THE INFLUENCE OF PARAMETERS OF RUNNING SYSTEMS AND THEIR SUSPENSION ON THE SAFETY OF OPERATORS OF MOBILE MACHINES AND ENERGY EQUIPMENT

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Abstract. The scientific work is based on the tasks of applied research on initiative topics on the topic: «Substantiation of parameters and modes of interaction of the drive wheel with the soil», state registration number 0117U006833. The authors' research is aimed at solving current problems of vibrational vibrations on the operators of technological means.

All machines and mechanisms used by man in production and in everyday life are sources of various mechanical measurements and, accordingly, hazards. Of all the types of hazards caused by mechanical influences, vibration is the most dangerous for humans. It is human physiology that contributes to the negative effects of vibration. Due to the fact that the human body consists of hard bones, soft muscles, joints, various internal organs, it can be considered as a complex oscillatory system, the mechanical reaction of which depends on the parameters of vibration. At high frequencies (less than 2 Hz), the body responds to total vibration like a hard mass. At higher frequencies, the body responds as an oscillating system with one or more degrees of freedom. This is manifested in resonance increases in the oscillations of individual organs of the body at certain frequencies. It is for the sitting body position (in which the mobile operator is most of the time) that the resonance is at a frequency of 4-6 Hz.

One of the most effective ways to reduce the negative impact of vibrational vibrations on the operator is to reduce the oscillations in the source of their occurrence, as well as the path of propagation from source to operator. This can be partially achieved, including the choice of rational

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pressure in the wheels of the vehicle, as well as high-quality and timely diagnosis of its individual components and units. This work is devoted to these important issues, and therefore its relevance is beyond doubt.

In the scientific work the question of influence of a condition of a basic surface and geometrical parameters of a wheel of a tractor on speed of its movement and frequency of vibration fluctuations which arise at it is investigated. This issue is of considerable theoretical and practical importance, because the road and wheel oscillations caused by road irregularities cause a significant deterioration in the performance of the tractor.

These issues have been studied by a number of researchers, but they have varied narrowly. That is why the task was to consider more deeply the connection between the state of the wheel and the coating with the parameters of vibration oscillations that occur during movement.

In theoretical studies, the relationship between the length of the wheel chords and the irregularities between the two points of contact of the wheel was established. The support surface equation was represented by a sinusoid with a variable amplitude coefficient. Depending on the ratio of the radius of the wheel and the geometric dimensions of the protrusions and depressions of the support surface, two groups of equations were obtained that describe the parameters of vibrational oscillations. The results of analytical studies were illustrated by the corresponding geometric relationships.

To verify the theoretical references, experimental studies were conducted with a system for measuring the parameters of vibration oscillations of controlled axles of wheeled agricultural tractors. The study was performed on two variants of the road surface. The results of experimental research are presented graphically in the form of oscillograms of vibration acceleration of the controlled axle of the tractor, as well as in tabular form.

Theoretical and experimental studies show that there is an inverse relationship between the value of the wheel radius and the parameters of vibrational oscillations. As the translational speed of the tractor increases, the parameters of vibration oscillations also increase.

The aim of the work is to reduce the negative impact of vibration load on the operator of a mobile vehicle by substantiating the rational parameters of the wheel and determining the location and method of diagnosing its individual components and units.

To achieve this goal you need to perform the following tasks: determine the causes of injuries in the operation of mobile vehicles; to analyze the harmful effects of vibration oscillations on the mobile operator; identify ways to reduce vehicle vibrations; to carry out mathematical formalization of the process of oscillations of the operator's workplace; to build a mathematical model of oscillations of the system «road – vehicle – operator».

In this research we used research methods to determine theoretical data based on mechanical and mathematical modeling of the interaction of elastic propulsion and curved support surface using the basic principles of theoretical mechanics and higher mathematics.

1. Introduction

The agro-industrial complex of Ukraine is characterized by extremely unsatisfactory technical condition of vehicles and means of production due to depletion of their resources, shortcomings in ensuring labor discipline due to seasonal and field nature of agricultural work, uncertainty over the status of labor protection control of small private farms. third-party uneducated persons, the lack of qualified specialists in the field of occupational safety and more [1; 2; 10; 11].

According to the statistics provided by the State Labor Protection Supervision for the last five years on the state of labor protection in agricultural production, two opposite trends can be observed: a monotonous decrease in the number of injuries and an increase in the severity of injuries. The decrease in the incidence of injuries in agriculture is primarily due to reduced production, hiding from investigations and accidents, reducing the number of medical facilities in rural areas, lack of funds to purchase medicines, but not due to preventive work on labor protection. Therefore, the opposite trend is more indicative for the analysis, as the rates of fatal injuries in agricultural production have not changed in recent years, significantly exceeding those in industry as a whole [2; 11; 12].

2. The main causes of injuries

Unsatisfactory working conditions on agricultural machinery are mainly due to exceeding the standard parameters of environmental impact on personnel, and exceeding the limit of agricultural machinery. It should be understood that even the use of modern domestic or leading foreign companies of agricultural machinery leaves room for risk of injury due to structural (in terms of safety and reliability) shortcomings, organizational miscalculations in the implementation of technological processes, low level of mastery of safe work methods. Currently, the existing fleet of agricultural machinery is physically and morally obsolete, the degree of wear due to operation at high levels of overload for a long period reaches 75%, virtually suspended repair of machinery in specialized workshops, and therefore unable to restore the elements that determine safety of the agricultural unit. Most often, among other specialties, fatalities are suffered by mechanics, drivers, workers, whose work profile is related to the use of mechanisms in animal husbandry. In recent years, the share of fatal injuries due to technical malfunctions of machines and mechanisms has increased: from 11.2% (2014) to 19.2% (2021) and as a result of structural deficiencies: from 3.7% (2014).) to 9.3% (2021). At the same time more than half of cases of malfunction of technical means concern cars after seven-eight years of operation.

Ongoing and comprehensive analysis of injuries and occupational diseases is considered as one of the main functions of occupational safety management and taking basic measures to eliminate the causes of injuries and diseases. The generally accepted classification of causes of occupational injuries is as follows.

Technical reasons that can be described as reasons that depend on the level of organization of labor in production, namely: imperfect technological process, design defects of equipment, tools and devices, insufficient mechanization of heavy work; imperfect fencing, lack of special protective equipment, means of signaling and blocking, insufficient strength and reliability of machines, harmful properties of the processed material, etc. These reasons are sometimes called constructive or engineering.

