Determination of the influence of soil irregularities on dynamic processes in caterpillar engines of a terrestrial robotic complex

S V Strutynskyi1,2, R V Semenchuk1

1 Department of Applied fluid mechanics and mechatronics, Igor Sikorsky Kyiv Polytechnic Institute, Prosp. Peremohy 37, Kyiv, 03056, Ukraine

2 Email: stratynskyi@gmail.com

Abstract. The paper describes the change of the geometry of the caterpillar of the terrestrial robotic complex depending on external factors. It is established that as a result of the action of centrifugal forces the caterpillar elongates, on the surface of the support rollers, the caterpillar repeats their shape, the upper part of the caterpillar acquires a convex shape, and the lower part of the caterpillar repeats the shape of the curve, which determines the unevenness of the soil. The dependence of the caterpillar shape on soil irregularities is established. The peculiarity of the geometry is that on the lower part of the caterpillar there is a ripple with the number of waves between the support rollers 1-2. It is established that the presence of soil irregularities, the harmonic components of the profiles of which have a period of about 4/3 of the distance between the extreme support rollers, leads to the greatest tensile loads in the caterpillar and the corresponding changes in caterpillar length. The dependences determining the elongation of the caterpillar, which is proportional to the square of the amplitude of the harmonic component of the soil roughness of the corresponding period are obtained.

1. Introduction.
Terrestrial robotic complexes are usually designed to perform special operations in difficult road conditions. They move at significant speeds on uneven ground. In this case, the caterpillars have intense dynamic loads. The study of dynamic processes in caterpillars is an urgent scientific problem.

The problem is associated with important theoretical and practical tasks of creating and using ground-based robotic systems for special purposes.

2. Analysis of recent research and publications.
Recent studies and publications have considered a number of designs of terrestrial robotic systems [1]. We established features of their characteristics [2] and determined the nature of dynamic loads on a mobile robotic complex [3]. In separate works, the studies of drives of complexes [4], in particular their manipulators [5] are described. Theoretical studies of robotic complexes are carried out [6] and methods of mathematical modeling are developed [7]. The results of the study, as a rule, relate to individual structures of complexes and do not allow to perform the design of robotic complexes for special purposes [8]. Special problems arise in determining the dynamic characteristics of robotic systems [9]. Dynamics analysis requires complex methods and equipment [10]. Experimental studies are performed using special equipment [11]. The studies cited in the literature refer to robotic complexes that move on smooth roads [12]. Some sources [13] include studies performed in the real road conditions. Methods for determining the dynamic characteristics of complexes are given [14].
There are studies of the characteristic modes of movement of the chassis with a caterpillar. [15] A number of publications present a study of the movement of the complex on the slope [16]. The basic requirements for the robotic complexes intended for work in field conditions are formulated [17]. In [18] the researches of perspective base of manipulators of robotic complexes are presented.

As a result of the analysis of the available information sources the conclusion is made about the absence in them of results of definition of influence of roughnesses of soil on dynamic processes in a caterpillar of a ground robotic complex. These questions relate to the previously unsolved part of the general problem of studying the characteristics of the caterpillar propulsion of a small complex of special purpose.

3. Defining the purpose and objectives of the study.
The purpose of the study is to determine the quantitative parameters of the influence of soil irregularities on the dynamic processes in the caterpillars of the ground robotic complex of special purpose. The objectives of the study include experimental determination of dynamic displacements of a caterpillar during the movement of a complex on open ground, substantiation of the scheme and mathematical model of interaction of a caterpillar with a road surface on modeling of influence of soil irregularities on dynamic processes in caterpillars of a ground robotic complex.

4. The main part of the study.
In terrestrial robotic complexes, caterpillar engines with caterpillars made of elastic polymeric materials that interact with the road surface are used. At the same time there are significant deformations of the caterpillar, which are especially significant when moving the robotic complex on the ground with an uneven surface.

Experimental determination of the shape of the caterpillar of the mobile ground-based robotic complex was performed when moving the complex on open ground and it includes video recording of the shape of the caterpillar of the mobile robotic complex with subsequent frame-by-frame video processing (Figure 1).

![Figure 1](image)

(a) (b)

**Figure 1.** The video frame of the mobile robotic complex when moving the complex at a speed of 3 km/h (a) and the corresponding contour of the caterpillar (b) is determined by this video frame.

A dynamic analysis of the shape of the caterpillar with the establishment of its characteristic areas was performed on the video footage. The upper part of the caterpillar between the points of its contact with the N1,N2 drums corresponds to the scheme of a moving massive thread with minimal bending resistance, which performs transverse oscillations. The lower part of the caterpillar has an area of contact with the ground between the points K1,K2.
In this video frame there is some sagging of the upper part of the caterpillar. There is a curved elastic line of the lower part of the caterpillar. There is a slight undulation at the bottom of the caterpillar.

