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Analysis of Parameters Affecting the Dynamic Stability of a Rocket Launcher

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This paper considers several different parameters of a rocket launcher (thrust level, rocket mass, launch ramp length, and others) which have the greatest effect on its dynamic stability. A relatively simple mechanical model, with both rigid and deformable elements, is formed for the purpose of stability analyses. The dynamic stability of the rocket launcher, as well as the launch ramp as its component subassembly, has been examined. The resulting analytical expressions have been verified by a numerical example for a real object. The actual results can be useful to engineers in the process of designing new or reconstructing the existing rocket systems, as well as to the technical support service responsible for issuing regulations regarding the handling this type of artillery armament.

Key words: **dynamic stability, rocket launcher, deformation, thrust level, rocket mass**.

Introduction

A rocket launcher belongs to the group of the artillery weapons intended for destruction of the enemy personnel as well as for destruction of certain points deep in the enemy rear. Therefore, military theorists classify it in the artillery arms group that supports the infantry. A rocket launcer is characterized by high fire power and manoeuevrability due to its possibility to move with other rockets set on the launch ramp.

The basic requirement for safe-handling a weapon like a rocket launcher demands both the stability of the observed object in respect to the overturning and stability of its vital elements and subassemblies, to which the rocket ramp belongs. The calculatons of the rocket launcher stability are not standardized in our country and there is a small number of papers analysing these problems. The stability of the rocket launcher in regard to the overturning has been considered on a mechanical model with five-degrees-of- freedom of motion in papers [1, 2, 3, 4]. The recommended model is based on the analogous model for the stability analysis of the track crane considered in papers [5, 6,7, 8, 9, 10, 11, 12]. The main advantage of the suggested method, compared with the existing stability calculations methods, lies in the fact that it takes into account the dynamics effects of the whole object as well as the elasticity of both the support i. e. the ground and the launch ramp.

Mechanical model

The mechanical model of the rocket launcher during launching the rocket (Fig.1), which is suggested here, consists of rigid bodies and deformable elements with elastic connectons. The bottom construction of the rocket launcher is composed of a truck frame (chassis), driver's cab, driving aggregates of weight G_1 (pos. 1) and supports that may be stabilizers of weight G_6 (pos. 2) or pneumatics (pos.3). The chassis with the aggregates and the elements on it is considered a rigid beam supported by appropriate springs. Such an appromaxion is allowable, especially by constructively strenthened chassis. The spring rigidity corresponds the rigidity of the ground. Since the rigidity of the stabilizer is much greater than the rigidity of the ground, it is alowed to approximate the stabilizer by rigid bodies. The top costruction of the launcher, which contains a radially axial bearing, mechanisms for elevating and revolving of the ramp of weight G_2 (pos. 4) and a carriage of weight G_3 (pos. 5), are considered rigid bodies supported by the chassis. The launch ramp of specific gravity q_4 (pos. 6) represents a cantilever beam (consol) (the shorter (lower) part of the ramp is neglected), which is elastic and deformable in the vertical plane. The rocket weight G_5 (pos. 7) represents a rigid body. Generally speaking, the considered system has infinite degrees of freedom of motion. However, taking into account the aim of the investigation and the introduced simplifications, this system may be substituted by model with four-degree-of-freedom of motion (Fig.2). The motion of such a system is defined by the following generalized coordinates:

- ξ_0 - the vertical moving (the moving in the direction of the z-axis) of the center of mass of the bottom construction (point C)
- ξ_1 - the rotation around the main transversal central axis of inertia of the bottom construction
- ξ_2 - the moving of the rocket along the launch ramp
- ξ_3 - the deflection of the launch ramp peak in the vertical plane in the direction of the undeformed ramp

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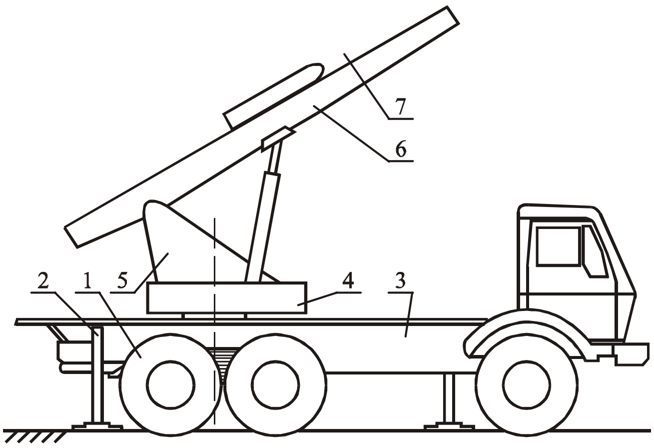