Organizational reasons that depend entirely on the level of organization of labor in production. These include: unsatisfactory condition of the territory, driveways, passages, violations of the rules of operation of equipment, vehicles, violations of technological regulations, violations of rules and regulations during transportation, assembly and storage of materials and parts; violation of norms and rules during scheduled maintenance and repair of equipment, vehicles and tools; shortcomings in training workers in safe working methods; insufficient technical supervision of dangerous works;

misuse of machines, mechanisms and tools; absence or unsatisfactory fencing of the working area; absence or non-use of personal protective equipment, etc.

Sanitary and hygienic reasons, which include: excess (relative) dust and air pollution of the working area; lack or insufficient natural light, increased pulsation of light flux; increased noise and vibration, infrasonic and ultrasonic vibrations in the workplace; increased levels of ultrasonic and infrared radiation, etc. [3].

The state of labor protection in Ukraine continues to be unacceptably low. The most eloquent evidence of this is the indicators of injuries in recent years. In his interview to one of the Internet sites, Deputy Head of the State Labor Service V. Sazhienko cited the following figures [4]. Over the last five years, the number of recorded accidents was (in the denominator – fatal accidents): 2016 – 315/50; 2017 – 265/46; 2018 – 278/42; 2019 – 275/46; 2020 – 208/28. 128/33 cases in the first nine months of 2021. Despite some positive trend over the years, the overall level of injuries, especially fatal, remains quite high. It was also noted that most injuries occur during the harvest. This is due to the maximum stress of the labor process, high temperature, which leads to erroneous actions, neglect of personal safety, lack of proper control over the safe performance of work by engineering and technical personnel and some other reasons. As you can see, most of the reasons (neglect of personal safety, lack of proper control over the safe performance of work) are organizational reasons, ie those that are of purely anthropogenic origin. But there are reasons (stress of the labor process, high temperature) that are related to the elements of the system «man – the labor process», ie are directly related to one of the components of labor protection, namely ergonomics. According to the International Organization of Ergonomics, which was adopted at the Congress in 2010: «Ergonomics is a scientific discipline that studies the interaction of man and other elements of the system, as well as the scope of theory, principles, data and methods of this science optimization of the overall performance of the system». According to this definition, ergonomics must perform the following tasks: conducting research aimed at adapting the elements of the system «man – the labor process» to the natural physical and psychological capabilities of the employee; ensuring maximum work efficiency; prevention of all possible threats to human health; optimize the cost of biological resources in the labor process. All these tasks fit organically into the purpose of labor protection, both a scientific discipline and a practical phenomenon, in this case in the system of labor protection in agriculture. This qualifies ergonomics as an element of a complex system of «labor protection» which is connected by intra-system connections with other elements of this system. In turn, ergonomics is a system for a number of relevant elements, the main of which are man and means of labor. During the labor process, they are inextricably linked, influence each other, their adequate interaction depends on both the outcome of the labor process and the health of the employee.

To implement the labor process requires at least two elements – man and means of labor. Usually, in most cases, the term «man-machine system» is used, although some means of labor, strictly speaking, are not machines [5; 7; 29].

The main task of labor protection is to ensure healthy and safe working conditions for people that minimize cases of occupational injuries and diseases. This requires a thorough study, including the internal relationships in the system «man – machine», the nature of their response to external disturbances while ensuring the regulatory performance of the system. This study is devoted to the study of these patterns.

In the modern methodology of scientific knowledge, the systems approach is characterized as a phenomenon based on the study of the object as a system: a holistic set of interconnected elements; sets of interacting objects; the totality of essence and relations. It is from this point of view that ergonomics-related systems should be studied.

When analyzing the latest research and publications on this topic, we must first pay attention to the works on the ergonomics of the workplace. It is noted that in contrast to the two-way relationship between man and machine (taking into account the emergence of feedback), the impact of microclimate and other parameters of the workplace on the employee is one-sided, ie the desire to change these conditions is not an end in itself [4].

It is noted that the operators are affected by a complex of harmful factors of production and labor process: uncomfortable heating microclimate, air pollution of the working area, noise, vibration, static and dynamic physical activity, uncomfortable working posture. All this leads to changes in hemodynamics and functional status, indicates the stress of regulatory systems and reduced adaptive capacity of the organism. Another conclusion concerns another element of the system under study, ie machines – with increasing service life of equipment, the degree of deviation of harmful factors from hygienic standards increases. Another work is devoted to the study of the influence of ergonomic indicators of the system on the reserves of the human adaptation system. The reliability of the human-machine system is largely determined by the ergonomics of technical systems, which in the long run can lead to deterioration of the functional state of the human operator. Having the appropriate functional reserves, the human body can significantly reduce the harmful effects not only of the technical system with which it is in long-term contact, but also of other environmental factors (environmental factors). Simultaneous consideration of ergonomic risk factors and the size of the functional reserve allows to improve the quality of diagnostic decisions about the state of the human body.

Other components of the system were studied, namely the issues of efficiency and reliability of agricultural machinery. Theoretical research was conducted to establish the laws of the probability of failure-free operation of «man-machine» systems, the level of reliability of which can be increased by improving the component «man-operator» [5].

Research of various systems is conducted in many directions with the use of modern methods. But we must also recognize that there are still many problems in this area of human life. This is eloquently evidenced by the statistics of occupational injuries (including fatalities) in agriculture of Ukraine. We have given data to only one industry, but in others the situation is slightly better, and in some – even worse. Therefore, the task of studying the functioning of this system, clarifying the interaction of its constituent elements, making adequate decisions to reduce possible risks to the ability to work and human health remains relevant [3; 4; 5; 6].

There are three stages in the interaction of man and machine:

1. Perception of information (perception) or by direct supervision of the production (or other) process, or by monitoring the indicators of control and measuring equipment, which reflect the parameters of the process. Perception is carried out with the help of human senses. The information received from them is transmitted to the central nervous system.

2. Processing (transformation) of the received information is carried out in the central nervous system and leads to acceptance of the certain decision (the decision can consist and that in the given situation to do nothing). The nature of the decision, its correctness and speed of adoption is

influenced not only by information coming from outside (from the car and the environment), but also internal information. Inside information comes from the memory of a person, which stores previously received information, instructions, experience. In addition, intuition plays an important role, which has a significant impact on decision-making.

3. The last stage of the labor process is the issuance of the decision by the executive body (for example, muscle groups of the arms and legs) to implement this decision. This last stage is called control and in the system «man – machine» is carried out by influencing the controls of the machine in order to make the necessary changes in the process taking place in the system. The «exit» in this case are the executive bodies, the «entrance» – the controls of the machine.

Thus, the perception, decision-making and its implementation form a closed system of labor process. The essence of the relationship between the two main elements of this system – man and machine is the process of information transfer and control. There is also feedback between machine and human, which works according to the scheme: signaling device – receptor – central nervous system – executive organs – governing bodies.

In cases where the feedback is built into the system itself and is carried out without human intervention, such a machine is a automaton. A distinctive feature of the machine is the presence in its design of feedback systems, which the operator does not need to influence.

