Research of dynamics of movement of grain and forage harvesters by methods of mathematical and imitating modeling

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\textbf{Annotation.} The mathematical model of movement of the grain and forage harvester is considered, the possibility of its algorithmization in the software complex is shown, as well as the data confirming its adequacy. The mathematical model includes dynamic and kinematic equations of relation of angular and linear velocities with angular and spatial coordinates. The peculiarity of the model is in the use of a set of coordinate systems, which allowed to take into account not only the weight and size and layout features of the type of machines under study, but also the nature of interaction of the elastic wheel with the damped base. In the given model the speed of movement of the combine is set not by the forced change of the coordinate of the center of mass of the skeleton, but is formed by the modeling of the process of interaction of driving wheels with the support base. This approach provides a more adequate description of the process of curvilinear movement of the combine, allows you to simulate the movement of the machine, acceleration, braking, overcoming obstacles, slipping and slipping processes, taking into account the characteristics of the tire and traction properties of the soil. The approach adopted ensures sufficient accuracy of the model with a minimum set of factors and requirements for calculation. Experimental and computational data obtained as a result of simulation are presented. Comparison of active forces and acceleration spectral densities in the main parts of the combine showed sufficient convergence of results. The revealed inaccuracy is caused by the discrepancy between the numerical description of the supporting surface and the test road, the presentation of the combine's frame as an absolutely rigid body, and differences in the elastic-viscous properties of tires. Conclusions are made and directions of the further researches providing improvement of operational properties of self-propelled combines at the expense of systems of suspension of wheels and working elements are defined.

\textbf{Introduction}

Today the main means of harvesting crops are self-propelled grain and forage harvesters, the efficiency of which largely determines the profitability of the agricultural sector as one of the priority areas of the economy \cite{1, 2}. The harvesters are equipped with more efficient working and functional organs, powerful power plants and increase their working and transport speeds to increase productivity \cite{3-6}. Such changes in design and operational properties, as a rule, lead to an increase in the curb weight of machines, which is unacceptable by the requirements of agroecology and is limited by the
norms of maximum pressure on the ground [7-9]. In this case, the development and implementation of systems to reduce dynamic loads on combines and improve their smooth running is an actual practical task of modern agricultural engineering [10, 11].

**Purpose of the study**

Nowadays the creation of machines and the study of their motion dynamics should be based on the methods of mathematical and simulation modeling, the basis of which is a mathematical description of the processes under study [12-18]. The development of mathematical models is a complex and knowledge-intensive process that determines the reliability of the results, the duration of research, the cost of research and development, as well as the properties of finished products. Thus, the main purpose of this work was to develop and verify the mathematical model of movement of self-propelled wheeled grain and forage harvesters.

**Materials and methods**

The requirements for a mathematical model of the dynamics of combines are determined by a set of tasks, in the solution of which it is necessary to obtain information for the evaluation of performance, in particular:

- the model should describe the joint dynamics of the frame, engine and running gear elements of combines with the accuracy necessary for stability when driving on non-deformable soils;
- the design features of wheeled propellers should be taken into account, as well as the unstoppable nature of the links imposed on the combine;
- the movement of the combine should be modeled taking into account the characteristics of resistance and grip of the ground, as the traction and coupling characteristics affect the speed of the machine.

When calculating the differential equations of the harvester's movement, a number of assumptions were made, which, on the one hand, should ensure the fulfillment of the requirements for the mathematical model, and, on the other hand, should limit the number of simulated parameters of the system to the most necessary ones. In accordance with the requirements to the mathematical model, the following assumptions are made:

- the weights of the harvester's sprung elements are reduced to the load-bearing system;
- the support base is considered non-deformable (the necessary pliability to the ground can be taken into account in the corresponding characteristics of the tyres of the wheels, and the tangential pliability of the soil is taken into account in the characteristics of its traction properties).

When modeling the dynamics of a combine harvester its body was considered as a spatial absolutely firm structure. The bond between kinematic parameters and external perturbations was described by means of differential equations that make up the mathematical model of the combine's motion.

The system of equations of motion of a self-propelled combine contains:

- the dynamic equations describing the movement of the combine, obtained on the basis of the law of preservation of the amount of movement and the moment of the amount of movement;
- the kinematic equations of the bond between angular and linear velocities and angular and spatial coordinates, obtained on the basis of equations of the bond between different coordinate systems.