Figure 1. Scheme of rocket launcher

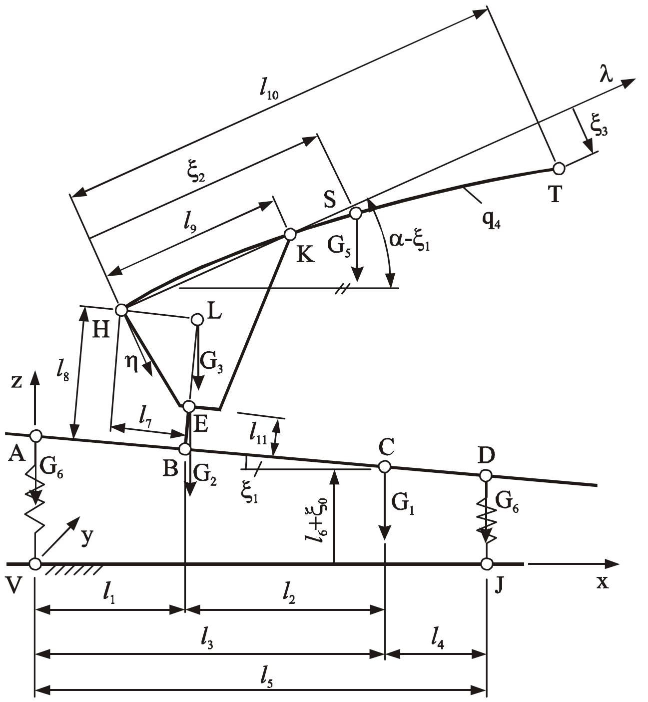

Figure 2. Mechanical model of rocket launcher

Differential equations of motion of a mechanical system

To derive the differential equations, we use Lagrange's equations of the second kind

$$\frac{d}{dt}\frac{\partial E_k}{\partial \dot{\xi}_i}-\frac{\partial E_k}{\partial \xi_i}+\frac{\partial E_p}{\partial \xi_i}=Q_i\,,\quad i=0,1,2,3 \tag{1}$$

where E_k, E_p and Q_i are the kinetic energy, potencial energy and corresponding generalized nonconservative forces, respectively.

The equaton of the elastic line of the launch ramp is unknown. In the papers dealing with the problems of the dynamic stability of the truck crane boom, different functions of the elastic lines, such as trigonometrical functions and polinomials, were suggested. In this paper the elastic line of the launch ramp has a polinomial form and satisfies all boundary conditions

$$\eta(\lambda)=\frac{\xi_3}{l_{10}\cdot(l_{10}-l_9)}\cdot\left(\lambda^2-l_9\cdot\lambda\right) \tag{2}$$

where l_9 and l_{10} are the corresponding lenghts (Fig.2).

The kinetic energy of the mechanical system has the following form

$$E_k=E_{k1}+E_{k2}+E_{k3}+E_{k4}+E_{k5}+E_{k6} \tag{3}$$

where E_{k1}, E_{k2}, E_{k3}, E_{k4}, E_{k5} and E_{k6} are the kinetic energies of the bottom construction, of the stabilizer, of the top construction, of the carriage, of the boom and of the rocket respectively.

The final expression for the kinetic energy has the following form

$$\begin{aligned}E_K=&\frac{1}{2\cdot g}\cdot\Big(G_1\cdot\dot{R}_C^2+G_2\cdot\dot{R}_E^2+G_3\cdot\dot{R}_L^2+\\&+G_5\cdot\dot{R}_S^2+G_6\cdot\dot{R}_A^2+G_6\cdot\dot{R}_D^2\Big)+\\&+\frac{\rho\cdot A_r}{2}\int_0^{l_{10}}\dot{\eta}^2d\lambda+\frac{1}{2}\cdot J_r\cdot\dot{\xi}_1^2\end{aligned} \tag{4}$$

where

$\dot{R}_C,\dot{R}_E,\dot{R}_L,\dot{R}_S,\dot{R}_A,\dot{R}_D$ - are the velocities of the characteristic points of the system

ρ - is the density of the launch ramp matherial

A_r - the average area of the launch ramp cross section

J_r - the corresponding moment of inertia of the launch ramp

The potential energy of the mechanical system has the form

$$E_p=E_{p1}+E_{p2}+E_{p3}+E_{p4}+E_{p5}+E_{p6}+E_{p7}+E_{p8} \tag{5}$$

where:

E_{p1} - is the potential energy due to the ground deformation

E_{p2} - is the potential energy of the bottom construction

E_{p3} - is the potential energy due to deformation of the connection between the chassis and stabilizer

E_{p4} - is the potential energy of the stabilizer

E_{p5} - is the potential energy of the top construction

E_{p6} - is the potential energy of the carriage

E_{p7} - is the potential energy of the boom

E_{p8} - is the potential energy of the rocket

The potential energy of the ground is defined by the expression

$$E_{p1}=0,5\cdot c\cdot\left[\left(\xi_0+l_3\cdot\xi_1\right)^2+\left(\xi_0-l_4\cdot\xi_1\right)^2\right] \tag{6}$$

where c - is the ground rigidity.

The potential energy of the bottom construction has the form

$$E_{p2}=G_1\cdot\left(l_6+\xi_0\right) \tag{7}$$

Analysis of the real construction shows that the girder AD is welded to the girder which is farther connected to the hydrocylinder. The connection of the girder can be modelled as a jamming. Since the girder AD is treated here as absolutely rigid, independent moving of supports A and D would cause deviations with respect to the right angle (angles ∠DAV and ∠ADJ-Fig.2). That contradicts the boundary condition for an absolutely rigid jamming with formulation as follows: the inclination of the elastic line is equal to zero. Since this connection is not absolutely rigid, but elastic, we shall introduce the support rigidity coefficient of the chassis grider (c_s). Thus, the deformations of two supports, connected by a grider, are conected. We can define the corresponding potential energy

$$E_{p3} = 0,5 \cdot c_s \cdot l_5^2 \cdot \xi_1^2 \tag{8}$$

The potential energy of the stabilizer has the form

$$E_{p4} = G_6 \cdot \left[2 \cdot (l_6 + \xi_0) + (l_3 - l_4) \cdot \xi_1 \right] \tag{9}$$

The potential energy of the top construction is defined by the following expression

$$E_{p5} = G_2 \cdot (l_6 + \xi_0 + l_2 \cdot \xi_1 + l_{11}) \tag{10}$$

whereas the potential energy of the carriage is

$$E_{p6} = G_3 \cdot (l_6 + l_8 + \xi_0 + l_2 \cdot \xi_1) \tag{11}$$

The potential energy of the boom has the form

$$E_{p7} = E_{p7,1} + E_{p7,2} + E_{p7,3} \tag{12}$$

where

$E_{p7,1}$ - the potential energy caused by the bending

$E_{p7,2}$ - the potential energy of the launch ramp caused by the axial force

$E_{p7,3}$ - the potential energy of the launch ramp caused by the transversal force

The potential energy caused by bending is defined by the following expression

$$E_{p7,1} = \frac{E \cdot I_{y,r}}{2} \cdot \int_0^{l_{10}} \left(\frac{\partial^2 \eta}{\partial \lambda^2} \right)^2 d\lambda \tag{13}$$

where

E - the ramp elasticity modulus

$I_{y,r}$ - the average moment of inertia of the launch ramp

The potential energy of the launch ramp caused by the axial force has the form

$$E_{p7,2} = \int_0^{l_{10}} \frac{N(\lambda)}{2} \left(\frac{\partial \eta}{\partial \lambda} \right)^2 d\lambda \tag{14}$$

The axial force is a function of the coordinate of length λ, of the geometric characteristics of the launch ramp and of the rocket position with respect to the launch ramp

$$N(\lambda) = \begin{cases} N_1(\lambda) & za \quad \xi_2 < \lambda \le l_{10} \\ N_2(\lambda) & za \quad 0 \le \lambda \le \xi_2 \end{cases}, \tag{15}$$

where

$$\begin{gathered} N_1(\lambda) = q_4 \cdot \sin(\alpha - \xi_1) \cdot (l_{10} - \lambda) \\ N_2(\lambda) = q_4 \cdot \sin(\alpha - \xi_1) \cdot (l_{10} - \lambda) + \\ + G_5 \cdot \mu \cdot \cos(\alpha - \xi_1) + G_5 \cdot \sin(\alpha - \xi_1) \end{gathered} \tag{16}$$

The potential energy of the launch ramp caused by the action of the transversal force is of the form

$$E_{p7,3} = \int_0^{l_{10}} \frac{F_t(\lambda)}{2} \frac{\eta}{\lambda} d\lambda \tag{17}$$