All this allows us to draw the following conclusion: when analyzing any technological process (both at the design stage and at the stage of production or making changes to an existing machine) it can not be considered only from a technical point of view, in terms of purely design solutions. The correct solution to the problem is the optimal combination of man and machine, ie the solution of the system «man-machine» as a single, integral whole. The human body, its brain, its nervous and muscular systems are an excellent «mechanism» for interaction. But this «mechanism» has limited physiological and mental capabilities. A design engineer or technologist must know the capabilities of a person so as not to create a machine that cannot be properly maintained. This postulate is especially relevant for agricultural machinery due to the real features of this industry [3].

In addition to the interaction of man and machine in agriculture, it is necessary to take into account the specifics of the material environment and external conditions in the workplace. In contrast to the two-way relationship between the main elements of the system (and taking into account the feedback that arises), the impact of microclimate and other environmental parameters on the worker is one-sided, ie trying to change these conditions will not be an end in itself. The same can be said about working conditions in the workplace (body position, size and shape of the seat, speed, speed of work and rest, etc.). It is always assumed that the design of the machine does not pose a direct threat to the health or life of the worker. All these factors affect the way the human-machine system interacts.

Therefore, a complete analysis of the entire system should also include an analysis of the material environment in the workplace [3; 19; 21; 23].

The functioning of the system in question is also influenced by the mode of operation, ie the duration of the work process and breaks. These elements of working conditions are of particular importance in ergonomics, as they can lead to such a negative phenomenon as fatigue. It should be borne in mind that even in the complete absence of such harmful factors as the possibility of poisoning, gassiness and others that can lead to occupational diseases, as well as minimizing the risk of accidents, the problem of fatigue always remains relevant, regardless of whether it is physical, nervous or mental fatigue.

Thus, modern concepts of labor protection to ensure the «minimum risk of injury» in the production system «worker – machine – environment» are particularly relevant for the conditions of agricultural production. Among them, an important direction in reducing the risk of injury to agricultural workers is the timely diagnosis of tractors and agricultural machinery in order to identify damage to machine parts and structural elements in the early stages, which can lead to an emergency [3; 11].

Therefore, special attention when diagnosing vehicles in the agro-industrial complex should be givento the chassis, electrical equipment, work equipment, control system and brake system [28; 32].

When driving on a road with an uneven surface, the tractor absorbs shocks and oscillates. The main components that protect the tractor from the dynamic action of the road and reduce oscillation and vibrations to an acceptable level are the steered axle and tires. A serviceable steered axle of a wheeled tractor provides optimal controllability, traffic safety, durability and reliability.

Working with faulty components of the steered axle impairs the handling and stability of the tractor, reduces the safety of its movement, impairs ergonomic performance. The experience of the machine-tractor fleet shows that the controlled axle is one of the least reliable and durable tractor units.

To conduct an experimental study of the geometric parameters of the engine of a wheeled vehicle and the roughness of the support surface with the speed and frequency of perturbing action, used a measuring system based on a personal computer and standard piezoceramic accelerators KD-35 (accelerometers), scheme which is presented in Figure 1. The study was performed on the steered axle of the tractor MTZ-80.1 with tires 7.5-20 (Ø910 × 165 mm) and 8.3-20 (Ø950 × 180 mm) [14; 15].

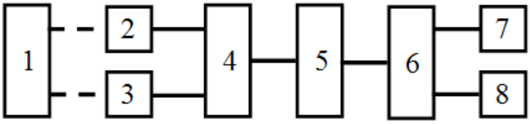


Figure 1. Diagnostic system for steered axles of wheeled tractors: 1 – steered tractor axle; 2, 3 – accelerometers; 4 – multiplexer; 5 – analog-to-digital converter; 6 – computing device; 7 – monitor; 8 – printing device

Experimental research will be performed on the following types of road sections: asphalt road (Figure 2, a); asphalt road with an obstacle (Figure 2, b).

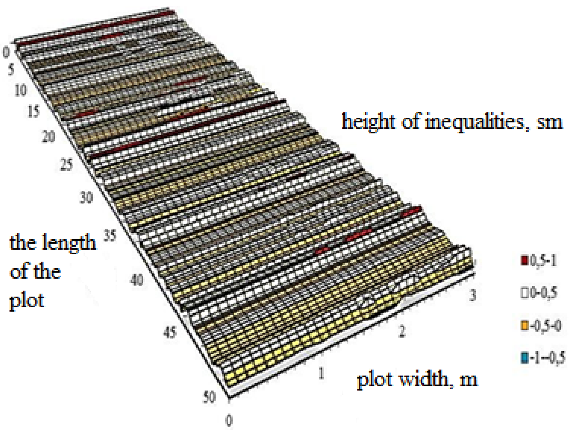
To determine the height of the unevenness of the selected road sections used a profilometer, which is part of the mobile laboratory based on the car GAZ-32213. The profilometer is designed not only to measure the microprofile of the road surface, but also to determine the depth of the track. It consists of twelve ultrasonic sensors that work in conjunction with other ultrasonic sensors installed on the car, which give a three-dimensional

a) b)

Figure 2. Areas of the road surface for the experiment: a) – asphalt road; b) – asphalt road with an obstacle

picture of the road surface (Figure 3) with an accuracy of one millimeter relative to the vertical component.

Given the design features of the steered axle of the MTZ-80.1 tractor, it was assumed that the oscillation of the steered wheels is equivalent to the



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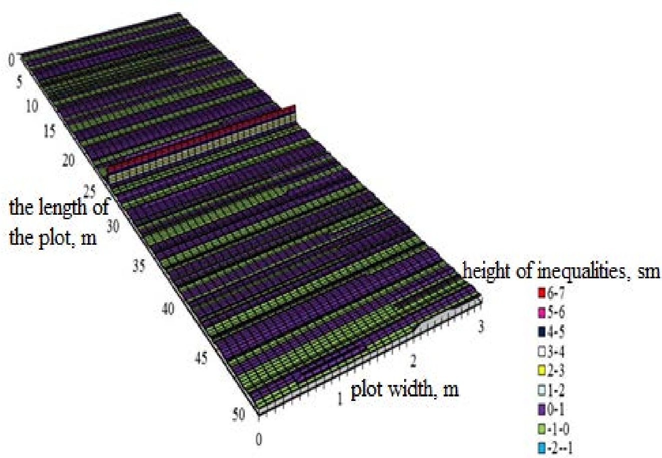


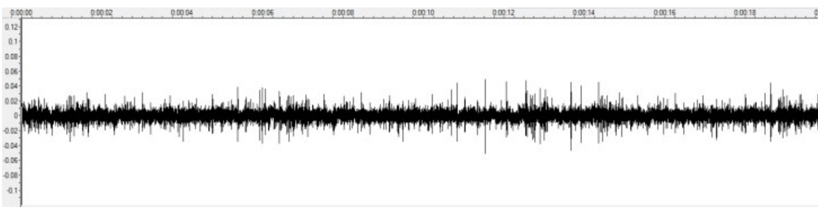
b)

Figure 3. Three-dimensional models of road surfaces for the experiment: a) – asphalt road; b) – asphalt road with an obstacle

oscillation of the steered axle [30]. The results of the experimental study are presented in the Figure 4 and Table 1.

