INVESTIGATION OF VIBRATION DYNAMICS IN VERTICAL PLANE OF TRACTORS WITH SINGLE AND DOUBLED WHEELS

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Abstract. The article presents the results of investigation of the dynamics of single and double-wheeled tractor systems in a vertical direction depending on the profile of the supporting surface. The study was conducted for tractors of the HTZ-240 series. It has been established that an increase in the efficiency and productivity of the machine and tractor aggregates is achieved by increasing the operating speeds, processing width and rational use of equipment. However, the uneven field surfaces and travel speeds cause additional vibrations that negatively affect the performance of the aggregates and can lead to increased soil compaction. To understand this process better, a mathematical model of the wheel has been developed that takes into account the rolling resistance coefficient, which depends on the pressure in the tyres, and on the speed. An equivalent dynamic model of single- and double-wheeled systems was also compiled in the MatLab/Simulink environment. Parameters of oscillations of the wheel system have been determined: the minimum radius of a single wheel is 0.7599 m, the maximum is 0.8605 m, and the span is 0.1006 m; for a doubled wheel, the minimum radius is 0.75 m, the maximum is 0.820 m, and the span is 0.07 m. Doubled wheel demonstrates a smaller amplitude and span of vertical oscillations, as well as a more stable dynamic radius, compared to the single wheel system. A conclusion has been drawn that the obtained results may be used to improve the designs of the tractor wheel systems in order to improve their performance characteristics and reduce the negative impact on the soil.

Keywords: dynamics, wheel, tractor, slippage, speed, dynamic radius.

Introduction

The efficiency of the machine-tractor aggregates (MTA) directly depends on the operating speeds, working width and rational use of the agricultural machinery [1]. However, uneven field surfaces and the speed of movement create additional vibrations that can negatively affect the performance characteristics of the aggregates [2; 3].

Detailed research of the characteristics of the relief of the field allows to improve the quality of technical solutions, aimed at reducing vibrations, decreasing the soil compaction and improvement of the operator working conditions. In the international standard ISO 8608:2016 [4] there are described methods for studying vertical accelerations that occur when the equipment is moving across uneven surfaces, as well as their impact on the operator's comfort and mechanical damage to the equipment. However, the direct methods for measuring the relief of the surface have limitations in accuracy and reproducibility since they do not always consider the soil deformations under the impact of the wheels of the vehicle [5; 6].

Additional vibrations of individual tractor elements lead to increased soil compaction, which makes it difficult for the plants to germinate, reduces fertility and may violate the agricultural requirements. In addition, such vibrations worsen the traction and grip properties of the tractor, accelerate the wear of its mechanisms and create unfavourable conditions for the operator [7; 8]. Thus, the research of the dynamics of a single- and double-wheeled tractor systems in the vertical direction, taking into account the profile of the supporting surface, is an urgent task that allows optimizing the design of the wheel systems and increasing the operational efficiency of agricultural machinery [9].

The contemporary methods for the assessment of the profile of the supporting surface of the field during the operation of the machine-tractor aggregate (MTA) have a number of limitations. The methods of direct measurement, such as optical technologies [10], often do not ensure sufficient accuracy and reproducibility since they do not consider deformations of the surface, caused by the movement of the wheels of the machinery. According to the Standard ISO 8608:2016 [4], when analysing vibrations of agricultural machinery, it is necessary to consider not only the roughness of the soil but also mechanical effects that influence the operator's comfort, and the durability of the equipment.

Indirect measurement methods of the field profile suggest the use of vibration characteristics of the tractor. For this purpose, in a number of investigations [11; 12] there was applied a two-stage methodology: first, the vertical accelerations of the tractor were determined under real operating conditions, then they were reproduced on a test bench in order to obtain comparable results. Such an approach allows for a detailed analysis of the dynamic processes, occurring in the tractor structure when moving across an uneven surface.

Experimental studies [13] have confirmed that the surface profile and the speed of movement have a significant impact on the dynamics of MTA. An analysis of the spectral characteristics of the oscillations showed that the greatest influence upon the behaviour of the tractor is exerted by disturbances with frequencies below 4 Hz. These data are consistent with the results of the agricultural machinery tests on standard test sites, conducted in accordance with ISO 5008 [14].