The transversal force is defined by the following expressions

$$F_t(\lambda) = \begin{cases} F_{t1}(\lambda) & za \quad l_9 < \xi_2 \le l_{10} \quad \wedge \quad \xi_2 < \lambda \le l_{10} \\ F_{t2}(\lambda) & za \quad l_9 < \xi_2 \le l_{10} \quad \wedge \quad l_9 < \lambda \le \xi_2 \\ F_{t3}(\lambda) & za \quad l_9 < \xi_2 \le l_{10} \quad \wedge \quad 0 \le \lambda \le l_9 \\ F_{t1}(\lambda) & za \quad 0 \le \xi_2 \le l_9 \quad \wedge \quad l_9 < \lambda \le l_{10} \\ F_{t4}(\lambda) & za \quad 0 \le \xi_2 \le l_9 \quad \wedge \quad \xi_2 < \lambda \le l_9 \\ F_{t3}(\lambda) & za \quad 0 \le \xi_2 \le l_9 \quad \wedge \quad 0 \le \lambda \le \xi_2 \end{cases}, \tag{18}$$

where

$$\begin{gathered} F_{t1}(\lambda) = q_4 \cdot (l_{10} - \lambda) \cdot \cos(\alpha - \xi_1), \\ F_{t2}(\lambda) = \left[q_4 \cdot (l_{10} - \lambda) + G_5 \right] \cdot \cos(\alpha - \xi_1), \\ F_{t3}(\lambda) = \left[q_4 \cdot (l_{10} - \lambda) + G_5 \right] \cdot \\ \cdot \cos(\alpha - \xi_1) - F_K, \\ F_{t4}(\lambda) = q_4 \cdot (l_{10} - \lambda) \cdot \cos(\alpha - \xi_1) - F_K, \\ F_K = (G_5 \cdot \xi_2 + 0,5 \cdot G_4 \cdot l_{10}) \cdot \frac{\cos(\alpha - \xi_1)}{l_9} \end{gathered} \tag{19}$$

The potential energy of the rocket is

$$E_{p8} = G_5 \cdot z_S \tag{20}$$

where the rocket position i.e. the z coordinate of the point S is denoted by z_s.

Since the direction of the rocket motion coincidies with the length axis of the launch ramp, the torsion of the launch ramp is neglected.

Generalized nonconservative forces are defined by the following expressions

$$Q_i^n = (F_{p,x} - F_{\mu,x}) \cdot \frac{\partial R_{S,x}}{\partial \xi_i} + (F_{p,z} - F_{\mu,z}) \cdot \frac{\partial R_{S,z}}{\partial \xi_i} \tag{21}$$

where

- F_p – the rocket thrust
- F_μ – the friction force between the rocket and launch lamp

The final form of Lagrange's equations, being extremely extensive is not given in this paper.

At the initial time moment the generalized coordinates, defining the deformations (ξ_0, ξ_1, ξ_3), will take the values equal to their static deformations. At the initial time moment the rocket was at rest at the base of the system of coordinates $H\eta\lambda$, meaning that $\xi_2(0) = 0$. Since for $t_0 = 0$ the whole system was at rest, then the first derivatives of the generalized coordinates with respect to the time will equal zero.

Criteria of stability

The considered system will be stable if the stability conditions of both the rocket launcher as an object and launch ramp as its most endangered constituent subassembly are fulfilled.

The rocket launcher, considered as an object, will be **stable** if the deflections of the ground under supports A (Δ_A) and D (Δ_D) are greater than or equal zero. If one of the deflections is less than zero, then the system can be considered **unstable** [16].

During exploitation, when launching the rocket depending on geometric characteristics of the launch ramp and thrust value, the rocket can sometimes drive the ramp up. This can cause its deformation to an extent greater than allowed, that influences the firing precision. We conclude that the launch ramp, in the practical sense, is **stable** if the deflection value of the ramp top, its maximum deformation, doesn't exceed allowable values. From the theoretic point of view, the launch ramp loses the stability if the maximum value of its deflection i.e. the deflection on its peak, tends to infinity [15].

A numerical example and the analysis of the results

On the basis of the established mechanical-mathematical model, using the program package MathCAD 2001, it is possible to analyse dynamic behaviour of the rocket launcher in real exploitation conditions. Some of the obtained results for the launch rocket system inquestion will be shown later in this paper.