3. Analysis of the harmful effects of amplitude-frequency characteristics of oscillations of the operator's workplace

Many oscillatory processes that occur in mechanical systems are called vibrations. There is no generally accepted definition that distinguishes vibration from other mechanical vibrations. Therefore, very often the terms



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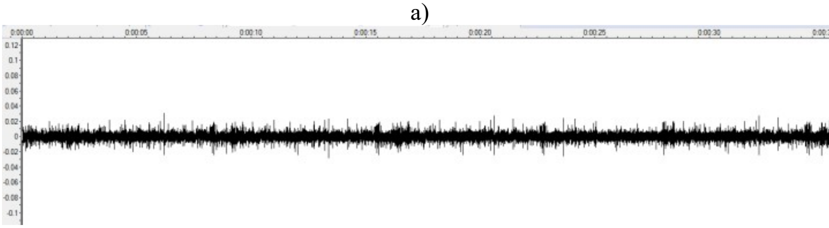

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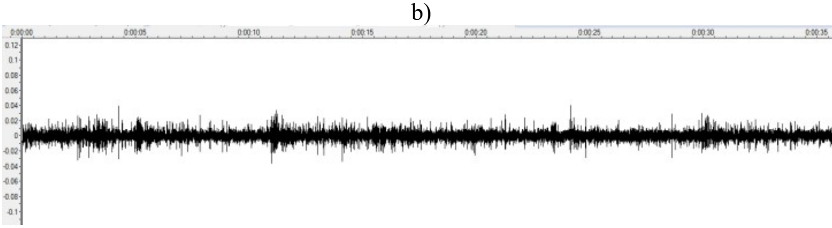

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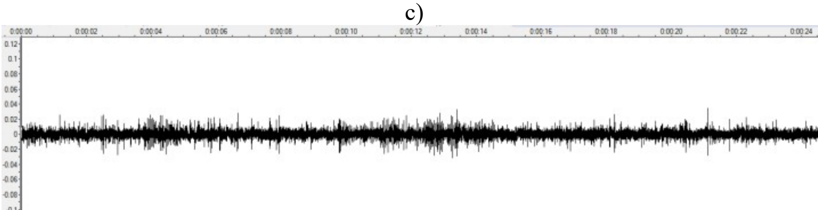

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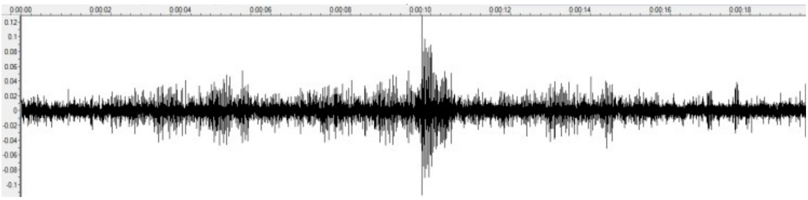

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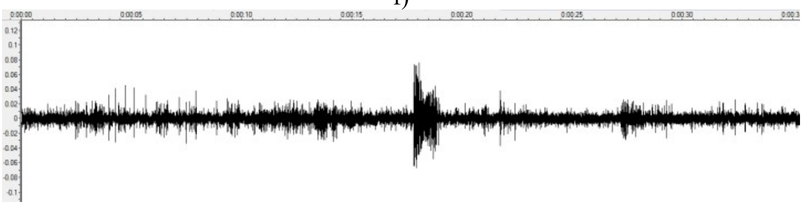

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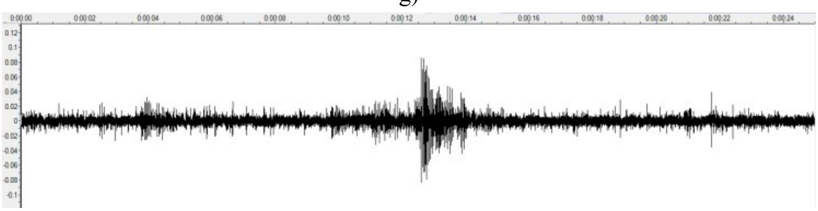

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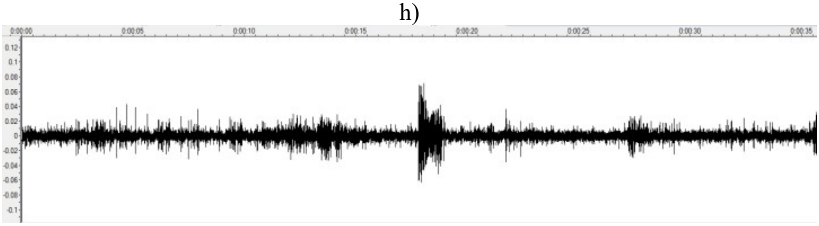


i)

Figure 4. Oscillograms of vibration acceleration of the controlled axle of the T-40 tractor:
a) – driving at a speed of 9 km/h with tires 7.5-20 on the asphalt road; b) – driving at a speed of 5 km/h with 7.5-20 tires on an asphalt road; c) – traffic at a speed of 9 km/h with tires 8.3-20 on the asphalt road; d) – traffic at a speed of 5 km/h with tires 8.3-20 on the asphalt road; f) – driving at a speed of 9 km/h with tires 7.5-20 on an asphalt road with an obstacle; g) – driving at a speed of 5 km/h with tires 7.5-20 on an asphalt road with an obstacle; h) – driving at a speed of 9 km/h with tires 8.3-20 on an asphalt road with an obstacle; i) – driving at a speed of 5 km/h with tires 8.3-20 on an asphalt road with an obstacle

Table 1

Results of the research

Brand tires	Speed tractor movement, km/h	Resonant frequency, Hz	General vibration acceleration, m/s^2
asphalt road			
7,5–20	9	3450–3500	7,2–7,8
7,5–20	5	3450–3500	7,0–7,4
8,3–20	9	3450–3500	6,5–7,0
8,3–20	5	3450–3500	6,3–6,7
asphalt road with an obstacle			
7,5–20	9	3650–3750	9,4–9,8
7,5–20	5	3650–3750	8,8–9,2
8,3–20	9	3650–3750	9,0–9,4
8,3–20	5	3650–3750	8,6–8,9

«vibration» and «mechanical vibrations» are considered synonymous. The first term is used in applied problems, while the second term is used mostly in theoretical matters. In technology, vibration is called mainly harmful oscillating motion in machines, structures and their elements [6; 8].

