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Article

Mathematical Model of a Vineyard Cultivator

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Abstract: The article presents information to describe the movement of a vineyard cultivator, the basics of the concept of graph theory are used, in which various interaction forces arise in articulated joints, a fixed rectangular system is chosen as an inertial coordinate system, as a multi-mass system. A general model of the vineyard cultivator functioning will use the most general principle of dynamics - the Dalembert principle.

Keywords: vineyard cultivator, vineyard, mathematical model

1. Introduction

When cultivating inter-bush zones in vineyards, the rotary implement is exposed to unbalanced unbalanced turning moments changing in magnitude and direction, caused by the difference of forces on the turning times [1]. The magnitude and duration of the turning moment depend on soil conditions, location of bushes in the rows, type and parameters of the attachment mechanism and other factors. Under the influence of these moments the mounted implement is displaced relative to the tractor in one or another direction, which worsens the work of the machine.

2. Materials and Methods

To build a general model of the vineyard cultivator functioning, we will use the most general principle of dynamics - the Dalembert principle [2], [3]. The structural scheme of the machine will be first of all characterized by its oriented graph and the corresponding incident matrix, and the generalized coordinates by its angular displacements relative to the selected reference frames.

The vineyard cultivator consisting of a tractor and rotary working tools for tillage of the bushy zones will be represented as a system of solid bodies (separate sections) in various hinge links. Under hinge we will understand such a connection between the rotary implement and the frame, through which one has a direct force effect on the other. Cylindrical joints (Figure 1) with one number of degrees of freedom are widely used for connecting different side sections.

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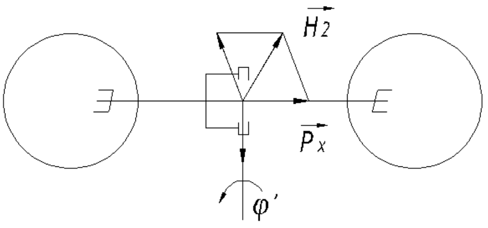


Figure 1. Structure of cylindrical hinge links

In the design of a vineyard cultivator, there are also more complex connections that are a combination of the considered hinges, for example, a suspension mechanism. However, in the first approximation, they can be considered as the hinges listed above, depending on the number of degrees of freedom. In particular, the hitching mechanism can be considered as a ball joint placed in an instantaneous center of rotation [2]. Various forces of interaction arise in articulated joints, to describe the structure of the relationships of a vineyard cultivator as a multi-mass system, we will use the basic concepts of graph theory [2], [3].

The graph of the system consists of points called vertices and lines connecting vertices and called edges (Figure 2). The vertices represent individual sections of the gun, and the edges are its hinges [3]. The vertex corresponding to the tractor is denoted by S_0, and the vertices and the edges defined by the sections of the gun, respectively, by S_1, S_2,..., S_n and U_i, U_2, ... , U_n.

If for any pair of vertices S_i, and S_j, the path between them is determined in a unique way, then the graph has a tree structure [4]. To describe the movement of a vineyard cultivator, it is necessary first of all to agree on reference systems. As an inertial coordinate system, we choose a stationary rectangular system OXYZ, connected to the surface of the field. We assume that the coordinate axes OX, OY, OZ have longitudinal, transverse and vertical directions, respectively (Figure 2).

To determine the position of the vineyard cultivator relative to the selected inertial reference frame OXYZ, consider the movable rectangular coordinate systems $O_oX_oY_oZ_o$ and $O_1X_1Y_1Z_1$ $O_2X_2Y_2Z_2$..., rigidly connected to the tractor and the sections of the tool. For a vineyard cultivator having an oriented graph with a structure on the side of the vineyard aisles, the origin of the coordinates O_o and O_1 O_2,... can be placed respectively in the center of mass of the tractor [2], [3] and in the hinge points of the tool, and the coordinate axes O_oX_o, O_oY_o, O_oZ_o, ... are directed in the original positions in the direction of the axes OX, OY, OZ.