Further investigations [15; 16] made it possible to identify regularities of the influence of vibrations upon the elastic elements of the tractor, such as tyres, cabin and shock-absorbing fastenings. It was found that various configurations of the wheel systems exert unequal effects upon the dynamics of the tractor. In particular, the doubled wheels exhibit a lower vertical oscillation amplitude and a more stable dynamic radius, which can help reduce the soil compaction and improve the traction characteristics.

To understand this process better, it is necessary to take into account the physics of the reaction of the tyre to the unevenness of the field surface. In particular, it is important to consider the influence of the elastic properties of the machine-tractor aggregate (MTA) when the wheel is moving at a constant speed along an obstacle, the length of which is significantly less than the contact length. This results in a change in the rolling radius of the tyre.

In studies [17; 18], four key factors influencing the behaviour of the wheels were identified: the properties of the tyre coating; the effective plane of the road; the effective rolling radius when rolling along a coil; and the kind of vibrations. Thus, the analysis of the existing investigations emphasizes the importance to consider the dynamic characteristics of the wheel systems when designing agricultural machinery. The modern modelling methods, such as the use of MatLab/Simulink, allow more accurate prediction of the tractor behaviour on various types of soil, which opens up prospects for further research and optimization of the design of the machine-tractor aggregates.

Materials and methods

The movement of a wheel when it hits an obstacle is accompanied by a change in the rolling radius, caused by its elastic deformation. Depending on the characteristics of the surface of the road, the speed of travel and the design of the tyre, the response of the wheel can vary significantly.

Fig. 1 shows a diagram of the reaction of the wheel to a disturbance, showing how its parameters change at a contact with an obstacle. It is important to take these changes into consideration for the analysis of the dynamics of the machine-tractor aggregate and for the determination of the optimal parameters of the wheel systems.

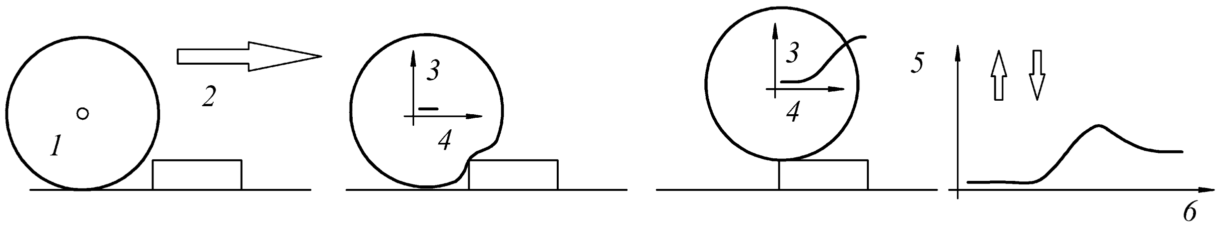

Fig. 1. **Scheme of the wheel reaction to a disturbance when passing obstacles:** 1 – elastic wheel; 2 – speed of movement; 3 – tire displacements; 4 – space/time; 5 – vertical displacements; 6 – time

The analysis of the amplitude characteristics shows that a decrease in the rotational speed affects the dynamic behaviour of the hub. A similar relationship is observed in the response of the tyres and seats, which has a significant impact upon the operator's comfort.

So, when doing standard tests, it is important to generate an input signal that excites the fundamental frequencies of MTA. It is these frequencies that have the greatest impact on the operator's working conditions and the efficiency of the technological process. To simplify the analysis of the vertical dynamics of the tractor and the assessment of the durability, comfort and strength of its elements, there is no need to conduct tests on complicated test tracks. It is sufficient to develop a single rough test surface that allows simulation of the required operating conditions [19]. This will allow for standardization of research and reduction of the testing costs.