In the vast majority of cases, oscillations are caused by periodic forces arising from periodic shocks, large accelerations of periodically moving unbalanced masses and shock actions of moving loads. Such oscillations are known to be forced, and the energy of these oscillations is supported by perturbing forces. Examples are torsional oscillation of the shafts, vibration of the foundations of machines and machines, vibration of turbine disks, drums, rotor bearings of turbogenerators or flywheels due to poor balancing or curvature of the shaft.

Some mechanisms have parts during which oscillations occur that resemble harmonies in shape. Such mechanisms include clamshell, crank, cam, leash, etc. Oscillations can also be caused by backlash in the joints of the mechanism, which causes rattling of parts. Such fluctuations are mostly chaotic. In practice, there are often cases of asymmetric changes in the shape of the sinusoid. This shape can occur both during the operation of the components of the elastic elements (springs, conical springs, etc.), and due to one-sided contact of vibrating parts with adjacent elements. In the latter case, the vibration becomes pulsating [6; 16; 18].

With incorrect gaps in the bearings and improper lubrication mode, vibrations of the oil wedge, which is one of the types of self-oscillations, very often occur. Variable vapor pressure, gas exhaust and other periodic influences can also be the cause of fluctuations in the operation of steam engines and internal combustion engines. At vibrations of any engine a part of the energy given to it is wasted on shaking of the base and the building. The efficiency of the engine is significantly reduced, and he himself, as well as the foundation or floor on which it is installed, wears out. These phenomena often lead to major accidents. In addition, such vibrations are often accompanied by noise, have an irritating effect on staff and in some cases are the cause of occupational diseases. Research on the long-term strength of machines and mechanisms in vibration is one of the most important prerequisites for creating strong and economical structures, safe and easy to operate.

Statistics show that about 70-80% of breakdowns and accidents in mechanical engineering are the result of unacceptable fluctuations. Thus, the damage caused by vibration is very great. According to American experts, it causes damage to the US industry, which is estimated at many millions of dollars annually. To assess the vibration state of machines developed standards and DSTU, where, depending on the speed of rotation of the machine are allowed allowable amplitudes of oscillations. For example, reliable operation of the mechanisms of some high-speed machines with parts rotating at a speed of 25,000 rpm can be ensured if the amplitude of oscillations does not exceed 1.5 microns.

Experiments have shown that in some cases, along with measuring the amplitude of oscillations, a significant factor in assessing the vibration state of the machine can also be the value of the maximum acceleration generated by vibration. Vibration is very harmful if its frequency coincides with the natural frequencies of structural elements [6; 17]. Therefore at designing try to consider it and in corresponding cases calculate natural frequencies of fluctuations of details. In addition, there is a list of rules that specify how to choose the material and design a part that works in vibration. This is stated, in particular, in the courses «Resistance of materials» and «Machine parts». In cases where it is impossible to achieve the destruction of vibration by appropriate design of parts, resort to various types of shock absorbers and vibration absorbers. Vibration reduction is achieved through the installation between the vibrating object (machine, engine) and its base of various elastic gaskets. Steel springs, air (balloon) cushions, rubber and cork gaskets, as well as gaskets made of rubberized or bitumen-impregnated fabric, etc. are used as shock absorbers. 2 times lower than the frequency of forced oscillations. When you have to reduce the vibration of any part of the object, then resort to vibration dampers (vibration absorbers).

The widespread introduction of plastic materials in many fields of technology requires a comprehensive theoretical and experimental study of the work of plastic parts as vibration dampers. Currently, nylon parts are widely used in high-speed machines. Nylon bearings, for example, help dampen the vibration of spinning machine spindles. Elastic plastic gears are more resistant to vibration than steel. Gears from textolite and kapron work silently without oil at high speeds. Nylon gears successfully withstand heavy loads. Nylon has a high elasticity and low coefficient of friction. It is almost insensitive to the concentration of voltages and shock loads. Lightweight plastic levers are absolutely indispensable in high-speed machines to reduce inertia. Nylon bolts are good for connecting moving parts, because the elastic properties of nylon allow you to keep the bolted connection in a tight state, protecting it from unscrewing when vibrating [34].

Elimination of machine vibration can be achieved as a result of a range of measures. As a rule, before designing the machine, the designer performs the necessary calculations to determine the frequency of natural oscillations of individual structural elements in order to eliminate the possibility of dangerous resonant oscillations; determines the forces of inertia created by moving parts of kinematically complex machines, and finds the conditions for their mutual equilibrium; assigns balancing tolerances and determines ways to correct unbalanced masses. After designing and manufacturing a prototype of the machine, the designer during its tests with the help of vibration measuring instruments examines vibrations, determines the causes that cause them, and finds the simplest means to eliminate them. Any vibrations that occur when processing parts by cutting on metalworking machines are harmful, because in their presence there are violations of the proper operation of the machine, premature wear of the tool and the deterioration of the quality of the treated surface [6; 27].

The main methods of combating harmful vibrations in mechanical engineering are:

– rational design and calculation of machines and structures aimed at eliminating resonant phenomena and creating conditions unfavorable for self-excitation oscillations;

– increase of dynamic durability at the expense of application of special materials, the correct technology of processing of details and giving them the form that promotes elimination of stresses dangerous to a design;

– balancing and careful assembly (elimination of unnecessary backlashes), proper operation in compliance with established regimes and timely repairs;

– development of vibration-insulating and vibration-damping structures for the vibration source itself and for the protected object.

In our case, the cause of fluctuations in the workplace are the following factors:

– unevenness of the plane of the support surface on which the engines of a mobile machine or power vehicle move; displacement data and their speeds are transmitted through absolutely rigid or deformed engines to the suspension elements (if any) or directly to the machine frame and can be transmitted directly to the operator, or partially attenuated in the presence of elastic viscous suspension of the operator;

– in the absence of an elastic-viscous suspension, the oscillations of the rigid or deformed propulsion (if the oscillations are not extinguished by the deformed propulsion itself) are transmitted to the workplace;

– all oscillating masses between the support surface and the workplace can create its oscillations if they are not damped by the elastic-viscous bonds through which these masses are connected and can change the amplitude-frequency characteristics of the oscillations of the workplace.

When considering oscillatory systems, along with dynamic variables, the dependence of which on time is the essence of the oscillatory process, we have to deal with other kinds of parameters – parameters that are included in the equation and are considered constant in time, but whose task may depend on the implementation mode. A highly qualified engineer of any specialty needs to know the properties and laws of oscillations, which will help him in practice to use useful oscillations and prevent harmful oscillations [6; 31].