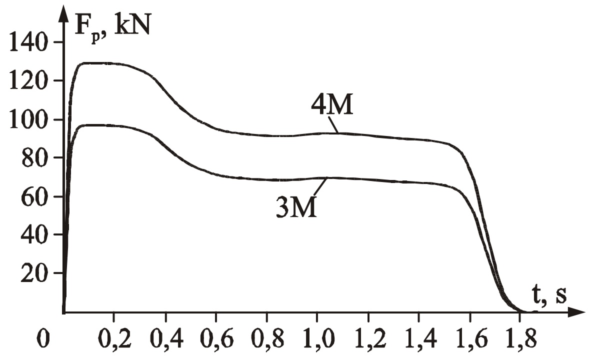

Figure 3. The thrust for the case of driving by three (3M) and four engines (4M)

The thrust change, as a time function, is defined by measuring in real exploitation conditions in case of three driving as well as four driving engines (Fig.3). Using the results of the measurings and applying the program package *TableCurve2D*, the conclusion is that they can be described by the following functions:

- driving by three engines

$$F_p = 492{,}1433 - 1488373{,}5 \cdot t + 957084{,}27 \cdot t^{1{,}5} - \\ - 96447{,}413 \cdot t^3 + 699233{,}73 \cdot t^{0{,}5},$$

- driving by four engines

$$F_p = 656{,}19106 - 1984498{,}1 \cdot t + 1276112{,}4 \cdot t^{1{,}5} - \\ - 128596{,}55 \cdot t^3 + 932311{,}64 \cdot t^{0{,}5}.$$

The rocket drive is induced by three or four engines In case of four engines drive, the time needed for the rocket to leave the ramp win be about 15% shorter than in the case of three engine drive (Fig.4). The rocket moving change analysis can also be carried out using a more simplified model with one-degree-of–freedom of motion. Fig.5 is present the graph describing the error made using the analysis of the rocket moving along the launch ramp (the during generalized coordinate ξ_2) the model with one generalized coordinate (ξ_2) with respect to the previously analyzed model with four-degrees-of- freedom of motion. The shows that the error increases with the time increasing i.e. with the launch ramp length increasing. However, the error is less than 0,5% and it can be neglected. The reason for such a small deviation lies in the fact that the rigidity of the whole system is large not to considerably affect the rocket motion sufficiently.

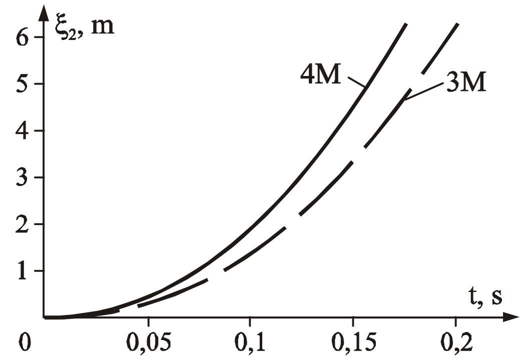

Figure 4. The graph of the moving change of the rocket along the launch ramp as a time function

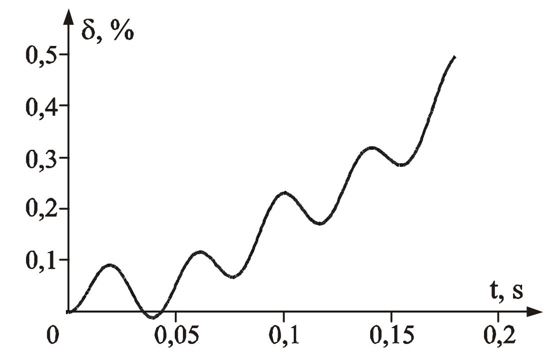

Figure 5. Comparison of the error that occures while using different models in the analysis of movining the rocket along the launch ramp

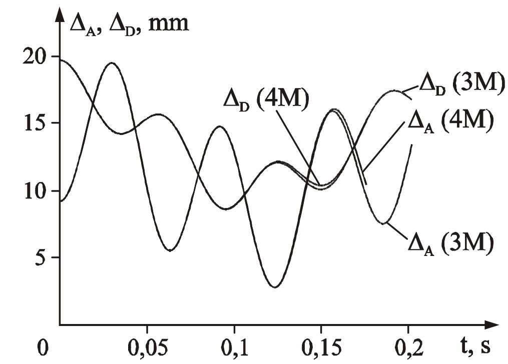

Figure 6. Chainging of the ground deflection under the stabilizer as a time function

Analysis of the graph of the ground deflection shows that the rocket launcher is stable, since the ground deflection under each support is greater than zero (Fig.6). This case of was checked for launching the rocket of mass 274 kg.. The ground deflections changes in case of three i.e. four drive engine does not differ significantly. Thus, the effect of the number of rockets to the rocket launcher stability is relatively small.