The contour of the upper part of the caterpillar, depicted in the video frame, has a characteristic protrusion between the points $N_1N_2$. The appearance of this protrusion is due to inertial forces acting on the flexible caterpillar, and the lower part of the caterpillar is a wavy curve that repeats the unevenness of the soil. In this case, there is a deformation of the soil under the support rollers in the areas $K_1$, $K_2$ and $K_3$. The deformation is most intense in the area of interaction of the front roller with the soil surface in the area $K_1K_4$. On the contour of the caterpillar there are areas in the form of arcs of circles $K_2N_2$ and $N_1K_1$, which correspond to the interaction of the caterpillar with the peripheral surfaces of the support rollers. There are wavy areas on the lower part of the caterpillar. There are three complete waves, the maximum of which is $\Delta H$ between the reference sections $K_1K_5$.

Changing the shape of the caterpillar depends on the speed of movement of the complex, the shape of the roadway and the angle of ascent and descent. To establish the features of the caterpillar shape, a series of video frames was processed (figure 2).

![Figure 2](image)

**Figure 2.** The shape of the caterpillar is determined by video frames at a speed of 5 km/h: (a) — movement on a horizontal surface; (b) — inclination of about 20°.

Increasing the speed of the complex does not change the qualitative picture of movements and the shape of the caterpillar. As before, the upper part of the caterpillar has some sagging. The protrusion $W_2$ on the contour in the area $N_2$ (Figure 2a) is explained by the interaction of the teeth of the drive roller with the holes of the caterpillar and the action of centrifugal forces.

The contour of the lower part of the caterpillar has a ripple, which is determined by the location of the intermediate support roller. Transverse waves can also be traced on the contour of the lower part of the caterpillar. Their maxima $\Delta H$ are located between the support rollers $K_3$, $K_4$. The lower part of the caterpillar repeats the soil surface, taking into account its deformation (crumpling).

The movement of the complex in the areas of ascent or descent (Figure 2b) leads to an additional complication of the shape of the caterpillar. On the contour of the caterpillar, the area of convexity $\Delta H$ is traced, which repeats the protrusions on the ground between the regions $K_2$ and $K_1$.

The upper part of the caterpillar has a convex shape and a protrusion $W_3$ between the points $N_1N_2$, due to the action of centrifugal forces and forces of inertia. The lower part of the caterpillar also acquires a convex shape.

During the movement of the ground-based robotic complex, the caterpillar is subjected to significant dynamic loads. Based on the experimentally determined shape of the caterpillar of the mobile robotic complex, the scheme of caterpillar loads due to the action of forces, in particular centrifugal forces, is substantiated. Under the action of the moment $M$, the drive roller rotates with an angular velocity $\omega$, moving the complex with a velocity $V$ (Figure 3).
Consider the movement of the complex on a level road. In the caterpillar, which wraps around the right and left support rollers, there are centrifugal forces. To determine them, we use a moving coordinate system $X_YZ$, which moves with speed $V_0$.

\[ q = \frac{mV^2}{r}, \]  

(1)

where $m$ [kg/m] is running mass of the caterpillar; $V = 2V_0$ is circumferential speed of the caterpillar; $r$ is the radius of the cylindrical surface of the drum.

The force that occurs at the intersection of the caterpillar is:

\[ F_V = q \cdot r = mV^2. \]  

(2)

The action of centrifugal forces, which causes the longitudinal load of the caterpillar leads to its stretching. In the first approximation, we assume a linear relationship between the force and deformation of the caterpillar. The change in caterpillar length will be:

\[ \Delta L_V = \frac{(2L_K + 2\pi r) mV^2}{ES}. \]  

(3)

where $E$ is the modulus of elasticity of the caterpillar material; $S$ is the area of its cross section.

In the initial state, the length of the caterpillar is greater than the nominal value due to the free installation (sagging) of the caterpillar. Denote the difference between the actual and nominal lengths $\Delta L_0$. Under the action of centrifugal forces, the total length of the caterpillar will be greater than the nominal length by $\Delta L_0 + \Delta L_v$. Thus, the caterpillar will interact freely with the support rollers and contact them only in the areas $K_1$ and $K_2$. Between these points, the caterpillar rests on the ground and its shape and tension are determined by the laws of interaction of the lower part of the caterpillar with the soil.