One of the methods of eliminating the harmful effects of oscillations of the operator’s workplace is to ensure its allowable amplitude-frequency characteristics by choosing elastic-viscous connections between oscillating masses depending on the geometric parameters of the bearing surface on which the machine moves, geometric and mechanical parameters speed, vibrational masses and mechanical parameters of the bonds between them. The geometric and mechanical parameters of the propulsion and the mechanical properties of the connections remain controlled.

However, if in some cases the mechanical vibrations that accompany the work of machines and structures are harmful and dangerous, in other cases the properties and features of mechanical vibrations are used to great advantage for various purposes [6; 24].

4. Formalization of the process of oscillations of the workplace and a mechanical model of the process of occurrence and transmission of oscillations

Even at the current level of development of machine mechanics and computer technology, a complete description of all aspects of the dynamic behavior of machine elements and the processes occurring in it is not possible, but necessary.

Therefore, the first stage of dynamic calculation is associated with a reasonable simplification of the original object, ie the replacement of some scheme or model, which seeks to reflect the most important factors of the problem. Since in this case we are talking about the problems of the dynamics of mechanisms, in the future it is more convenient to use the term «dynamic model», meaning the idealized representation of the system used in its theoretical study and engineering calculations [6].

We assume that when considering any real mechanical system, we inevitably have to abstract from some of its partial features. That is why such an improved model cannot be made that would fully correspond to its original. Thus, the dynamic model is limited and suitable only under certain conditions and range of issues. On the other hand, it follows that in a dynamic study of the same mechanism may correspond to a number of dynamic models. The degree of idealization of a real system in its reflection by a dynamic model depends on many factors. Thus the number of degrees of freedom depends on the frequency spectrum of the forced forces; sometimes without compromising the accuracy of the results, any group of forces may not be taken into account, but taken into account in the linear approximation, etc.

It is extremely important that when choosing a dynamic model, idealization does not conflict with the possibilities of a fundamental nature in the description of certain oscillatory phenomena. The study of parametric oscillations must take into account changes in system parameters, and the study of self-oscillations – nonlinear characteristics of the system. As you can see, the procedure for choosing a model already requires a certain level of knowledge and understanding of the qualitative picture of the studied phenomena. In some cases, the design features of the mechanism are such that allow you to make one or more models on which to base dynamic calculations. In more complex cases, it requires preliminary calculations, and sometimes even a search experiment. The greatest role in choosing a model is played by engineering intuition, which is based on the experience of preliminary calculations and experimental studies, as well as the practice of operation of various machines and mechanisms [33].

Despite the fact that the type of model is largely determined by specific conditions, it is possible to select a number of typical models inherent in most mechanisms, both for the purpose of dynamic calculation and the ability to display the most important dynamic properties. Dynamic models of mechanisms have distinctive features that distinguish them in a separate class with its own specific properties. One of the features is that the program movement of cyclic mechanisms is a source of kinematic excitations, due to which there are dynamic errors and additional loads on the links. Another feature – the absolute coordinates during the passage of the kinematic chain can be subjected to nonlinear transformations in accordance with the geometric characteristics [6].

When analyzing the amplitude-frequency characteristics of the oscillations of the operator's workplace, we can introduce some assumptions and simplifications:

– disturbing effect from the unevenness of the supporting surface is harmonious;

– mechanical parameters of the propulsion can be represented by two types: absolutely rigid body, deformed body with existing elastic-viscous properties;

– amplitude-frequency perturbations from the propulsion can be transmitted up to the working month through elastic-viscous ligaments, which are characterized by linear connection of elastic forces with displacements and linear connection of viscous forces with displacement velocities;

– all oscillations are considered in the form of one-dimensional displacements.

The relationship between the geometric parameters of the propulsion and the irregularities of the support surface is related to the speed and frequency of the disturbing action.

The movement of the propulsion, in the simplest case, the wheels of the machine on the support surface, schematically, can be represented as the following diagram (Figure 5).

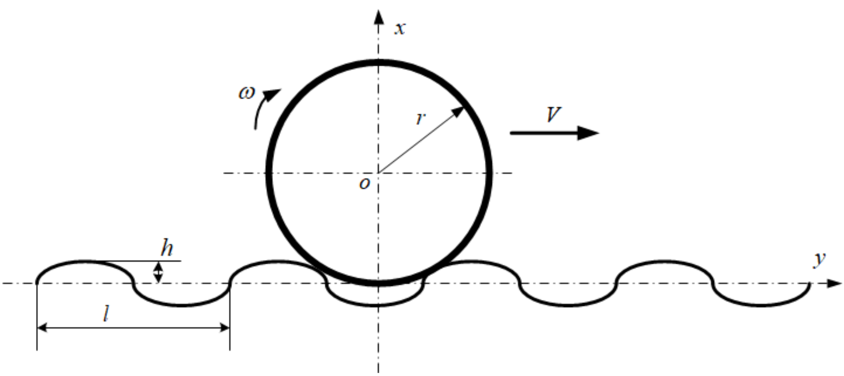


Figure 5. The scheme of movement of the engine (wheels) on a curvilinear harmonic bearing surface

In the diagram: *r* – wheel radius, *V* – speed of linear movement of a wheel (portable movement), ω – angular velocity of the wheel, *h* – height of inequality (depth of inequality), *l* – distance fur adjacent protrusions. Using the parameters *h* and *l* we can describe the inequalities by a harmonic function in the axial direction *oy*, де where where the displacement *y* will be the argument of the perturbed vertical displacement function of the propulsion *x*.

To analyze two possible cases of perturbed vertical motion of the propulsion, it is necessary to enter the functions of wheel chord lengths and irregularities between the two points of contact of the wheel with the irregularities of the support surface. Chord lengths:

– roughness of the support surface

$$a_n = 2\sqrt{2h(l/4) - h^2}\ , \qquad (1)$$

– wheels

$$a_k = 2\sqrt{2r(l/4) - r^2}\ ;\ l = 4h\ . \qquad (2)$$

The equation of the reference surface can be represented as:

$$x = b(l/4)\sin[8y]\ . \qquad (3)$$

The curve of this surface has the form (depending on the value of *b*), presented on Figure 6.

