Research units of flexible working body motion, cutting branches

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Abstract. There are significant tilts of the working body, clamping, hitting an insurmountable obstacle when the machine is working in the forest, due to the unevenness of the soil, stumps, and fallen trees. Therefore, circular saws and cutters often fail. Flexible working body is able to deviate from insurmountable obstacles, which increases the reliability of the machine. Since each link of the flexible working body can move relative to the other, the use of analytical methods for describing kinematics is possible only for the cases with a large number of known input parameters, which we have shown in the mathematical model of the rotor. A virtual prototype of a rotor with a flexible working body has been created to describe the movement of a flexible working body with a minimum number of input parameters. 3d contact between the links, their geometrical parameters, initial position, weight, gravity, torque applied to the shaft are given in the simulation model of the rotor. Thus, (having only geometric and mass characteristics of the links of a flexible working body at the input based on a simulation experiment) dependencies have been obtained to determine the kinematics of the links of a flexible working body, taking into account its bending in the vertical and horizontal plane.

1. Introduction

A flexible working body in the form of a cable or chain can theoretically be represented as a system of material points that can move relative to each other in three planes, which reduces this task to the problem of rotating bodies relative to their centers of mass. A great contribution to the development of the mechanics of systems of material points and solids was made by V G Vilke [1, 2].

In the works of Hui Ma, a model of a rotor with blades that takes into account lateral and torsional shaft deformations was studied [3]. A shaft and a hard disk are described by multiple points of concentrated mass connected by massless springs. The blade is represented as a single solid, while we need to consider a system of flexible body.

The work of Chen Yong [4] is devoted to the study of the kinematics of rotating links with the help of virtual prototyping. In it, the paths of movement of the milling head are obtained using the Motion SolidWorks module; the range of its rotation is determined.

Rotating systems are an important component of many machines, with increasing speed, special attention should be paid to the stability of the rotors. Saeed Bab [5] showed that with undamped vibration in the plane of the blades, the system loses stability.

In the works of V P Ivanovsky it is described that the force interaction of the cutter with the workpiece determines the energy consumption (work) for the implementation of the cutting process
and, together with the speed (cutting or feed), the power consumption in the directions of the cutting and feed movements. The solution to this problem is facilitated by the fact that there is no need to know the true picture of the force interaction. It suffices to have the total projection of all the acting forces on the direction of the velocity vector (cutting or feed). The product of this total projection of forces acting in the cutting zone at an appropriate speed will give the value of the required power for cutting or feed [6].

Thus, to use the cutting theory for our case, it is necessary to obtain the positions of the links of the flexible working body at any time, taking into account their dynamic parameters, which will speed up the process of developing and improving machines with this type of working bodies.

2. Materials and methods

The principle of operation of the rotor with flexible inertial-cutting working bodies (chain) is as follows. With the help of the engine, the rotor with flexible working bodies is driven into rotation. In the process of rotation, kinetic energy accumulates in flexible working bodies. They occupy a radial position. When meeting with the branches of the kinetic energy becomes potential and the cutting process begins. After the cutting process, the lost energy is restored due to the power coming from the engine. In the process of the rotor with flexible working bodies when they are in contact with the branch, branch cutting, breaking at the base or deviation will be observed. The rotor was developed at Voronezh State Forestry University and is a flywheel weighing 10 kg with a diagonal of 0.3 m to which chain links with a weight of 0.35 kg each are attached. The rotor through the flange is attached to the shaft of the hydraulic motor. Brand hydraulic motor MG2.28 / 32 manufacturer Shakhty plant GIDROPRIVOD. The working volume is 28 cm³, the rotational speed is 25-4800 rpm, the torque is 83 Nm, the nominal pressure of the working fluid is 20 MPa.

2.1. Analytical model of flexible working body movement

In the process of movement, the flexible working body simultaneously performs rotational and portable translational motion (figure 1).

Figure 1. Rotor with flexible working bodies: (a) projections of the material points of the working body in the XYX plane; (b) projections of material points of the working body in the XOZ plane.
Since the angular velocity is an order of magnitude greater than the translational velocity, the latter one can be neglected. Given the possibility of moving the material points of the working body in both the horizontal and vertical planes, we obtain:

\[
\begin{align*}
    x_k &= r_k \cdot \sin(\omega_k \cdot t); \\
    y_k &= r_k \cdot \cos(\omega_k \cdot t); \\
    z_k &= r_k \cdot \sin(\omega_{b_k} \cdot t),
\end{align*}
\]

where \( x_k, y_k, z_k \) – the coordinates of the \( k \)-th point of the flexible working body, m; \( r_k \) – the length of the working body from the point of attachment to its \( k \)-th point, m; \( \omega_k \) – the angular velocity of the \( k \)-th point of the flexible working body in the horizontal plane, \( \text{s}^{-1} \); \( \omega_{b_k} \) – the angular velocity of the deviation of the \( k \)-th point of the flexible working body in the vertical plane of the axis, \( \text{s}^{-1} \).