The projections of the centrifugal forces on the $x$-axis have different directions in different areas of the caterpillar. Therefore, the cross-sections of the caterpillar are pushed away from the surfaces of the support rollers, and the contour of the caterpillar is deformed and stretched in the direction of the $x$-axis. The caterpillar is in contact with the rollers in the areas $N_1$ and $N_2$, and between these points, the position of the caterpillar corresponds to a straight line with some deflection by the value of $\Delta$ in the middle of its upper part. In sections $K_1N_1$ and $K_2N_2$, the centrifugal forces are balanced by tensile forces acting on the axial line of the caterpillar. In the upper section of the caterpillar between the points $N_1N_2$, the caterpillar is loaded at the edges by centrifugal forces in the sections $N_1N_1'$ and $N_2N_2'$. The caterpillar practically does not resist a bend under the influence of loadings, on edges it acquires the form of a convex curve with an arrow of a deflection $\Delta$. 

![Diagram of caterpillar interaction](image-url)
Assume that between the points $K_1$ and $K_2$ of contact of the rollers with the road surface (Figure 3) the caterpillar is stretched by some force, which depends on the centrifugal forces and irregularities of the road.

In the presence of depressions of the soil (pits) between points $K_1$ and $K_2$, the length of the caterpillar in this area remains unchanged and is $L_{K}$. In the presence of a protrusion (Protrusion), the caterpillar wraps around it and lengthens by some value $\Delta L$, which is determined by the difference in the length of the curve that determines the profile of the road surface in the area between points $K_1$ and $K_2$ and the length of the straight line $L_{K}$. Assume that the road profile is described by some dependence:

$$z = z(x).$$

(4)

Let us define the derivative of the road profile:

$$\frac{dz}{dx} = \frac{dz(x)}{dx} = \tan \alpha,$$

(5)

where $\alpha$ is the angle of inclination of the tangent profile.

The elementary section of the arc of the road profile has a length $dL$ and is determined by the derivative of the contour of the caterpillar. A Fourier series was used to mathematically describe the contour of the caterpillar. In order to simplify the calculations, a symmetric problem is considered by extending the contour of the caterpillar from the point $K_1$ to the left coordinate half-plane. The resulting symmetrical contour of the caterpillar will have a period of $2L_{K}$ from point $K_2$ to $K_2$. To describe a symmetric contour, the Fourier series will have only cosine components and will be determined by the dependence:

$$z(x) = \sum_{k=0}^{\infty} a_k \cdot \cos \left( \frac{k \pi}{L_k} \cdot x \right).$$

(6)

When the shape of the caterpillar changes, its total length changes. Consider an infinitesimal element of the caterpillar, respectively, its length:

$$dx = dL \cdot \cos \alpha.$$

(7)

Using the dependence (5), we find:

$$dL = dx \sqrt{1 + (dz/dx)^2}.$$

(8)

Let us determine the total length of the contour of the caterpillar between points $K_1$ and $K_2$:

$$L_H = \int_0^{L_K} dL \sqrt{1 + (dz/dx)^2} dx.$$

(9)

The change in the length of the caterpillar due to the unevenness of the road will be:

$$\Delta L_H = L_H - L_{K}.$$

(10)

Let us determine the derivative of the dependence of the shape of the caterpillar on the longitudinal coordinate. To do this, use formula (6). After differentiation we obtain:

$$\frac{dz}{dx} = - \sum_{k=1}^{\infty} a_k \frac{k \pi}{L_k} \cdot \sin \left( \frac{k \pi}{L_k} x \right).$$

(11)

Dependence (11) defines the derivative as the sum of a series. For a separate sinusoidal component of the series we have:

$$\left( \frac{dz}{dx} \right)_k = \frac{a_k k \pi}{L_k} \sin \left( \frac{k \pi}{L_k} x \right).$$

(12)

Let us determine the change in the length of the caterpillar for one sinusoidal component of the series:

$$\Delta L_H = \int_0^{L_k} \sqrt{1 - \left( \frac{a_k k \pi}{L_k} \right)^2} \sin^2 \left( \frac{k \pi x}{L_k} \right) dx - L_{K}.$$

(13)
To calculate the integral (13), it is reduced to the form of a normal elliptical integral of the second kind of the following type:

\[ E(\phi, \gamma) = \int_0^\phi \sqrt{1 - \gamma^2 \sin^2 \phi} \cdot d\phi. \]  

(14)

To do this, new constants are introduced in dependence (13):

\[ \phi = \frac{k\pi x}{L_k} \]  

(15)

\[ \gamma = \frac{k\pi a_k}{L_k} \]  

(16)