It is possible to consider emergence of vertical movements of the propulsion at its movement on a curvilinear basic surface on an example of movement of a wheel. [9]. In this case, it is necessary to distinguish two

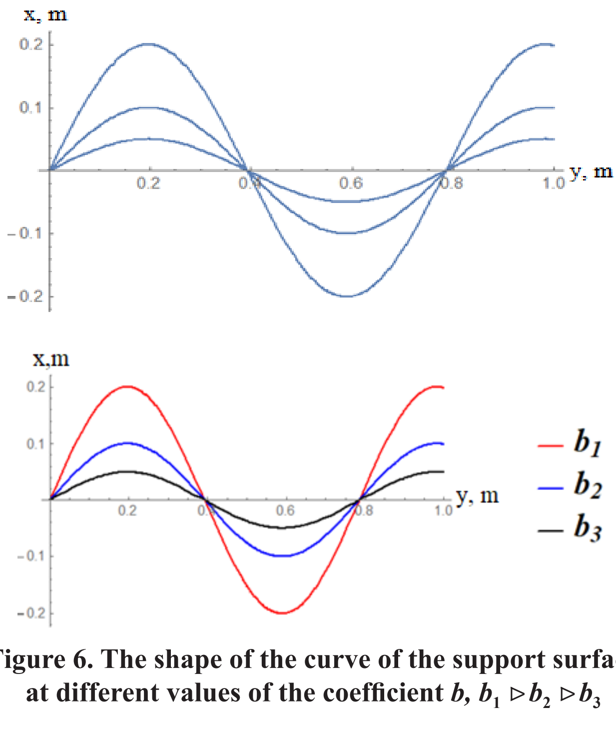


Figure 6. The shape of the curve of the support surface at different values of the coefficient *b*, $b_1 \triangleright b_2 \triangleright b_3$

cases of movement of such a propulsion system depending on the ratio of the radius of the wheel and the geometric parameters of the protrusions and depressions of the support surface.

Case 1. $r \,''\, l/4; a_k \,''\, a_n$. In this case, the possible vertical amplitudes of the wheel axis will be:

$$x = b\left(\frac{k+n}{2}\right)h\sin[y]; y \to \{l, ml\}; m \to \{1,2,3...\}; l \to 4h, \qquad (4)$$

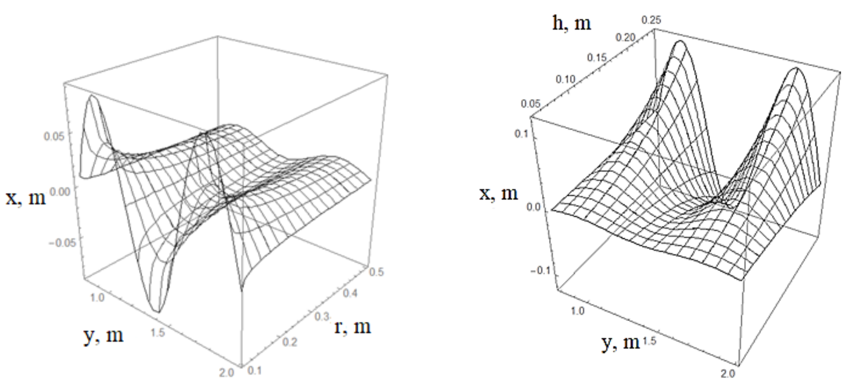
where k, n – coefficients that take into account the deformation of the wheel and the bearing surface, respectively [1; 25].

Case 2. $r \geq l/4; a_k \geq a_n; a_n = a_k$. In this case, the possible vertical amplitudes of the wheel axis will be:

$$x_k = r - \sqrt{r^2 - \left(a_k^2/4\right)}, a_k = a_n, a_n = 2\sqrt{2h(l/4) - h^2}, l = 4h;$$

$$x = \left(\frac{k+n}{2}\right)\left(r - \sqrt{-h^2 + r^2}\right)sin[y]; y \to \{l, ml\}; m \to \{1,2,3...\}. \qquad (5)$$

Graphically, the vertical displacements for this case are presented in Figure 7. To establish the frequency characteristics of the wheel oscillations,



a) b)

Figure 7. Graphs of the dependence of the vertical displacements of the wheel axis on its radius *r* at constant parameters of the support surface profile (a) and from the parameter of the support surface profile *h* at a constant wheel radius (b)

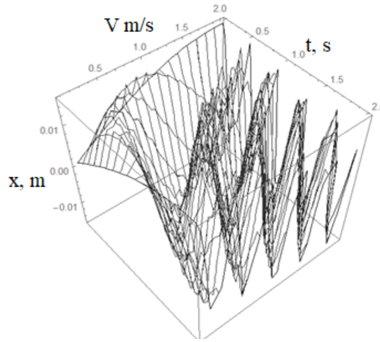


Figure 8. Graph of vertical movements of the wheel axis from the speed of the machine V

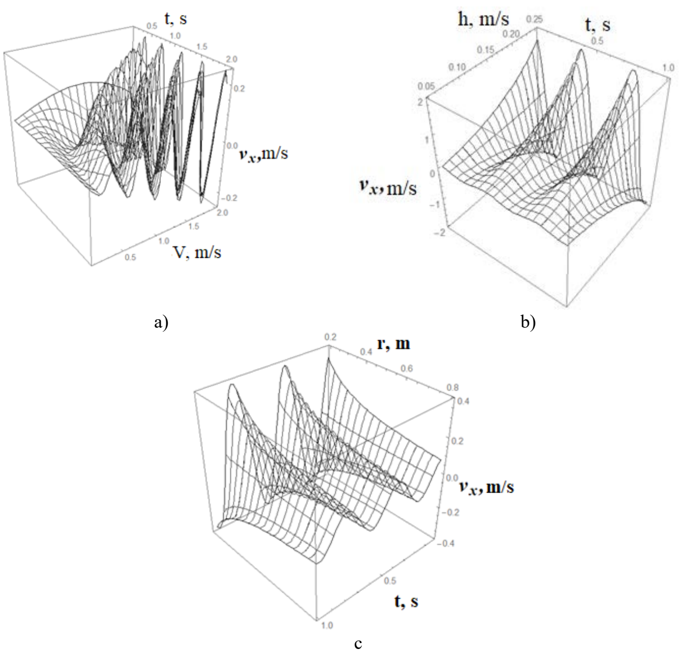


Figure 9. Graphical interpretation of the speeds of vertical movements of the wheel axis from the translational speed *V* (a), the profile of the bearing surface *h* (b) and the radius of the wheel *r* (c)

you can enter the replacement of the travel distance through the speed V and time t : $y = V(t)$. In this case, you can analyze the vertical movement of the wheel from time to time (Figure 8).

After substituting the function of time and speed in equation (5) and its time differentiation, you can get the speed of vertical movements of the wheel axis:

$$v_x = \frac{d}{dt}\left(\left(\left(\frac{k+n}{2}\right)\left(r - \sqrt{-h^2 + r^2}\right)\right)\sin\left[T8V\,t\right]\right) =$$

$$= 4(k+n)\left(r - \sqrt{-h^2 + r^2}\right)Tvcos\left[8tTV\right] \quad (6)$$

Graphically, the dependence (6) is presented on Figure 9.

