rollover angle values for some combinations of unmanned modules (platforms) and small arms samples

No.	Name	Weapons	AT deg.
1	Unmanned robotic module "Scorpion"	7.62 mm PKT machine gun	34.9
		12.7 mm NSVT machine gun	9.2
2	Unmanned logistics platform "Turan"	7.62 mm PKT machine gun	44.2
		12.7 mm NSVT machine gun	31.7
3	Robotic platform "Laska 2.0"	7.62 mm PKT machine gun	35.8
		12.7 mm NSVT machine gun	14.2
4	Logistics and evacuation platform "Taira"	7.62 mm PKT machine gun	3.8
		12.7 mm NSVT machine gun	–

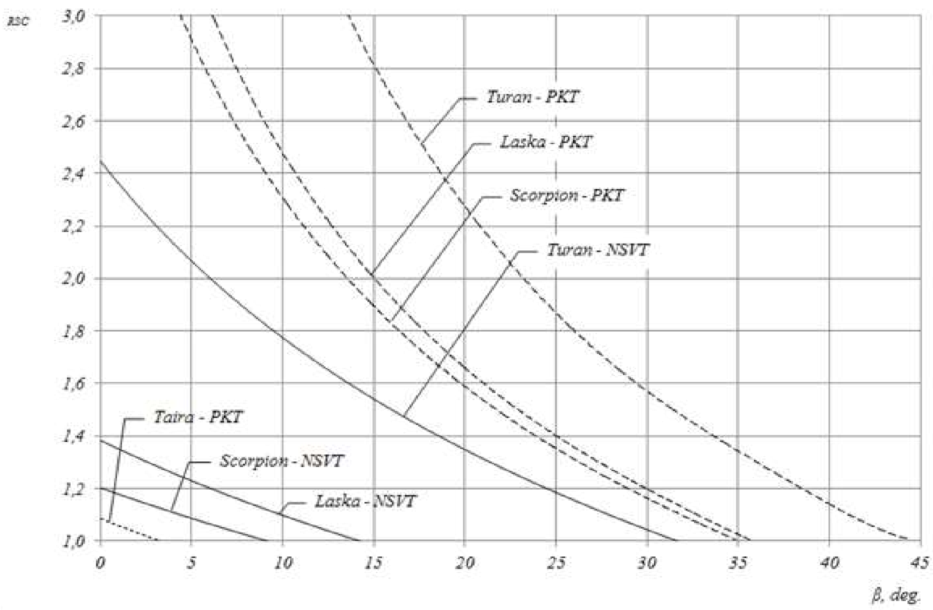

Figure 4 – Dependence of the relative stability factor on the angle of inclination for some combinations of unmanned platforms with small arms samples at $h_в$ = 1,3 m, $\Theta_0 = \beta$

The intersection of the curves with the x-axis, as in the previous Figure 3, corresponds to the tipping angle β_o. However, unlike the previous case, the tipping angle now corresponds not to a zero value of the coefficient, but to a value equal to one, as follows from formula (6).

The proposed stability coefficient and relative stability coefficient allow for the evaluation of the stability margin in both absolute and relative terms. These coefficients enable decision-making regarding the operational potential of combat vehicles under specific conditions or the use of more powerful weapons with correspondingly greater recoil forces.

Conclusions

1. The mathematical expression that defines the condition of vehicle stability against tipping on a surface with a side slope during firearm use has been improved. Unlike known expressions, this one takes into account the effect of the weapon's recoil force and the resulting tipping and stabilizing moments.

2. A stability coefficient and a relative stability coefficient have been proposed, which allow for the evaluation of the combat vehicle's stability margin during firearm use in both absolute and relative terms, as well as decision-making regarding the operational potential of combat vehicles under specific conditions or the use of more powerful weapons with correspondingly greater recoil forces.

The direction of further research is the study of the impact of suspension stiffness on vehicle stability against tipping on a surface with a side slope during firearm use.

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УМОВА СТІЙКОСТІ АВТОМОБІЛЯ ДО ПЕРЕКИДАННЯ НА ПОВЕРХНІ З БІЧНИМ УХИЛОМ ПІД ЧАС ВЕДЕННЯ ВОГНЮ ЗІ ЗБРОЇ

Досвід воєнних конфліктів свідчить про постійно зростаючу роль безпілотних бойових машин. На відміну від традиційних, зазвичай безпілотні бойові машини мають менші масо-габаритні характеристики. Це позитивно відбивається на їхніх прихованості, бойовій живучості, а також вартості, що в цілому підвищує ефективність застосування таких машин. Проте через порівняно малі значення колії та бази виникають проблеми зі статичною та динамічною стійкістю під час подолання перешкод.

Іншим чинником, що погіршує стійкість безпілотних бойових машин, є сила віддачі вогнепальної зброї, яка створює перекидний момент. У порівнянні з традиційними бойовими машинами сила віддачі для менших за масо-габаритними характеристиками безпілотних бойових машин є більш значущою. Це обумовлюється відношенням перекидного моменту від сили віддачі до стабілізувального моменту, що є пропорційним до маси машини.

У статті визначено умови стійкості автомобіля до перекидання на поверхні з бічним ухилом під час ведення вогню зі зброї.

Удосконалено математичний вираз, що визначає умову стійкості автомобіля на поверхні з бічним ухилом під час ведення вогню зі зброї. Зазначений вираз на відміну від відомих виразів ураховує дію сили віддачі зброї та утворювані нею перекидний і встановлювальний моменти.

Запропоновано коефіцієнт стійкості та відносний коефіцієнт стійкості, які дають змогу оцінювати запас стійкості до перекидання бойової машини під час ведення вогню зі зброї, а також приймати рішення щодо можливостей застосування бойової машини у тих чи інших умовах або використання більш потужної зброї з відповідно більшою силою віддачі.

Ключові слова: *бойова машина, стійкість до перекидання, віддача зброї, умова стійкості автомобіля, коефіцієнт стійкості, перекидний момент.*

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