During its operation MTA is exposed to many external factors that change the vertical loads on the chassis and the engine. Such factors include heterogeneity of the physical and mechanical properties of the soil, uneven relief, and uneven traction resistance from the aggregated agricultural machinery. These effects are random in nature and are described by stochastic functions. In addition, MTA itself is a source of vibrations, caused by the operation of the engine and the transmission.

Research [20] showed that the movement of the tractor across a field during technological operations is accompanied by slippage of the driving wheels. Depending on the operating conditions the degree of slipping may variate within the range from 0 to 15%, which makes a significant impact upon the dynamics of the tractor [21-24]. Among the factors influencing the wheel slippage, there are the wheel load, torque, tyre pressure and other operating parameters [25; 26].

To analyse the dynamic characteristics of the wheel system of the tractor, a mathematical model has been developed that considers the influence of the relief of the supporting surface, the elastic properties of the tyre and the speed of movement.

When driving across uneven surfaces, the wheel vibrations depend on a number of parameters, including:

- the elastic properties of the tyre;
- the coefficient of the rolling resistance;
- changes in the vertical load;
- the speed of movement;
- the profile of the supporting surface.

As noted earlier, the HTZ-240K series tractors can be equipped with both single-wheel and double-wheel systems [27]. During the study there were assessed the dynamic characteristics of a single wheel when moving along an uneven support surface.

A mathematical model of the movement of a single wheel has been developed, which takes into consideration the impact of the relief irregularities, the elastic properties of the tyre and the speed of the tractor. To investigate the dynamic characteristics of a single wheel, a simulation model was developed in the MatLab/Simulink environment. It allows to analyse the oscillations of the centre of mass of the wheel in a vertical direction depending on the profile of the supporting surface and the speed of movement. The model takes into account the following key parameters: the relief of the supporting surface – it is modelled as a harmonic function, which allows for various types of irregularities; the dynamic radius of the wheel – it changes depending on the elastic properties of the tyre and the pressure in it; the forces acting upon the wheel – they include the normal reaction of the surface, the rolling resistance forces and the traction force; the rolling resistance coefficient – it varies depending on the speed of movement and the pressure in tyres.

Fig. 2 shows a diagram of a single wheel model, implemented in MatLab/Simulink. During the simulation the dependences of the amplitude and frequency of oscillations of the centre of mass of the wheel were determined, as well as the impact of the parameters of the tyre upon its stability.

The results of simulation indicated that a single wheel is subject to significant vertical oscillations, which can lead to increased soil compaction and reduced traction characteristics of the tractor. Later a similar model was made for a doubled wheel, which made it possible to evaluate its advantages.

The shape of the profile of the supporting surface is modelled using a harmonic function, which allows considering the main peculiarities of the soil relief and its impact upon the dynamics of the movement of the tractor.

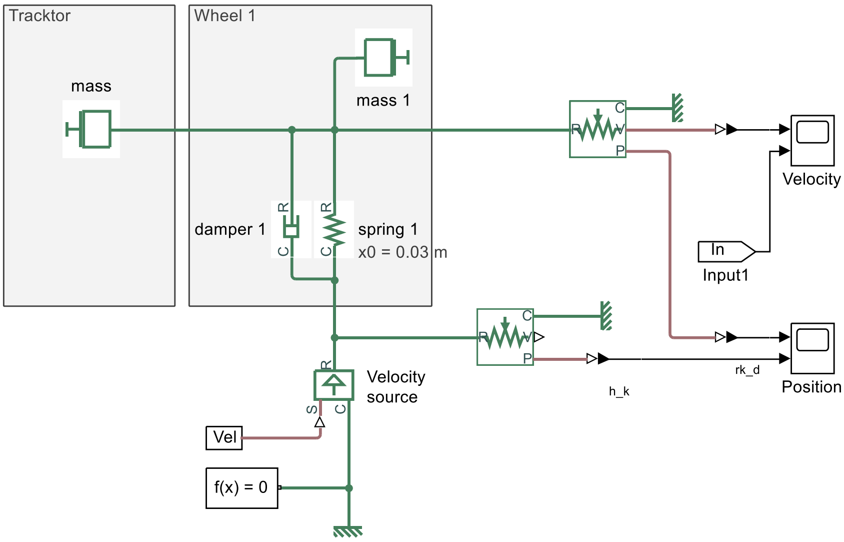

Fig. 2. **Model of a single wheel in MatLab\Simulink**

In order to investigate the dynamics of the doubled wheels, a diagram of the wheel system design was compiled, as well as an equivalent model of elastic and dissipative elements.