**Results and discussion**

The developed model uses three different coordinate systems (Fig. 1), which is due to the structure and form of the equations of motion of the object. The first, stationary coordinate system $O_2X_2Y_2Z_2$, is used to simulate the given ground and road conditions of movement. The origin of the system coordinates (point $O_2$) coincides with the beginning of the simulated trace (Fig. 1 a). The second, semi-located coordinate system $O_1X_1Y_1Z_1$, is characterized by the fact that its beginning point $O_1$ always coincides
with the center of mass of the combine and moves with it in space. The axes $O_1X_1, O_1Y_1, O_1Z_1$ are parallel to the corresponding axes of the unrelated coordinate system (Fig. 1 a). The third coordinate system $OXYZ$, used for mathematical description of the combine's motion, is a mobile coordinate system (MCS), its center of gravity $O$ always coincides with the center of gravity $C$, and the axes coincide with the main axes of inertia of the combine (Fig. 1 a). The equations of the combine harvester dynamics were recorded in the linked coordinate system, therefore the projections of linear $(V_X, V_Y, V_Z)$ and angular $(X, Y, Z)$ velocities on the linked axes were taken as the motion parameters. The use of a linked coordinate system to record the self-propelled combine dynamics equations is determined by the following considerations:

- Let's consider that mobile axes with the beginning of coordinates in the center of masses of the wheeled car are the main axes of inertia of a body and moments of inertia concerning them do not depend on change of kinematic parameters;
- The main external forces acting on the coordinate system are oriented relative to the body and the most simply expressed in the coordinate axes rigidly connected to it.

Fig. 1. Position of the self-propelled harvester in space (a) and micro-mobile coordinate system (b): $C$ - center of mass of the harvester; $\varphi, \psi, \Theta$ - angles of trim, roll, course, respectively; $q_i$ - vertical coordinate of the road surface

In this case, the self-propelled combine dynamics equations recorded in MCS are the simplest and most convenient for the subsequent solution with a sufficiently complete reflection of the processes of interaction between the moving body and the environment. We introduce a micromovable coordinate system (MMCS) to determine the forces acting on the ground side of the combine and understand it as the $O_TX_TY_TZ_T$ system, the center of which $O_TX_TY_TZ_T$ coincides with the geometric center of the wheel contact spot, the $O_TX_T$ axis coincides with the projection of the longitudinal axis of symmetry of the wheel on the bearing surface, and the $O_TY_T$ axis respectively with the projection of the wheel axis (Fig. 1 b).

We obtain the general equations of motion of a self-propelled combine using the theorems of changing the amount of body movement and the amount of motion moment in projections on the MCS axis:
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\[
\begin{align*}
\frac{dV_{CX}}{dt} + m_e (\omega_Y V_{CZ} - \omega_Z V_{CY}) &= G_X + F_X + \sum_{i=1}^{N} R_{Xi}; \\
\frac{dV_{CY}}{dt} + m_e (\omega_Z V_{CX} - \omega_X V_{CZ}) &= G_Y + F_Y + \sum_{i=1}^{N} R_{Yi}; \\
\frac{dV_{CZ}}{dt} + m_e (\omega_X V_{CY} - \omega_Y V_{CX}) &= G_Z + F_Z + \sum_{i=1}^{N} R_{Zi}; \\
I_X \frac{d\omega_X}{dt} + \omega_Y \omega_Z (I_Z - I_Y) &= M_X (F) + \sum_{i=1}^{N} M_X [R_{Zi}] - \sum_{i=1}^{N} M_Z [R_{Yi}]; \\
I_Y \frac{d\omega_Y}{dt} + \omega_Z \omega_X (I_X - I_Z) &= M_Y (F) - \sum_{i=1}^{N} M_Y [R_{XZ}] + \sum_{i=1}^{N} M_Y [R_{Zi}]; \\
I_Z \frac{d\omega_Z}{dt} + \omega_X \omega_Y (I_Y - I_X) &= M_Z (F) + \sum_{i=1}^{N} M_Z [R_{XZ}] - \sum_{i=1}^{N} M_X [R_{Yi}] + \sum_{i=1}^{N} M_{ski}
\end{align*}
\]

where \(G_X, G_Y, G_Z\) – projections of gravity vector on the MCS \(OXYZ\) axis; \(F_X, F_Y, F_Z\) - projections of external force vector on the axis MCS \(OXYZ\); \(R_{Xi}, R_{Yi}, R_{Zi}\) – projections of the interaction force between the wheel and the reference surface on the MCS \(OXYZ\) axis; \(M_X (F), M_Y (F), M_Z (F)\) – projections of torque from the force of external influence on the MCS \(OXYZ\) axis; \(M_X [R_{Zi}], M_Y [R_{XZ}], M_Z [R_{Yi}]\), \(M_{ski}\) – projections of moments of influence on the MCS \(OXYZ\) axis; \(I_{X}, I_{Y}, I_{Z}\) – moments of inertia of the combine relative to the axes MCS \(OXYZ\); \(m_e\) – weight of the combine; \(N\) – number of the combine wheels.

The position of the self-propelled combine in space at any time is determined by the relative position of the semi-linked and mobile coordinate systems, which are characterized by three angular coordinates - Euler-Krylov’s angles: \(\Theta\) yaw angle; \(\phi\) "trim" angle; \(\psi\) "roll" angle. The connection of Euler-Krylov's angles with other kinematic parameters of rotational motion - projections of angular velocity on the connected axes - is established on the basis of kinematic relations which are called equations of rotational motion connection:

\[
\begin{align*}
\frac{dy}{dt} &= \omega_X \cos \phi + \omega_Z \sin \phi; \\
\frac{d\Theta}{dt} &= \frac{\omega_Z \cos \phi - \omega_X \sin \phi}{\cos \psi}; \\
\frac{d\psi}{dt} &= \omega_Y - \omega_X \cos \phi - \omega_Z \sin \phi.
\end{align*}
\]

Since the case of a machine overturn is not considered, i.e. \(\psi < \pi/2\), the system (1) does not degenerate.

