Perspectives of increasing smooth ride of wheeled vehicles without suspension with pneumatic damping system

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Abstract. In the article the analysis of a modern research condition in the field of increase of smoothness of a course of wheeled vehicles without suspension with pneumatic damping system is resulted. The reasons limiting the solution of a global problem of the further development of wheeled vehicles without suspension and growth of productivity and safety of work at performance by them of transport, agricultural and road-building works are formulated. The basic ways of the decision of the given problem solution, consisting in increase of damping properties of pneumatic tyres for wheeled non-suspended vehicles without increase in resistance to rolling of wheels and decrease in a resource of tyres are analyzed. Thus development of essentially new innovative structures of wheels, improving smoothness of a course and other operation al properties of non-suspended vehicles is offered.

1. Introduction
The suspensionless wheeled vehicles (agricultural tractors and combines, self-propelled road-building and special-purpose machinery) operate at resonant speeds in the field and on broken roads, which leads to their intense fluctuations, reduced productivity and diseases of operators. The additional suspension of cabins and seats used in suspensionless vehicles does not solve the problem of significant reduction of vibrations and increase of average travel speeds. This constrains the solution to the global problem of further development of suspensionless vehicles and the growth of productivity and safety in the performance of their transport, agricultural and road-building works, which leads to significant annual economic losses for the country.

2. Possible solutions to the problem of smooth ride of wheeled vehicles without suspension
One of the directions of solution of the above mentioned problem is a significant increase of damping properties of pneumatic tyres for the suspended vehicles without increasing the rolling resistance of wheels and reducing the service life of tyres. This is possible by reducing the radial stiffness of the wheels while maintaining static deflection and increasing the inelastic resistance of the tyre when the vehicle body vibrates. To ensure these new qualities, it is necessary to search for new wheel structures that have no analogues in the world, and to conduct appropriate scientific research. The solution of this extremely difficult task will allow to reduce significantly the vibrations of tractors and road-building vehicles, increase their productivity and significantly improve the working conditions of operators.
In this regard, the challenge of developing innovative wheel structures that improve the smoothness and stability of the drive, fuel efficiency, controllability and braking properties of the suspensionless vehicles is urgent.

3. Analysis of the current situation in the field of smooth ride of wheeled vehicles without suspension

The tyres are continuously being improved and dozens of patents are granted each year for new tyre designs. However, the analysis of modern tyres shows that for the past 175 years since the day of invention in 1844, the design of the tyre has not changed fundamentally. As in R.W. Thomson's pioneering invention, a tyre is an elastic shell that forms elastic support surfaces around the rims, filled with compressed air. Nowadays it is impossible to create high-speed vehicles without tyres.

The development of tyre design has taken two directions: development of increasingly low-profile tyres for the «good roads» and tyres with high profile heights for the «bad roads» and off-roads. The introduction of tyres with a high profile height has made it possible to eliminate the use of spring suspension, which has made it possible to create suspensionless vehicles with a simpler design.

Nowadays, a variety of mobile wheeled vehicles with tyres with a high profile height have been designed, operated and continuously improved.

First of all, they are so-called suspensionless vehicles: wheeled tractors, combine harvesters, agricultural, road construction and special-purpose vehicles. These machines are widely used in transport, agricultural, construction and other works.

Secondly, they are vehicles with suspension: heavy dump trucks, various army vehicles, including mobile missile systems, for which the task of increasing the speed of movement on broken ground roads and terrain while ensuring the preservation of the transported product and the efficiency of the crew is very important.

It has been established by the conducted researches that the characteristics of tyres - their dynamic rigidity smoothing and absorbing abilities — have the greatest influence on smooth running of the vehicles having a suspension and tyres with the big height of a profile [1–4].

Many scientists, both in Russia and abroad, have studied the output characteristics and modeling of pneumatic tyres [1–25].

The analysis of domestic and foreign literary sources has shown that in order to solve this problem, first of all, it is necessary to develop a methodology for the synthesis of innovative pneumatic wheels with internal structural elements, providing for the solution of three contradictory scientific problems, each of which can be considered fundamental without exaggeration.

3.1. The first conflicting scientific task

The first conflicting task is to improve the vibration protection properties of pneumatic tyres. The problem situation, currently unresolved in domestic and foreign science, here is that it is necessary to reduce the radial rigidity of the tire without increasing its static deflection.