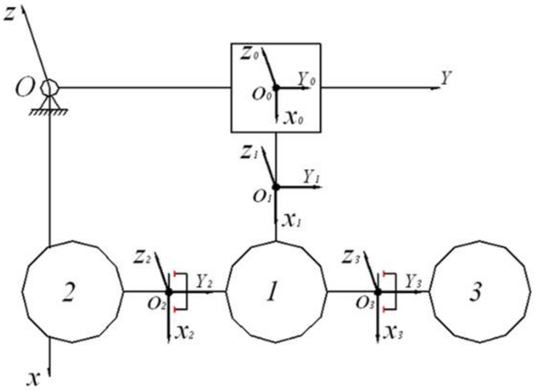


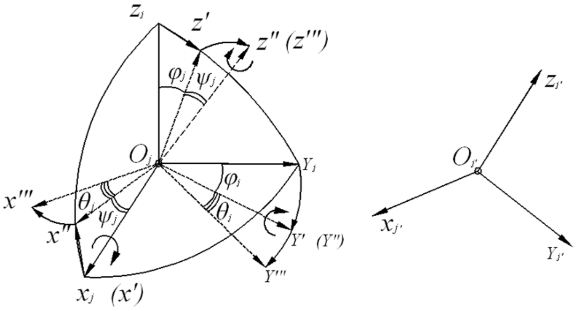
Figure 2. Calculation scheme of the vineyard cultivator

Then, to determine the angular orientation of the j-th rotary section of the gun in the inertial reference frame OXYZ, it is sufficient to determine the angular orientation of the moving coordinate system $O_jX_jY_jZ_j$, rigidly connected to this section. This can be done by sequentially setting the angular coordinates of adjacent sections relative to each other.

Let φ_j, ψ_j, and θ_j be the angles characterizing the rotations of the coordinate system $O_jX_jY_jZ_j$ in the transverse-vertical, longitudinal-vertical, and horizontal planes, respectively (Figure 3).

It is known [2], [3] that at the same orientation of the coordinate axes the transition from one rectangular system to another can be realized by parallel transfer and three consecutive rotations by Euler, Bryant, etc. angles. The choice of angles can be made in various ways, but it is important that at small deviation of the system from the initial position all three angles remain small [4]. Thus, for example, rotating the coordinate system $O_jX_jY_jZ_j$, rigidly connected with the j-th section of the gun, sequentially by the Bryant angles (Figure 3) and performing a parallel transfer, we obtain a system of coordinate.

Figure 3. Angular displacements of the system



$O_j^1X_j^1Y_j^1Z_j^1$, rigidly connected with the j^1-th section of the gun. Then the transformation matrix for small angles can be found by the formula:

$$G_j = \begin{Vmatrix} 1 & -\theta_j & \psi_j \\ \theta_j & 1 & -\varphi_j \\ -\psi_j & \varphi_j & 1 \end{Vmatrix}. \tag{1}$$

It should be answered that depending on the number of degrees of freedom of the j-ro joint and its orientation in space, the introduced angles φ_j, ψ_j, and θ_j can be considered as generalized coordinates (j=1,..., n). Thus, for a cylindrical joint, j requires one of the angles φ_j, ψ_j, or θ_j for the longitudinal, transverse, or vertical location of the axis of rotation, respectively. For a universal joint, the two angles are ψ_j, and θ_j, and φ_j, and θ_j, and θ_j, or φ_j and ψ_j, depending on the longitudinal, transverse, or vertical orientation of the plane of its axes of rotation. Finally, for a ball joint, all three angles are required [5].

Therefore, the transformation matrix G_j for the j-ro joint of the tillage unit is determined by formula (1) at zero values of angles that are not generalized coordinates. (Figure 2), five generalized coordinates φ_1, ψ_1, θ_2, φ_2, ψ_3, can be introduced, and the transformation matrices have the form:

$$G_j = \begin{Vmatrix} 1 & -\theta_1 & \psi_1 \\ \theta_1 & 1 & -\varphi_1 \\ -\psi_1 & \varphi_1 & 1 \end{Vmatrix};\ G_2 = \begin{Vmatrix} 1 & 0 & 0 \\ 0 & 1 & -\varphi_2 \\ 0_1 & \varphi_2 & 1 \end{Vmatrix}; G_3 = \begin{Vmatrix} 1 & 0 & 0 \\ 0 & 1 & -\varphi_3 \\ 0_1 & \varphi_3 & 1 \end{Vmatrix}. \tag{2}$$

The angular orientation of the tractor can be given by three angles φ_0, ψ_0, и θ_0, characterizing respectively roll, pitch, and yaw motion, and the transformation matrix is found similarly by formula (2) at j=0.