The design of a doubled wheel: In this configuration the wheel system rests on the support surface between the outer and inner wheels, which ensures a more uniform load distribution; the elasticity and compliance of the tyres in the vertical direction are the same for the outer and the inner wheels, which allows the wheel to adapt efficiently to unevenness of the terrain; due to the doubled design the vibration amplitude is reduced, and the dynamic rolling radius remains more stable, compared to single wheels.

The equivalent model of elastic and dissipative elements includes: the tyre rigidity – it characterizes the elastic resistance to deformation; the tyre compliance – it reflects the ability of the wheel system to adapt to the changing terrain; the dissipative elements – they model the energy losses due to internal friction in the tyre material.

A theoretical analysis of the dynamics of a doubled wheel in the vertical direction has been performed. It considers its interaction with the supporting surface. To simulate the dynamic processes, a similar dynamic model of a doubled wheel was developed in the MatLab/Simulink environment (Fig. 3).

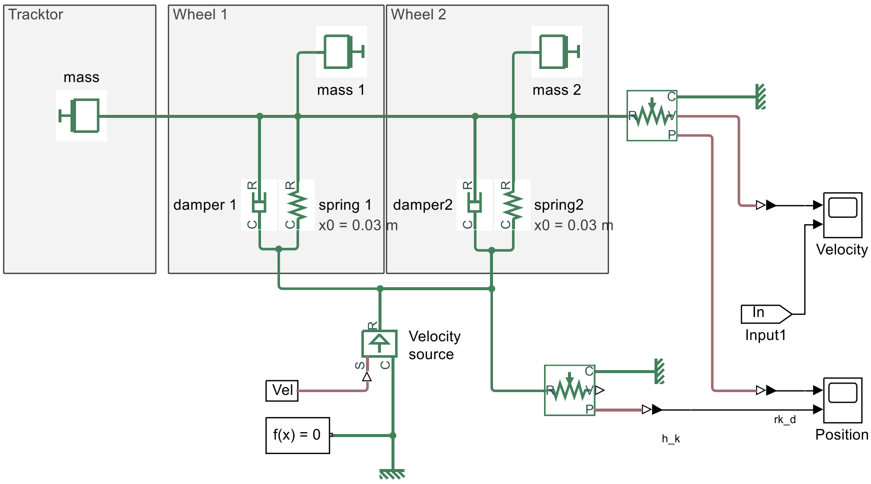

Fig. 3. **Model of a doubled wheel in MatLab\Simulink**

This model allows: to evaluate the impact of the surface relief upon the amplitude and frequency of the wheel oscillations; to determine the dependence of the dynamic rolling radius on the soil characteristics; to analyse the differences in the behaviour of single and doubled wheels when moving across uneven surfaces.

Results and discussion

Fig. 4 depicts the dependences of the rate of change of the height of the support surface profile and the centre of mass of a single wheel in a vertical direction. These dependencies allow to evaluate the impact of the soil relief upon the movement of the tractor and to determine the critical parameters at which the wheel vibrations have the greatest impact onto the traction characteristics and vibration loads.

The calculated height of the support surface profile confirms that unevenness of the soil creates dynamic disturbance affecting the rolling radius of the wheel and the amplitude of its vertical oscillations. This must be taken into consideration when designing the tractor wheel systems and selecting optimal operating speeds.