From relations (15) and (16) it follows:

\[ x = \phi \cdot \frac{L_k}{(k\pi)}, \]  

(17)

\[ dx = d\phi \cdot \frac{L_k}{(k\pi)}. \]  

(18)

Accordingly, formula (13) takes the form:

\[ \Delta L_H = \frac{L_k}{k\pi} \int_0^{k\pi} \sqrt{1 - \gamma^2 \cdot \sin^2 \phi} \cdot d\phi - L_k. \]  

(19)

To calculate the integral included in the dependences (15) and (16), it is reduced to the form of a tabular complete elliptic integral of Legendre of the second kind:

\[ E_n(\gamma) = \int_0^{\pi/2} \sqrt{1 - \gamma^2 \cdot \sin^2 \phi} \cdot d\phi. \]  

(20)

Consider the contour shapes of the lower part of the caterpillar, described by cosine functions with different periods, which coincide with the distance between the support rollers of the caterpillar and correspond to the components of the series (6). There are significant components of the series with numbers \(k = 1.2\), which correspond to the characteristic irregularities of the roadway (Figure 4).
of the distance between the extreme support rollers. In this case, the intermediate roller has little effect
on the deformation of the soil and does not smooth the protrusions of the roadway. Road bumps with
this period are accepted as the most influential on the deformation of the caterpillar. Therefore, the
characteristic changes in the length of the caterpillar are determined by the dependence (13) at \( k = 2 \).
The number of quarters of cosine periods that must be taken into account when calculating the
elliptical integral will be 2 (two) because the depression on the road does not increase the length of the
caterpillar.

Accordingly, to determine the changes in caterpillar length, the dependence was obtained:

\[
\Delta L_H = L_k \left[ \frac{1}{2\pi} E_{II} \left( \frac{2\pi a_2}{L_k} \right) - 1 \right],
\]

where \( E_{II}(y) \) is the complete elliptic Legendre integral of the second kind given in the form (20).

For small values of arguments, this integral is approximately determined by the dependence:

\[
E_{II}(y) = \frac{\pi}{2} \left( 1 - \frac{y^2}{4} - \frac{9y^4}{192} - \ldots \right).
\]

After substituting the value of the integral from (22) to (21) taking into account (15), (16) we
obtain:

\[
\Delta L_H = -L_H \left[ \frac{\pi^2 a_2^2}{L_k^2} + \frac{144\pi^4 a_2^4}{192 L_k^4} \right].
\]

Thus, it was found that the most significant changes in caterpillar length occur when moving the
complex on a road that has the form (figure 5b), and the largest changes in caterpillar length according
to (23) are proportional to the square and fourth degree amplitude \( a_2 \) of road irregularities.

Based on the calculated change in the length of the caterpillar due to road irregularities according
to Hooke’s law there is an increase in the force of quasi-static tension of the caterpillar:

\[
\Delta F = \Delta L_H \cdot ES / (2L_k + 2\pi r).
\]

Thus, the centrifugal forces and the action of road conditions lead to a change in the length and
tension of the caterpillar. The action of centrifugal forces leads to the elongation of the caterpillar, and
the unevenness of the road reduces the length of the upper free part of the caterpillar. The general
changes in the length of the caterpillar relative to the nominal value are:

\[
\Delta L >> \Delta L_0 + \Delta L_V - \Delta L_H.
\]

In some cases, the presence of appropriate protrusions on the road is set approximately equal to the
length of the upper part of the caterpillar and its nominal value, and accordingly \( \Delta L = 0 \).

With significant road protrusions, when:

\[
\Delta L_H > \Delta L_0 + \Delta L_V,
\]

there is an additional tension of the caterpillar with the appearance of additional tensile force.

Determining the tension force of the caterpillar determines the reliability of its operation and
durability of the ground robotic complex [19]. Therefore, the results are an important contribution to
the development of special robotics [20].

5. Conclusions

As a result of the study, it was found that the shape of the caterpillar depends little on the speed of the
complex, and mainly depends on the unevenness of the soil. The upper part of the caterpillar acquires
a convex shape, and the lower part of the caterpillar has a ripple with the number of waves between
the support rollers 1-2, and the lower part of the caterpillar repeats the shape of the curve, which
determines the unevenness of the soil.

The presence of soil irregularities, the harmonic components of the profiles of which have a period
of about 4/3 of the distance between the extreme support rollers, leads to the greatest tensile loads in
the caterpillar and the corresponding changes in its length. The elongation of the caterpillar is proportional to the square of the amplitude of the harmonic component of the soil roughness of the specified period.