The launch ramp peak deflection at the initial time moment, when the system is at rest, equals the statistical value of the deflection (Fig.7). If the rocket moves, i.e. if the generalized coordinate increases, the observed deflection decreases, and after 0,06 s it takes negative values. This matches the real practical problems. One of the greatest problems during the exploitation of the rocket launcher is the situation in which, depending on the construction parameters of the rocket launcher as well as on the rocket drive, the rocket "pulls" the launch ramp in the direction of the "*z*" coordinate (Fig.2). In the analysed example the deformations are within allowable bounds, i.e. this situation is not expected.

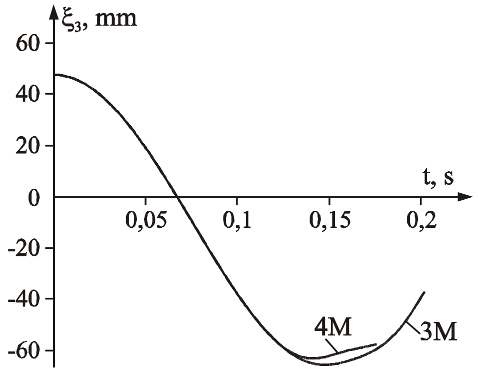

Figure7. Chainging of the launch ramp peak deflection as a time function

Comparing the deflection values of the launch ramp peak at the moment when the rocket leaves the ramp, it can be noticed that the deflection in the case of of three drive engines is less than in the case of four drive engines (Fig.7).

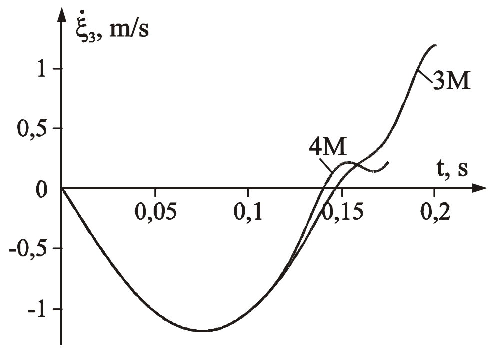

Figure 8. Chainging of the velocity of the launch ramp peak deflection as a time function

The rocket velocity associated with the generalized coordinate ξ_3 at a given time moment in the case of three drive engines is greater in respect to the case of four drive engines (Fig.8). This fact is considered very important in the analysis of the rocket range, since the rocket velocity associated with the generalized coordinate ξ_3 "pulls" the rocket to the ground, causing the rocket range to decrease. Based on this, it can be concluded that the range of the rocket can be increased if the rocket velocity, the velocity associated with the generalized coordinate ξ_3 at the moment of leaving the ramp is less than or equal zero. That can be done by changing the length of the launch ramp. For example, if the ramp length increases, the negative value of the generalized coordinate ξ_3 (Fig.9) increases, but, on the other side, the ramp peak deflection increases (Fig.10) and also the value of the deflection under the critical stabilizer "A" decreases (Fig.11). If the increment of the ramp lenght is large, e.g. L_{10}=10 m, then the ramp peak deflection will exceed allowable values. For this reason, engineers have to compare characteristic deformations (Δ_A, ξ_3) with their allowable values, realizing by that the maximum rocket range. However, solving this problem can be the subject of yet another research.

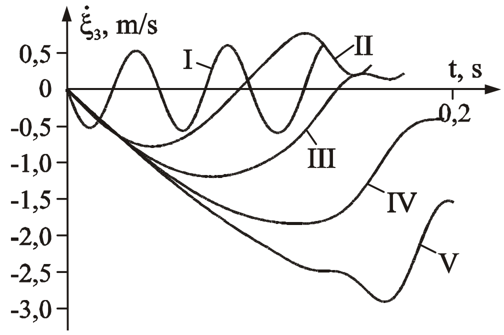

Figure 9. Chainging of the velocity of the launch ramp peak deflection as a time function, for different ramp length (curve I – l_{10}=3,5 m; curve II – l_{10}=5 m; curve III – l_{10}=6,3 m; curve IV – l_{10}=8 m; curve V – l_{10}=10 m;)