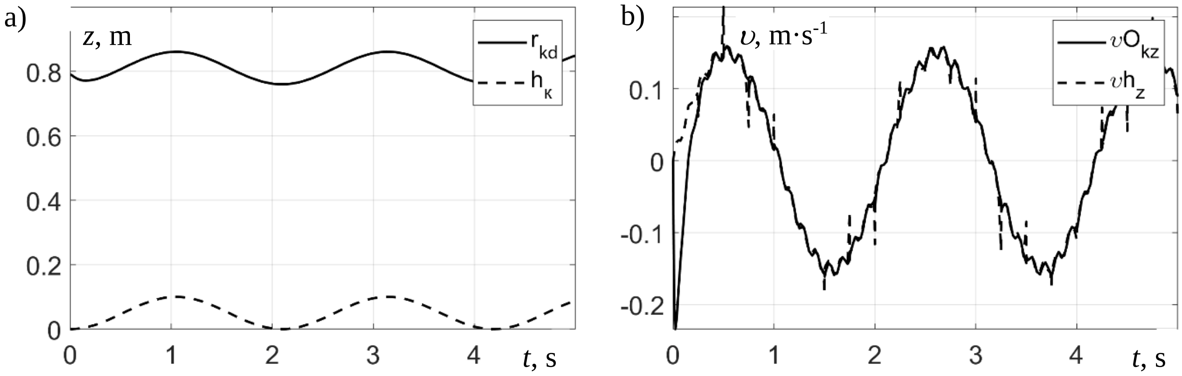

Fig. 4. **Dependencies of the heights and speeds of the support surface profile and the centre of mass of the wheel:** a – change in the height of the profile of the supporting surface and the centre of mass of a single wheel in time; b – rate of change of the height of the profile of the supporting surface and the centre of mass of the wheel; r_{kd} – dynamic radius of a single wheel, m; h_k – height of the support surface profile, m; υO_{kz} – speed of the movement of the centre of mass of the wheel in the vertical direction, m·s^{-1}; υh_z – speed of movement of the height of the support surface profile in the vertical direction, m·s^{-1}

From the simulation results it was established that: the range of oscillations of the support surface profile is 0.1 m with a period of 2.11 s (Fig. 4, a). This confirms that the surface relief has a significant effect on the dynamic behaviour of the wheel; the rolling radius of a single wheel varies within the range of 0.759-0.860 m, and its oscillation range is 0.101 m with the same period of 2.11 s.

The analysis of the speed characteristics shows that the speeds of a change of the height of the support surface profile and the centre of mass of a single wheel have an identical period (2.11 s), which indicates the synchronization of their dynamic reactions (Fig. 4, b); the minimum speed of a change of the height is 0.14 m·s^{-1}, the maximum is 0.157 m·s^{-1}, the range is 0.297 m·s^{-1}. These results demonstrate that a single wheel responds to the surface irregularities with a certain shift of time, and its dynamic characteristics depend on the shape and profile parameters of the soil.

To describe the dependence of the speed of the centre of mass of a single wheel in the vertical direction upon the rate of changes of the height of the support surface profile, a transfer function is used that has the following form:

$$H(s) = \frac{78.24 \cdot s^2 + 38.08 \cdot s + 673.1}{s^3 + 8.526 \cdot s^2 + 46.73 \cdot s + 41.46}. \quad (1)$$

There are calculated and shown in Fig. 5 the rates of change of the height of the support surface profile and the centre of mass of the doubled wheel in a vertical direction, and the height of the support surface profile is determined. There were calculated (Fig. 5) dependences of the speeds of the support surface profile and the centre of mass of a doubled wheel on time in a vertical direction.

It has been established from the results of the research that the rolling radius of the doubled wheel varies within the following limits: minimum value – 0.75 m; maximum value – 0.82 m; the range of radius oscillations – 0.07 m (Fig. 5, a).