References

[1] Jun Qian, Bin Zi, Daoming Wang, Yangang Ma, Dan Zhang 2017 The design and development of an omni-directional mobile robot oriented to an intelligent manufacturing system Sensors 2017, 17, 2073.

[2] Sberbank robotics laboratory 2019 Analiticheskii obzor mirovogo rynka robototekhniki. p 272.

[3] Baoquan Li; Yongchun Fang; Guoqiang Hu; Xuebo Zhang 2016 Model-Free Unified Tracking and Regulation Visual Servoing of Wheeled Mobile Robots Journal Sensors and Actuators A: Physical, IEEE Transactions on Control Systems Technology (Volume 24, Issue: 4 ), pp 1328–39.

[4] Voloshina A., Panchenko A., Panchenko I., Zasiadko A. 2019 Geometrical Parameters for Distribution Systems of Hydraulic Machines Modern Development Paths of Agricultural Production. Springer, Cham, pp 323-336.

[5] Korayem M.H., Dehkordi S.F. 2018 Derivation of motion equation for mobile manipulator with viscoelastic links and revolute–prismatic flexible joints via recursive Gibbs–Appell formulations Robotics and Autonomous Systems Volume 103, pp 175-198.

[6] Chepkov I.B., Dovhopolyu A.S., Huslyakov O.M. 2019 Kontseptual’nii zasady stvorennya vitchyznyanych udarno-rovdivual’nykh robotyzovanykh kompleksiv vazhkooho klasu. Ozbroyennya ta viys’kova tekhnika. Kyiv: TSNDI OVT №3 (23). pp16-25.

[7] Serhii Strutyński, Waldemar Wójcik, Sandugash Orazaliyeva 2019 Grounds for mechatronic system development of the optical devices position dynamic stabilization of a mobile terrestrial robotic system Photonics Applications in Astronomy, Communications, Industry, and High-Energy Physics Experiments Volume 11176, 1117610.

[8] The U.S. Army 2017 Robotic and Autonomous Systems Strategy. 31p.

[9] Hyun-Min Joe Jun-Ho Oh 2018 Balance recovery through model predictive control based on capture point dynamics for biped walking robot Robotics and Autonomous Systems Volume 105, pp 1-10.

[10] Strutyński S.V., Hurzhii A.A. 2017 Definition of vibro displacements of drive systems with laser triangulation meters and setting their integral characteristics via hyper-spectral analysis methods Scientific Bulletin of the National Mining University №1. pp 43-51.

[11] Panchenko A., Voloshina A., Milaeva I., Lузan P. 2019 Operating Conditions’ Influence on the Change of Functional Characteristics for Mechatronic Systems with Orbital Hydraulic Motors. Modern Development Paths of Agricultural Production. Springer, Cham, pp 169-176.

[12] Kot Tomas, Novak Petr 2018 Application of virtual reality in teleoperation of the military mobile robotic system TAROS International journal of advanced robotic systems, January-February. pp 1-6.

[13] Paul Ritzen, Erik Roebroek, Nathan van de Wouw, Zhong-Ping Jiang 2016 Trailer Steering Control of a Tractor–Trailer Robot IEEE Transactions on Control Systems Technology (Volume:24 , Issue: 4 ), pp 1240–52.

[14] Strutyński S., Kravchuk V., Semenchuk R. 2018 Mathematical modelling of a specialized vehicle caterpillar mover dynamic processes under condition of the distributing the parameters of the caterpillar International Journal of Engineering & Technology, 7 (4/3), pp 40-46.

[15] Volosnikov S.A. 2016 The methodology for determining the critical velocity of the track of the skid platform Mechanics and mechanical engineering. Kharkiv: NTU "KPI" №1 pp 36-44.

[16] Strutyński V., Hurzhii A., Kozlov L. 2019 Determination of static equilibrium conditions of a
mobile terrestrial robotic complex Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu №5 pp 79-86.

[17] Ugis Romanovs Maris Andzans 2019 Digital infantry battlefield solution. Research and Innovation. DIBS project. Part Three. Milrem robotics p 120.

[18] Strutynskyi S., Nochnichenko, I. 2019 Design of parallel link mobile robot manipulator mechanisms based on function oriented element base Eastern-European Journal of Enterprise Technologies, № 4/7(100). pp54-64.

[19] William G. Braun, III Kim Richard Nossal & Stefanie von Hlatky 2018 Robotics and Military Operations. Kingston conference on International security series. 75 p.

[20] A. Y. Varshavskiy 2017 Problemy razvitiya progressivnykh tekhnologiy: robototekhnika (MIR (Modernizatsiya. Innovatsii. Razvitiye.)) pp 682-697.