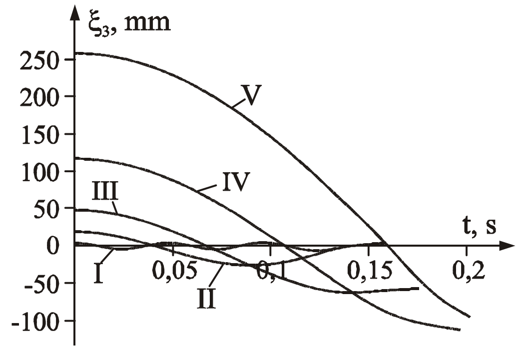

Figure 10. Chainging of the launch ramp peak deflection as a time function for different ramp length (curve I – l_{10}=3,5 m; curve II – l_{10}=5 m; curve III – l_{10}=6,3 m; curve IV – l_{10}=8 m; curve V – l_{10}=10 m;)

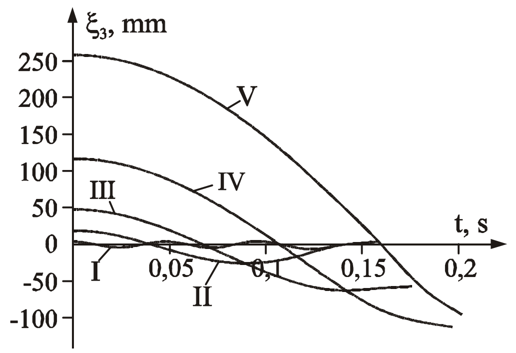

Figure 11. Chainging of the ground deflection under the stabilizer "A" as a time function for different ramp lenghts

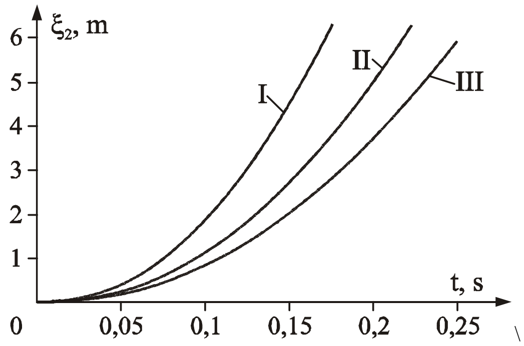

Figure 12. Graph of the changing of the rocket moving along the launch ramp as a time function for different values of the rocket mass (curve I – m_5=274 kg; curve II – m_5=450 kg; curve III – m_5=600 kg)

The rocket, launched from the rocket launcher which is the subject of this analysis comes, is three different masses: 274 kg, 450 kg i 600 kg. The graph shows that the increment of the rocket mass causes the increase of time necessary for the rocket to leave the launch ramp. For example it takes a rocket of 450 kg mass 27% more time in compared to the rocket of 274 kg, whereas in the case of a rocket of 600 kg mass, that increment is 47%. The effect of the rocket mass to the ground deformation under the support (fig.13) and to the launch ramp peak deflection (fig.14) is negligible, the rocket spending a considerable period of time in contact with the ramp.

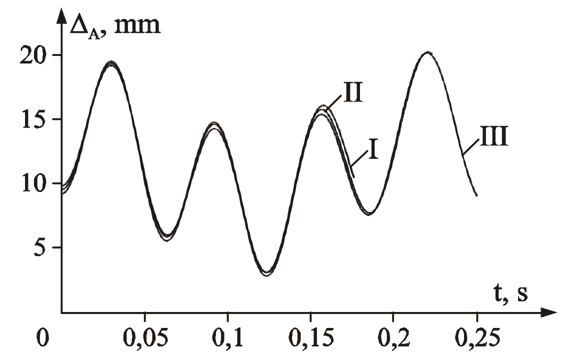

Figure 13. Change of the ground deformation under the support "A" as a time function for different of the rocket (curve I – m_5=274 kg; curve II – m_5=450 kg; curve III – m_5=600 kg)

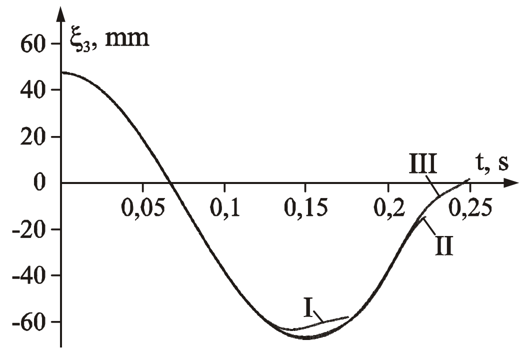

Figure 14. Change of the launch ramp peak deflection as a time function for different masses of the rocket (curve I – m_5=274 kg; curve II – m_5=450 kg; curve III – m_5=600 kg)

The effect of the coefficient of friction between the rocket and launch ramp, on the dynamic behaviour of the examined system is negligibly small.