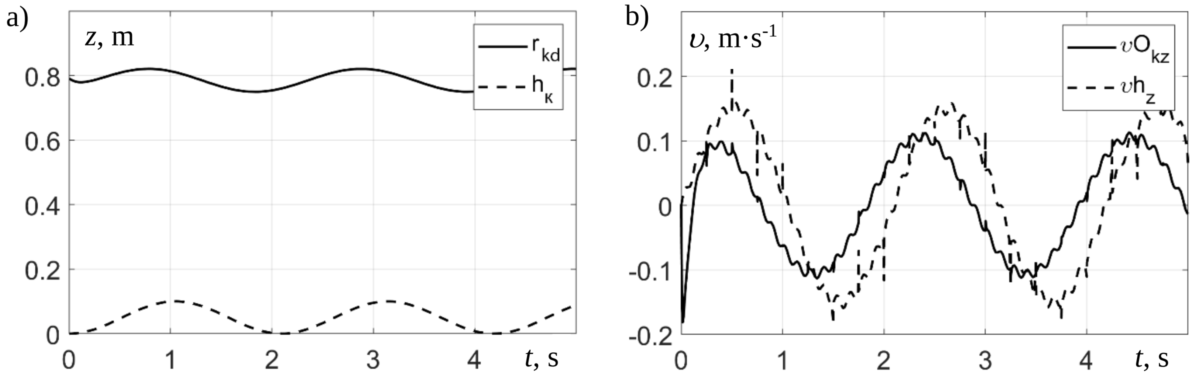

Fig. 5. **Dependencies of the heights and speeds of the support surface profile and the centre of mass of the doubled wheel:** a – change in the height of the profile of the supporting surface and the centre of mass of a doubled wheel in time; b – rate of change of the height of the profile of the supporting surface and the centre of mass of the doubled wheel; r_{kd} – dynamic radius of a dual wheel, m; h_k – height of the support surface profile, m; υO_{kz} – speed of movement of the center of mass of the wheel in the vertical direction, m·s^{-1}; υh_z – speed of movement of the height of the support surface profile in the vertical direction, m·s^{-1}

The period of oscillations of the radius of the doubled wheel coincides with the period of the single wheel and is 2.11 s. This confirms that the interaction of the wheel system with an uneven terrain remains similar, but the doubled wheels provide more stable dynamic characteristics. The doubled wheel demonstrates a smaller amplitude and range of oscillations of the centre of mass velocity in the vertical direction (Fig. 5, b) than the single wheel. The range of fluctuations in the speed of the centre of mass of the doubled wheel is 0.204 m·s^{-1}. The minimum speed is 0.105 m·s^{-1}, the maximum speed is 0.09 m·s^{-1} (Fig. 5, b).

The transfer function of the dependence of the speed of the centre of mass of the doubled wheel in the vertical direction υO_{kz} upon the rate of changes of the height of the support surface profile υh_z looks like this:

$$\boldsymbol{H(s) = \frac{33.42 \cdot s^2 - 3.317 \cdot s + 195.7}{s^3 + 14.42 \cdot s^2 + 40.72 \cdot s + 12.57}}. \tag{2}$$

The logarithmic amplitude-phase frequency characteristic of the speed of the centre of mass of a single and a doubled wheel in the vertical direction is calculated using formulas (1), (2) and is shown in Fig. 6.