3. Results and Discussion

Thus, by sequentially setting the orientation of the implement sections with respect to the frame and of the central section with respect to the tractor, it is possible to determine the position of the machine in relation to the inertial reference frame. To do this, it is enough to find the transformation matrices A_0, A_1, ... , characterizing angular orientation of systems $O_oX_oY_oZ_o$, $O_1X_1Y_1Z_1$, ... , rigidly connected with tractors and implement sections, with respect to the inertial coordinate system OXYZ.

The computation of matrices can be organized according to the structure of the oriented graph:

$$A_j = G_0^{-1} G_1^{T_{1j}} G_2^{T_{1j}} \ldots G_n^{T_{nj}}, \tag{3}$$

where T_{1j}, T_{2j},..., T_{nj} are the elements of the j-th column of the inverse incidence matrix $T = S^{-1}$. Then, using formula (1), we obtain:

$$A_j = \begin{Vmatrix} 1 & \theta_0 - \sum_{i=1}^{n} T_{ij}\theta_i & -\psi_0 + \sum_{i=1}^{n} T_{ij}\psi_i \\ -\theta_0 + \sum_{i=1}^{n} T_{ij}\theta_i & 1 & \psi_0 - \sum_{i=1}^{n} T_{ij}\psi_i \\ \psi_0 - \sum_{i=1}^{n} T_{ij}\psi_i & -\varphi_0 + \sum_{i=1}^{n} T_{ij}\varphi_i & 1 \end{Vmatrix}, \tag{4}$$

and the angles that are not generalized coordinates must be identically equal to zero.

Thus, for a tillage unit consisting of a tractor and a vineyard cultivator (Figure 2), the transformation matrices are as follows:

$$A_1 = \begin{Vmatrix} 1 & \theta_0 & -\psi_0 \\ -\theta_0 & 1 & \psi_0 \\ \psi_0 & -\varphi_0 & 1 \end{Vmatrix}; \quad A_1 = \begin{Vmatrix} 1 & \theta_0 + \theta_1 & -\psi_0 - \psi_1 \\ -\theta_0 - \theta_1 & 1 & \varphi_0 + \varphi_1 \\ \psi_0 + \psi_1 & -\varphi_0 - \varphi_1 & 1 \end{Vmatrix};$$

$$A_2 = \begin{Vmatrix} 1 & \theta_0 + \theta_1 & -\psi_0 - \psi_1 \\ -\theta_0 - \theta_1 & 1 & \varphi_0 + \varphi_1 + \varphi_2 \\ \psi_0 + \psi_1 & -\varphi_0 - \varphi_1 - \varphi_2 & 1 \end{Vmatrix};$$

$$A_2 = \begin{Vmatrix} 1 & \theta_0 + \theta_1 & -\psi_0 - \psi_1 \\ -\theta_0 - \theta_1 & 1 & \varphi_0 + \varphi_1 + \varphi_3 \\ \psi_0 + \psi_1 & -\varphi_0 - \varphi_1 - \varphi_3 & 1 \end{Vmatrix}. \tag{5}$$

The transformation matrices A_0, A_1, ... , An will be used by us when deriving the equations of motion of the tillage machine.

Then the main vector of external forces, the line of action of which passes through the center of mass of the section C_j and the main moment of external forces act on the j-th section of the implement (j = 1, ... , п) (Figure 4, a). The internal forces applied in the joints *j′*, *j″*, ..., are combined into the main vectors of reactions of links ,.. $\vec{N}_{j'}, \vec{N}_{j''}$,..., passing through the hinge points, and the directions of forces are consistent with the oriented graph (Figure 4, b). The moments of internal forces caused, for example, by friction in the joints will be neglected.

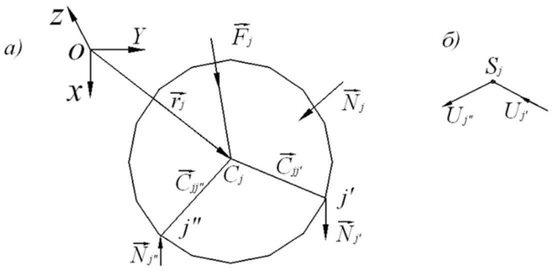


Figure 4. a) Scheme of forces acting on the j-th section, of the gun; b) Fragment of the oriented graph of the gun

According to Dalembert's principle

$$m_j\ddot{\vec{r}}_j = \vec{F}_j - \vec{N}_{j'} + \vec{N}_{j''} + \ldots, \tag{6}$$

where m_j is the mass of the j-th section of the gun;

$\vec{r}_j$ — radius-vector directed from the origin of the inertial reference frame O к center of mass of the section C_j.