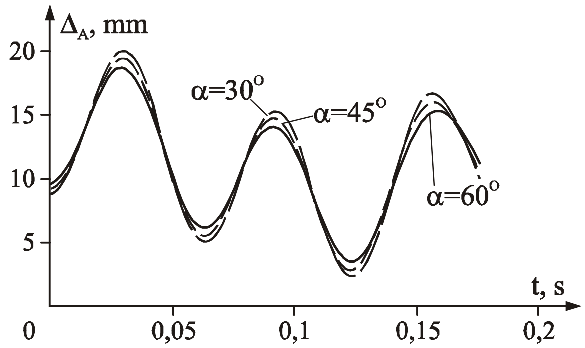

Figure 15. Change of the ground deformation under the support "A" as a time function for different angles α

In the previous examples the analysis has been made for the case when the angle between the launch ramp and horizontal ground surface equals α=45^{O}. Additional analysis has established the effect of the angle α on the rocket moving along the launch ramp is negligible. However, if the observed angle is decreased, the ground deflection under the support A (Fig.15) also decreases but the deflection of the launch ramp peak increases (Fig.16). It can be concluded that the decrease of the angle between the launch ramp and horizontal surface makes it more probable that some of the criteria of stability given above will not be satisfied.

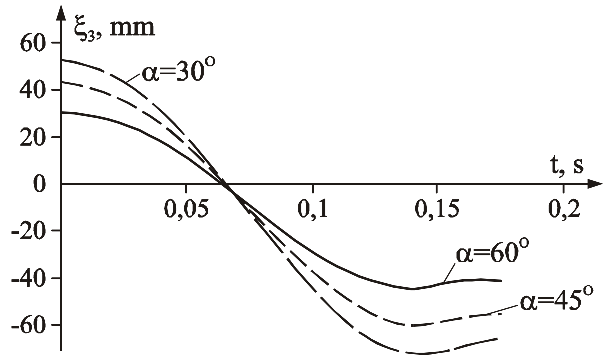

Figure 16. Change of the launch ramp peak deflection as a time function for different angles α

Conclusion

Numerical example, in which actual rocket launcher parameters have been used established how certain parameters effect the dynamic stability of the rocket launcher as an object as well as the launch ramp as its constituent subassembly. The resulting conclusions can be useful for designers in the process of designing new and reconstructing the already existing rocket systems. With slight modification model, can be applied in other similar constructions.

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Analiza parametara uticajnih na dinamičku stabilnost raketnog lansera

U radu se razmatraju različiti parametri (sila potiska, masa rakete, dužina lansirne rampe i dr.) koji imaju najveći uticaj na dinamičku stabilnost raketnog lansera. U cilju egzaktnog i relativno jednostavnog rešenja problema, postavljen je mehanički model sa krutim i deformabilnim elementima. Analizirana je dinamička stabilnost raketnog lansera i lansirne rampe kao njenog sastavnog, vitalnog sklopa. Dobijeni analitički izrazi su verifikovani numeričkim primerom za realni objekat. Rezultati mogu da budu i od značaja projektantima u procesu projektovanja novih i rekonstrukciji već postojećih raketnih sistema kao i tehničkoj službi koja propisuje uputstva za rukovanje sa ovim artiljeriskim orudjem.

Ključne reči: **dinamička stabilnost, raketni lanser, deformacija, sila potiska, masa rakete.**

Анализ параметров влияющих на динамическую устойчивость ракетной пусковой установки

В этой работе рассматриваны различные параметры (сила реактивной тяги, масса ракеты, длина пусковой наклонной плоскости и.т.д.), которые оказывают наибольшее влияние на динамическую устойчивость ракетной пусковой установки. С целью точного и относительно простого решения проблем, установлена механическая модель со жесткими и деформированными элементами. Тоже сделан анализ динамической устойчивости ракетной пусковой установки и пусковой наклонной плоскости как ее составного и важного узла. Полученные аналитические выражения верификованы цифровым примером для реального объекта. Результаты могут быть значительны для инженеров в процессе конструкции новых и реконструкции уже существующих ракетных систем, а в том числе и технической службе, которая предписывает и устанавливает правила и инструкции для обслуживания и управления этим артиллерийским оружием.

Ключевые слова: динамическая устойчивость, ракетная пусковая установка, деформация, сила реактивной тяги, масса ракеты.