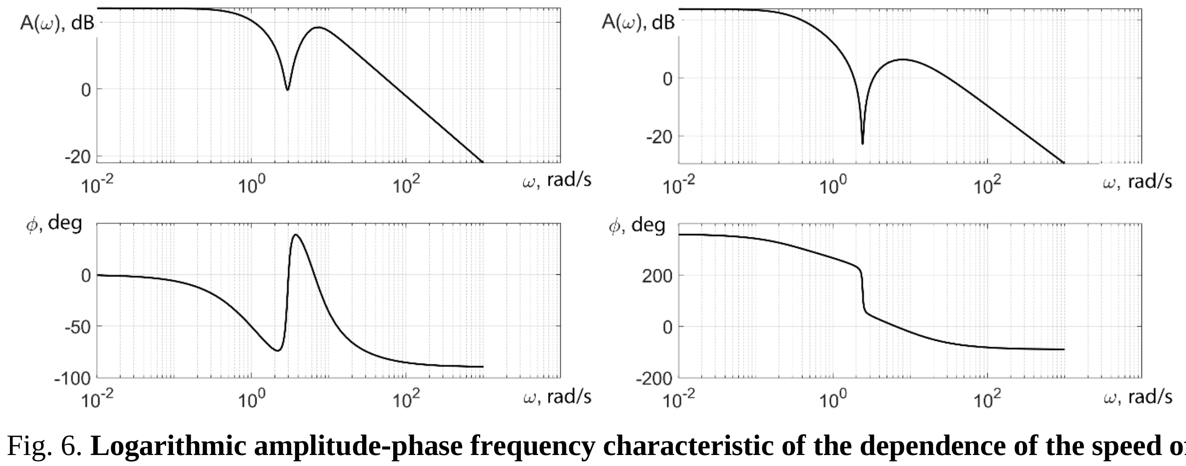

Fig. 6. **Logarithmic amplitude-phase frequency characteristic of the dependence of the speed of the centre of mass of a single wheel in the vertical direction upon the rate of changes of the height of the support surface profile**

It should be noted that the doubled wheel exhibits fewer vertical dynamics, compared to the single wheel (Fig. 6). This is due to the distribution of the load between the two tyres, which reduces the amplitude and range of oscillations. The oscillation period of the rolling radius of the doubled wheel is 2.11 s, which corresponds to the oscillation period of the single wheel.

However, the speed of movement of the centre of mass of the doubled wheel in the vertical phase does not coincide with the speed of changes of the height of the support surface profile.

The reasons of the speed mismatch: elastic deformation of tyres; doubled wheels have a more uniform load distribution, which slows down the reaction to changes in the soil profile; the damping effect. Adaptation to uneven surfaces. The doubled design allows the wheel to smooth out small changes in the height of the surface profile, which slows down the rate of vertical movement of the centre of mass.

Installation of dual wheels on a tractor increases its traction properties, which was previously studied in the works [1; 27]. The paper examines the wheel doubling and its impact upon the dynamic parameters, such as the height of the wheel centre of mass and the speed of the height of the wheel centre of mass in the vertical direction, which, in turn, affects the vibrations of the tractor frame. The use of dual wheels results in a decrease in the speed of the wheel centre of mass in the vertical direction by 0.04 $m \cdot s^{-1}$ when moving along the same support surface. The developed models of single and dual wheel dynamics can be used in further studies of the tractor frame vibrations. The transfer functions (1), (2) may be used to evaluate the smoothness of the tractor movement and to study the smoothness of the tractor cabins.

Author contributions:

Conceptualization, V.B., V.A., R.A., A.R., methodology, V.B., V.A., R.A., A.A. and A.R., software, I.H., I.B., validation, R.A., I.H., formal analysis, R.A., I.B., O.T. and Ye.I., investigation, A.A., O.T. and I.B., data curation, I.H., writing – original draft preparation, R.A., writing – review and editing, I.B., A.R., A.A., visualization, O.T., Ye.I. All authors have read and agreed to the published version of the manuscript.

Conclusions

1. Research has been conducted of the dynamics of single and doubled wheel systems of the HTZ-240K series tractor in the vertical direction, depending on the profile of the supporting surface. It has been established that an uneven terrain and the driving speed have a significant impact upon the vibrations of the wheel and, accordingly, upon the dynamic behaviour of the tractor.
2. Parameters of the oscillations of the wheel system have been determined: the minimum radius of a single wheel is 0.759 m, the maximum is 0.860 m, and the span is 0.101 m; for a doubled wheel the minimum radius is 0.750 m, the maximum is 0.820 m, and the span is 0.07 m; the doubled wheel demonstrates a smaller amplitude and span of vertical oscillations, as well as a more stable dynamic radius, compared to the single wheel.
3. Mathematical models of single and doubled wheels have been developed in the MatLab/Simulink environment, which made it possible to reproduce their dynamic behaviour and calculate the logarithmic characteristics of the amplitude-phase frequency. It has been determined that the doubled wheels reduce the amplitude of vertical oscillations of the centre of mass, which leads to a decrease in the vibration loads, a decrease in the soil compaction and an increase in the traction characteristics of the tractor.
4. The obtained results may be used to improve the design of the tractor wheel systems in order to improve their performance characteristics and reduce the negative impact upon the soil.

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