We adopt a flexible working body, as a system of material points that can move relative to each other (figure 1). Since we consider the work of a flexible working body in three-dimensional space, the coordinates that determine its position are found as projections of points on the corresponding axes:

\[
\begin{align*}
    x_k &= r_k \cdot \sin(\omega_k \cdot t) \cdot \cos(\omega_{k-1} \cdot t - \omega_k \cdot t); \\
    y_k &= r_k \cdot \cos(\omega_k \cdot t) \cdot \cos(\omega_{k-1} \cdot t - \omega_k \cdot t); \\
    z_k &= \sqrt{(x_k - x_{k-1})^2 + (y_k - y_{k-1})^2 + (z_k - z_{k-1})^2} \cdot \sin(\omega_{b_k} \cdot t).
\end{align*}
\]

Add links that allow each point to rotate relative to each other, but do not allow to change the length of the working body. To do this, we calculate the length of the working body, on the basis of the system (2),

\[
R_k = \sqrt{(x_k - x_{k-1})^2 + (y_k - y_{k-1})^2 + (z_k - z_{k-1})^2}.
\]

Add the coefficient to the system (2) that allows scaling the coordinates of points; it will be equal to the ratio of the constant length of the flexible working body \( r_k \) to the length obtained after the increment of the angles of rotation of its points – \( R_k \).

\[
\begin{align*}
    x_k &= r_k \cdot \sin(\omega_k \cdot t) \cdot \cos(\omega_{k-1} \cdot t - \omega_k \cdot t) \cdot \frac{r_k}{R_k}; \\
    y_k &= r_k \cdot \cos(\omega_k \cdot t) \cdot \cos(\omega_{k-1} \cdot t - \omega_k \cdot t) \cdot \frac{r_k}{R_k}; \\
    z_k &= \sqrt{(x_k - x_{k-1})^2 + (y_k - y_{k-1})^2 + (z_k - z_{k-1})^2} \cdot \sin(\omega_{b_k} \cdot t) \cdot \frac{r_k}{R_k}.
\end{align*}
\]

This mathematical model (1-4) enables to calculate the trajectory of a flexible working body, for known angular velocities of its constituent links [7].

2.2. Simulation model of flexible working body movement

We developed a simulation model of a rotor operating in a horizontal position Using the Motion SolidWorks module (figure 2).

Inertial forces, gravity and acceleration characteristics are taken into account in the study of the rotor kinematics. The general formulation of the problem is as follows:

\[
[M]\ddot{s}(t) + [C]\dot{s}(t) + [K]s(t) = f(t),
\]

where \([K] \) – stiffness matrix; \([C] \) – damping matrix; \([M] \) – mass matrix; \( s(t) \) – displacement vector; \( \dot{s}(t) \) – speed vector; \( \ddot{s}(t) \) – acceleration vector.
Figure 2. The rotor revolving in a horizontal plane with two chains moving in three planes.

Modeling settings in Motion SolidWorks: material – steel (dry); dynamic friction velocity $v_d = 10.16 \text{ mm/s}$, dynamic friction coefficient $\mu_{kd} = 0.25$; static friction velocity $v_s = 0.1 \text{ mm/s}$, static friction coefficient $\mu_{ks} = 0.3$; rigidity 100,000 N, exponent 1.5, maximum damping 49.91, penetration 0.1 mm; 3d contact accuracy 0.01, cycle frequency 3, type of integrator GSTIFF, maximum number of iterations 25, size of initial step of integrator 0.0001, minimum step size of integrator 0.0000001, maximum step size of integrator 0.01, repeated Jacobi maximum estimate. The mass of the rotor is 10.82 kg, the mass of one chain link is 0.35 kg, the center of gravity of the rotor is $X = 0$, $Y = 0$, $Z = 10 \text{ mm}$. The initial positions of the chain links are given in Table 1.

Table 1. The initial position of the gravity centers of the links in two flexible chains.

| No. of a chain link on the right | No. of a chain link from on the left | Center of gravity, mm | Center of gravity, mm |
|---------------------------------|-------------------------------------|-----------------------|-----------------------|
|                                 |                                     | $X$       | $Y$       | $Z$       | $X$       | $Y$       | $Z$       |
| 1                               | 5                                   | -142.93   | 1.2       | -17.95    | 140.4     | -3.6      | -16.7     |
| 2                               | 6                                   | -150.09   | -0.65     | -94.84    | 138.8     | -9.1      | -99.89    |
| 3                               | 7                                   | -154.8    | -0.68     | -175.2    | 138.3     | -10.1     | -183.1    |
| 4                               | 8                                   | -158.27   | 5.78      | -257.2    | 134.5     | -9.44     | -265.7    |

Rotation is transmitted from the engine to the rotor (the direction is indicated by the arrow). Acceleration occurs in 5 seconds, after which the steady motion comes (figure 3).