When examining the dynamics of the combine harvester's movement, it is necessary to take into account the existing moving parts as a complex dynamic system. The axle of driving wheels is the only moving part of the existing assemblies of self-propelled combines, the calculated scheme of angular oscillations of which is presented in Fig. 2.

The differential equation of the angular oscillations of the bridge relative to the longitudinal axis passing through the point \(D\) in MCS has the form
\[
J_{mX} \frac{d\omega_m}{dt} = \frac{(R_{z2} - R_{z4}) B \cos(\phi_m)}{2},
\]

where \( J_{mX} \) – moment of inertia of the bridge to the axis \( X \).

**Fig. 2.** Calculated diagram of angular oscillations the rear axle of the self-propelled machine relative to the body:

\( \omega_m, \phi_m \) - angular speed and rotation angle of the axle relative to the longitudinal axis passing through point \( D \); \( B \) - wheel track.

The specifics of interaction of the wheel with the support base are presented in accordance with the known and approved methods [9-15] as a rolling elastic wheel on the roughness of the non-deformable base. In this case, in the mathematical model, the speed of the combine is set not by changing the coordinates of the center of mass of the body, but by modeling the process of interaction of driving wheels with the support base. This makes it possible not only to more adequately represent the motion of MSC along the unevenness, but also to simulate machine movement, acceleration, braking, overcoming obstacles, slipping and slipping processes, taking into account the characteristics of the tire and ground traction properties.

**Fig. 3.** RSM 2650 forage harvester (a), its schematic (b) and 3D animated model in «Simulink».
The developed model was implemented in the «Simulink» of the MATLAB software package, which allowed to evaluate its performance on the example of the RSM 2650 forage harvester (Fig. 3 a). As the initial data we used mass and dimensional characteristics of the main elements of the combine in the most common and commercially available modification. The performance characteristics of tyres are based on data provided by the tyre manufacturer. Fig. 3 shows the generated schematic animation of modeling results in "Simulink" (Fig. 3 b), as well as 3D-animation obtained by superimposing on the model of the combine's appearance and visualizing the dynamics of its movement (Fig. 3 c).

The experimental researches and modeling of the dynamics of the combine's movement RSM2650 showed the spectrograms of the operating forces (reactions) in the vertical plane, transmitted from the wheels to the beam of the driving axle \( (Z_T) \) (Fig. 4), as well as the acceleration spectra on the driving axle \( (G_Z) \) (Fig. 5) when the combine moves along the unpaved road at a speed of 8 km / h.

![Oscillograms of force on the beam of driving wheels in the vertical plane, obtained experimentally (a) and by results of simulation modeling (b)](image)

**Fig. 4.** Oscillograms of force on the beam of driving wheels in the vertical plane, obtained experimentally (a) and by results of simulation modeling (b)

The data obtained indicate sufficient convergence of results. Thus, the average values of loads differ from the experiment by 4÷7%, and peak values by 8÷17%. The differences are caused, first of all, by the discrepancy between the numerical description of the bearing surface and the road on which the full-scale tests were carried out. The accuracy of the calculation was also affected by the presentation of the combine model as an absolutely rigid body, although in reality the load-bearing structure has a certain pliability, which is difficult to take into account at this stage of research.

![Acceleration spectral density on the axle of driving wheels obtained experimentally (a) and by results of simulation modeling (b)](image)

**Fig. 5.** Acceleration spectral density on the axle of driving wheels obtained experimentally (a) and by results of simulation modeling (b)

The high convergence is also noted in the diagrams reflecting the spectral density of signals on the axle of the front wheels (Fig. 5), where two modes of vibration are distinguished, which, as shown by previous studies [19, 20], reflect the vertical and longitudinal angular vibrations of the combine on pneumatic tires. The graphs show some shift in the maximum signal frequency value: the curve obtained as a result of modeling has a maximum at a frequency of 1.1 Hz, and according to the results of experimental studies - 1.2 Hz. The difference can be explained by the difference between the parameters of the elastic-dissipative properties of the tires in the model and the actual values.
Conclusion

1. The developed mathematical model based on fundamental laws of dynamics possesses sufficient accuracy for research of dynamics of movement of grain and forage harvesters and can be used for the purpose of estimation of level of operating loads in various parts and elements of harvesters that allows to apply it for researches, designing of new machines or modernization of existing ones.

2. It is impossible to reduce significantly the loads from kinematic disturbances for the adopted design and layout of combines because of the lack of suspension systems and rigid links between the main elements, and therefore it is necessary to consider non-traditional methods of stabilization for self-propelled machines, for example, due to dynamic damping of vibrations in the adapter suspension.

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