The studies of the smoothness of the 8x8 high cross-country vehicle movement conducted by foreign researchers under the guidance of B.D. van Deusen have shown that the greatest influence on the value of the mean square acceleration of the suspended parts in various road conditions is provided by the tire rigidity, which was regulated by the pressure change [2]. The reduction of suspension rigidity and the installation of shock absorbers had a much smaller effect. The greatest effect was obtained with simultaneous reduction of tire rigidity, suspension and installation of shock absorbers.

Professor N.N. Yatsenko notes that in order to increase the smoothness of the movement of wheeled suspensionless machines it is necessary to reduce the radial stiffness of tyres by 2–3 times while keeping the static deformation of the tyres [3, 4]. He also notes that the reduction of radial stiffness can be achieved in the design of ultra low pressure wide tyres. However, the static deformation of tyres is very high, which reduces their service life. In addition, these tyres have large dimensions, so they are not suitable for most common wheeled transport vehicles.

As the elastic characteristic of the tyre is almost linear, a reduction in stiffness is only possible if the static deformation of the tyre increases. However, the high static deformation of the tyres reduces...
their durability and increases the rolling resistance coefficient, which in turn leads to higher operating costs for the machine. Therefore, the only way to reduce the radial stiffness of a tyre without increasing its static deformation is to change the elastic characteristic from linear to non-linear — S-shaped. According to Professor Rothenberg R.V., this characteristic is considered to be ideal for the vehicle suspension, as it provides high vibration protection properties and reduces the probability of a breakdown. [5]. It is not possible to obtain such elastic characteristics of the tyre by changing its profile or the value of the filling pressure, because the elastic characteristics of tyres of all profiles and at any pressure are progressive. Their rigidity in the small initial part of the elastic characteristic increases with increasing deformation, and then becomes almost linear. The S-shaped elastic characteristic of a tyre must have a constant stiffness of 2 to 3 times less than that of a conventional tyre in its static deformation zone. The determination of this section from the mean square deformation of the tyre, which occurs during the motion of the unevenness, is a different task. A wheel that implements the calculated S-shaped elastic characteristic of the tyre can only be created by introducing the internal structural elements into the wheel.

3.2. Second conflicting scientific task

The second conflicting task is to improve the damping properties of pneumatic tyres to effectively dampen the vertical vibrations of the wheels and the vehicle as a whole. The problem situation, which is currently also unresolved in domestic and foreign science, here is that it is necessary to increase the damping properties of tyres without increasing their coefficient of rolling resistance.

In order to evaluate the absorbing properties of the tire, an elliptical-steppe model of viscosity resistance in the tire material [6] has been spread, the use of which approximates the calculated statistical characteristics of the occurring processes to the similar characteristics obtained from observations and measurements in a field experiment. The absorbing or damping capacity of the tire material manifests itself in the vibrations of its deformation in the vertical, longitudinal and lateral directions and is determined by the amount of mechanical energy converted into thermal energy at its deformation. It can be estimated by the area of the hysteresis loop of the elastic characteristic, the dynamic coefficient of resonance oscillations of the load on the tire, the damping coefficient or the relative attenuation coefficient ψ.

Figure 1 shows the dependence of the damping factor in the tire on the deformation frequency and rolling speed in linear coordinates [7].

The figure shows that the damping in the tyres is very small. Up to a rolling speed of 30 km/h, the damping factor $k_t$ decreases with the increase in the deformation frequency $\omega$, and at speeds above 30 km/h, $k_t$ is virtually independent of $\omega$. Even a slight increase in travel speed from 0 to 10 km/h at a tyre deformation rate of 16 rads/s (typical for wheeled tractors in agricultural work) leads to a 4–5 times reduction in $k_t$. For trucks with speeds ranging from 0 to 60 km/h and frequencies of 45 rad/sec, and for cars moving at speeds ranging from 0 to 100 rad/sec at 75 rad/sec, the damping factor $k_t$ is reduced by more than 10 times.

In the works of Professor N.N. Yatsenko and other scientists it was established that the relative attenuation coefficient of tyres is very small [3, 4]. For non-rotating tyres it is within the limits of $\psi = 0.03 \ldots 0.05$, and for rotating tyres it is 3 ... 5 times less than static tyres. Obviously, in [3] the rolling speeds of the tyres were low, because according to the data in Fig. 3 at typical truck and passenger car travel speeds, the damping factor for vertical vibration is more than 10 times lower than that for non-rotating tyres and is $\psi = 0.003 \ldots 0.005$.