3. Results and discussion
The mathematical model (1-4) enables to obtain the trajectories of movement of the flexible working body. The initial positions and speeds of the five material points are shown in Table 2.
Figure 3. Characteristics of the rotor acceleration and the direction of its rotation.

Table 2. The speed of material points in the horizontal and vertical planes and their distances relative to the center of rotation.

|     | \(k_0\) | \(k_1\) | \(k_2\) | \(k_3\) | \(k_4\) |
|-----|--------|--------|--------|--------|--------|
| \(\omega_k\) (s\(^{-1}\)) | 94     | 94     | 94     | 94     | 94     |
| \(\omega_{k,b}\) (s\(^{-1}\)) | 0      | 30     | 30     | 30     | 30     |
| \(r_k\) (m)       | 0.12   | 0.2    | 0.28   | 0.36   | 0.44   |

The calculation is made for the time \(t = 0-2\) s. Dependences of coordinate changes in time for the fourth chain link are shown in figure 4. Similarly, you can get the dependence of the coordinates \(x, y, z\) on time and between each other for other links.

Figure 4. Changing the \(X\) and \(Y\) coordinates of the gravity center of the fourth chain link based on the mathematical model.

The simulation model enables to obtain the position of the mass center of the links with regard to their inertial characteristics (figure 5). In contrast to the mathematical model, the angular velocities here are not constant, but depend on the inertial characteristics of the links. Therefore, the changes in coordinates over time are of a different nature.
The dependence of the displacement of the $X$ and $Y$ coordinates relative to each other for the last (fourth) link has been constructed to determine the working area of the flexible inertial-chopping body.

Based on those obtained in figures 6-7 dependences it is seen that the maximum working area is 0.88 m. It decreases to 0.8m and in the process of rotation for the given parameters. Based on the simulation model, it can be seen that at the initial moment of time the center of gravity of the fourth link was located in the coordinates $X_0 = -0.158$, $Y_0 = 0.00578$ m, and gradually shifted to the outer radius corresponding to the chain length. Since the mathematical model does not take into account the mass characteristics of the links and sets constant angular velocities, the dependence character differs from the imitative one.

Based on the simulation model, we obtained changes in the vertical coordinate of the gravity center of the fourth link, and changes in the resulting linear velocity of the fourth link in figures 8-9. Figure 8 shows that at the beginning the link was located below the rotor at a distance of $-0.257$ m. At the beginning of the simulation, the links dropped down under contact with each other under the action of gravity. Then the link went up due to the rotation of the rotor, then the motion became steady in the plane of rotation because of the flexibility of the chain acquired an oscillatory motion and starting from 2 seconds.
Figure 8. Changes in the $Z$ coordinate of the fourth link based on the simulation model.

Figure 9. Changes in the linear velocity of the fourth link on the basis of a simulation model.

Figure 9 shows that the change in the chain speed was oscillatory in nature with a gradual increase in its value in the first 2 seconds of acceleration. Starting from 2 seconds, the inertia forces reached a value at which they significantly tightened the chain and the speed fluctuation stopped. Further, the speed increased because the rotor accelerated in accordance with figure 3, after which it is stabilized with minor deviations at the level of 45 m/s. At the initial time, the chains of the horizontally operating rotor are downy, and they rise under the action of inertial force during acceleration. After 2 seconds the oscillations about the horizontal plane are minimal and they are about 5 mm. Laboratory experiments were carried out on the stand developed by us. It is a frame with an installed hydraulic motor that is connected to the pumping station (figure 10).

Figure 10. Laboratory stand with flexible inertia-cutting working bodies.

The nature of the movement of the flexible working body has confirmed the dependencies obtained in analytical and simulation modeling.

Conclusion
The trajectories of the movement of a flexible inertial-cutting working body were calculated on the basis of the obtained mathematical and simulation models.

The change in the working area of the circuit during its rotation was calculated for the given input parameters, which was 0.08 m.
The change in the linear speed of the circuit with the given input parameters is determined. It enables to study their effect on the speed fluctuations of the links of the flexible inertia-cutting working body. The circumferential speed of the fourth link of the chain fluctuated within 5 m/s in the first two seconds of acceleration. After this the oscillations decreased to 0.1 m/s and the resulting speed reached 45 m/s, which enable to accumulate enough kinetic energy for cutting thin branches.

The conducted laboratory experiment confirmed that obtained by simulating the trajectory of a flexible inertial-chopping working body.

The obtained results enable to justify the parameters of the chain, which is the basis for the development of machines with the working bodies of this type.

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