Then taking into account the elements of the incident matrix [2], [3], [6]:

$$m_j\ddot{\vec{r}} = \vec{F}_j + \sum_{i=1}^{n} S_{ji}\vec{N}_i$$

which in matrix form is written as:

$$m = \begin{Vmatrix} m_1 & 0 & \ldots & 0 \\ 0 & m_2 & \ldots & 0 \\ \ldots & \ldots & \ldots & \ldots \\ 0 & 0 & \ldots & m_n \end{Vmatrix}, \ \vec{r} = \begin{Vmatrix} \vec{r}_1 \\ \vec{r}_2 \\ \ldots \\ \vec{r}_n \end{Vmatrix}, \ \vec{F} = \begin{Vmatrix} \vec{F}_1 \\ \vec{F}_2 \\ \ldots \\ \vec{F}_n \end{Vmatrix}, \ \vec{N} = \begin{Vmatrix} \vec{N}_1 \\ \vec{N}_2 \\ \ldots \\ \vec{N}_n \end{Vmatrix} \tag{7}$$

S — is the incident matrix of the oriented graph.

Multiplying both parts of equation (7) on the left by the inverse matrix $T=S^{-1}$, we obtain the bond reaction forces

$$\vec{N} = T(m\ddot{\vec{r}} - \vec{F}).$$

4. Conclusion

In particular, for the unit consisting of tractor MTZ-82.1 and vineyard cultivator UK-3 (Figure 5).

$$\begin{aligned}
&\vec{F}_1 = \vec{G}_1 + \vec{Q}_{11} + \vec{Q}_{12} + \vec{R}_{11} + \vec{R}_{12} + \vec{R}_{13};\\
&\vec{F}_2 = \vec{G}_2 + \vec{Q}_{21} + \vec{R}_{21} + \vec{R}_{22} + \vec{R}_{23};\\
&\vec{F}_3 = \vec{G}_3 + \vec{Q}_{31} + \vec{R}_{31} + \vec{R}_{32} + \vec{R}_{33};\\
&\vec{M}_1 = \vec{l}_{11} \times \vec{Q}_{11} + \vec{l}_{12} \times \vec{Q}_{12} + \vec{q}_{11} \times \vec{R}_{11} + \vec{q}_{12} \times \vec{R}_{12} + \vec{q}_{13} \times \vec{R}_{13};\\
&\vec{M}_2 = \vec{l}_{21} \times \vec{Q}_{21} + \vec{q}_{21} \times \vec{R}_{21} + \vec{q}_{22} \times \vec{R}_{22} + \vec{q}_{23} \times \vec{R}_{23};
\end{aligned} \tag{8}$$

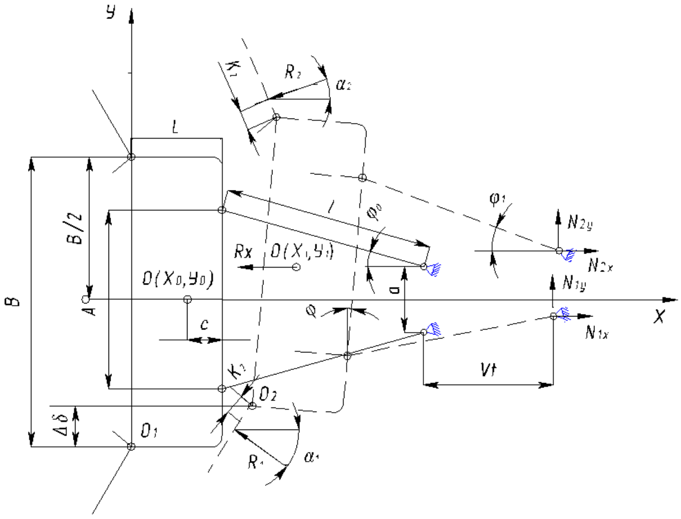


Figure 5. External forces acting on the vineyard cultivator during movement

Thus, to describe the motion of the vineyard cultivator the basis of the graph theory concept is used in which different interaction forces arise in the hinge joints, choosing a non-moving rectangular system as a multi-mass system as the inertial coordinate system.

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