That's why at high-frequency (resonance) influence from road roughness pneumatic tires weaken vibrations of the machine body, and at resonance frequencies - considerably strengthen (in 10 and more times). The experience of operation of wheeled suspended machines and the conducted research show that when performing transport work they have insufficient smoothness of movement and do not provide observance of norms of vibroload of the operator-driver and crew, even when driving on the improved roads. The reason for this is the low vibration protection properties of pneumatic tyres and their inability to absorb the energy of the body's vertical vibrations. In order to reduce the vibrations on the driver's body, as well as to ensure traffic safety, the driver has to reduce the speed of the machine, which impairs fuel efficiency, reduces productivity and efficiency of its use.
The analysis of the literature has shown that with increase in speed of movement of the machine influence of a hysteresis in a material of the tyres on damping of vertical fluctuations of the case of the machine decreases. When the tire rotates, its radial deformation is distributed around the tire circumference, as the vertical deformation rate is much lower than the linear speed of the tire. This results in a significant reduction in the effectiveness of the vertical vibration damping due to the loss of material in the tire material, and the higher the speed of rotation of the tire.

So experimentally it is established [8] that at rotation of the tyre of the wheeled car with linear speed of 10 km/h, characteristic for wheeled tractors on agricultural works, its absorbing properties decrease in 4–5 times in relation to the nonrotating tyre (figure 2) [9]. The optimum relative attenuation coefficient required for smooth running should be within the limits of $\psi = 0.15 \ldots 0.25$. Thus, the tyres have a very low damping capacity, which creates a problem of smooth running of wheeled suspensionless machines. Therefore, it is necessary to find an opportunity to increase the damping capacity of the tyres with vertical vibrations in 15–25 times to approach the required optimum value of $\psi = 0.25$ without increasing the coefficient of resistance to rolling. Moreover, the damping properties of the tyre should not be reduced when the rolling speed of the tyre increases.
In the works of Professor I.M. Ryabov it is shown that it is possible to improve the damping properties of tyres without increasing the coefficient of rolling resistance only due to internal structural elements [1, 9, 10]. Thus, in 1998 I.M. Ryabov proposed a way to solve this problem and received a patent of the Russian Federation for the invention № 2108240 for the wheel of a vehicle, the tire which contains an internal pneumatic damping system. It is made in the form of an inner shell mounted on the rim with the possibility of axial rotation of the inner shell with a truncated lower part, the cavity of which communicates with the tire cavity through valves and throttling holes [9]. However, the wheel proposed by I.M. Ryabov was not sufficiently studied on physical models and was not manufactured. Also, the theory and methods of optimization of damping system parameters were not developed. It has been established that this wheel can not provide the increase of damping of vertical vibrations of the suspensionless machine to the required level. In addition, the proposed wheel does not provide the necessary reduction of tire rigidity, which makes it necessary to search for new structures of internal elastic damping elements of the wheel and conduct research to optimize their parameters.

3.3. Third conflicting scientific task
The third conflicting task is in the complex area of increasing the smoothness of movement, controllability and stability of the wheeled vehicle. At the same time, it is necessary to reduce the stiffness of tyres and increase their resistance to side retraction, but it is very difficult to do so, because with a decrease in the rigidity of tyres (by reducing the pressure), their resistance to side retraction decreases.

The insufficient resistance to tyre sideways retraction impairs the stability and controllability of the wheeled vehicle, reduces the safety of the vehicle and the average speed of the vehicle, and leads to rapid fatigue for the driver and crew.

It is known that the resistance coefficient to the side retraction of the tyre is the maximum value at the nominal load on the tyre and decreases both with the increase of the normal load and with its reduction, and the underload of the tyre has a greater impact than its overload. The increase in the side drive resistance coefficient results in a reduction in the height of the tyre profile. However, its vibration protection properties decrease. To solve this controversial problem, that is to increase resistance to side retraction of pneumatic tyres without reducing the height of the profile, it is possible only through the introduction of internal structural elements into the wheel.

4. Conclusions
The above analysis of the current state of research in the field of influence of the structure and parameters of the internal elements of the innovative wheel with pneumatic tire on its elastic damping
properties and frequency characteristics of oscillations in the process of rolling shows that these data are not enough to create innovative solutions that significantly improve the vibration-protective properties of pneumatic tires and the quality wheeled vehicles without suspension with pneumatic damping system.

Thus, the search for new wheel structures and the determination of the optimal parameters of the built-in elastic damping elements, which ensure a smooth ride without increasing the rolling resistance of the wheel, is an urgent task.

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