5. Mathematical models of oscillations of multimass systems

The mechanical model of transmission of oscillations from the deformed bearing surface through the deformed wheel and an elastic-viscous suspension to a workplace can be presented by the scheme (Figure 10).

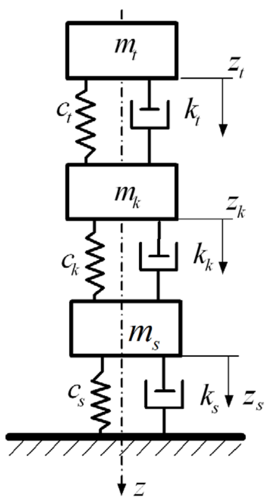


Figure 10. The scheme of transmission of oscillations from the deformable support surface to the operator's workplace

The transmission of oscillations from the bearing surface to the operator's workplace can generally be represented by a multi-mass system with elastic-viscous bonds [1; 2; 20; 22; 26]. It is assumed that the distributed masses are reduced to concentrated. In the model, replace all vertical movements of the wheel x_k by z_k. All movements are marked with a variable z.

The following notations are accepted in the scheme: m_s, z_s, k_s, c_s – reduced mass, displacement, modulus of viscosity and modulus of elasticity of the bearing surface; m_k, z_k, k_k, c_k – reduced mass, displacement, viscosity modulus and elasticity modulus of the deformed wheel; m_t, z_t, k_t, c_t – given workplace mass, displacement, viscosity modulus and elasticity-viscosity suspension modulus.

To compile the equation of motion of the elements of the system, you can use the classical approach using the Lagrange equation of the 2nd kind:

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}_i}\right) - \frac{\partial T}{\partial q_i} = -\frac{\partial P}{\partial q_i} - \frac{\partial F}{\partial \dot{q}_i} + Q_i, \qquad (7)$$

where T – kinetic energy of the system, P – potential energy of the system, F – Rayleigh function, which characterizes the linear viscous properties of energy dissipation, Q_i – components of generalized forces, q_i, $\dot{q}_i$ generalized displacements and generalized displacement velocities, respectively [2; 13].

The components of the Lagrange equation have the following form:

– kinetic energy of the system $T = \frac{1}{2} m\, \dot{q}_i^2$;

– potential energy of the system $P = \frac{1}{2} c_i\, q_i^2$.

Potential energy of the system for gravitational forces:

$$Pg = m\, g\, q_i.$$

Rayleigh function, which characterizes viscous dissipation:

$$F = m\, \dot{q}_i.$$

The generalized force (perturbing force) for translational motion can be expressed taking into account expression (6), the derivative of which is an acceleration in time:

$$\ddot{z} = \frac{d}{dt}\left(4(k+n)\left(r - \sqrt{-h^2 + r^2}\right)Tv\cos[8tT\,V]\right) = \\ = -32(k+n)\left(r - \sqrt{-h^2 + r^2}\right)T^2 v^2 \sin[8tTv].$$

In this case, the generalized force, taking into account the acceleration, will look like:

$$Q_i = m\,\ddot{z}.$$

The kinetic energy for the above model will look like:

$$T = \frac{1}{2}\left(m_t z_t'[t]^2 + m_k z_k'[t]^2 + m_s z_s'[t]^2\right). \quad (8)$$

Potential energy from the action of the elasticity of the connecting elements:

$$P = \frac{1}{2}\left(c_s(z_s[t])^2 + c_k(z_s[t] - z_k[t])^2 + c_t(z_k[t] - zt[t])^2\right). \quad (9)$$

Potential energy of gravitational forces:

$$P_g = m_t g\, z_t[t] + m_k g\, z_k[t] + m_s g\, z_s[t], \quad (10)$$

g – acceleration of gravity.

Taking into account that the initial offsets at the time are zero – $\partial_{(z_t[t]\to 0, z_k[t]\to 0, z_s[t]\to 0)} Pg = 0$. The potential energy of gravitational forces is zero.

Rayleigh viscous bond function:

$$F = \left(\frac{1}{2}\left(k_s(z_s'[t])^2 + k_k(z_s'[t] - z_k'[t])^2 + k_t(zk'[t] - z_t'[t])^2\right)\right). \quad (11)$$

Turning to the components of the Lagrange equation, we can write for the first term for the mass m_t:

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}_i}\right) = \frac{d}{dt}\left(\frac{\partial}{\partial z_t{}'[t]} T\right) = m_t z_t''[t] = m_t \ddot{z}_t. \quad (12)$$

The first addition to the mass wheel m_k:

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}_i}\right) = \frac{d}{dt}\left(\frac{\partial}{\partial z_k{}'[t]} T\right) = m_k z_k''[t] = m_k \ddot{z}_k. \quad (13)$$

The first term for the mass of the reference surface brought to the point of contact, but the attached mass m_s:

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}_i}\right) = \frac{d}{dt}\left(\frac{\partial}{\partial z_s{}'[t]} T\right) = m_s z_s''[t] = m_s \ddot{z}_s. \quad (14)$$

The second term of the Lagrange equation for the case under consideration for the above components will look like:

$$\frac{\partial T}{\partial q_i} = \frac{\partial T}{\partial z_t} = 0;\ \frac{\partial T}{\partial q_i} = \frac{\partial T}{\partial z_k} = 0;\ \frac{\partial T}{\partial q_i} = \frac{\partial T}{\partial z_s} = 0;$$

The first term of the right-hand side of the Lagrange equation of the 2nd kind for the corresponding masses:

$$P_t = \left(\frac{\partial}{\partial z_t[t]}\left(P + P_g /. P_g = 0\right)\right) = -c_t(z_k[t] - z_t[t]); \quad (15)$$

$$P_k = \left(\frac{\partial}{\partial z_k[t]}\left(P + P_g /. P_g = 0\right)\right) = \\ = \frac{1}{2}\left(-2c_k(-z_k[t] + z_s[t]) + 2c_t(z_k[t] - z_t[t])\right); \quad (16)$$

$$P_s = \left(\frac{\partial}{\partial z_s[t]}\left(P + P_g /. P_g = 0\right)\right) = \frac{1}{2}\left(2c_s z_s[t] + 2c_k(-z_k[t] + z_s[t])\right). \quad (17)$$

Generalized viscosity forces are applied to the model elements:

$$F_t = \frac{\partial}{\partial z_t'[t]} F = k_t(-z_k'[t] + z_t'[t]); \quad (18)$$

$$F_k = \frac{\partial}{\partial z_k'[t]} F = (k_k + k_t) z_k'[t] - k_k z_s'[t] - k_t z_t'[t]; \quad (19)$$

$$F_s = \frac{\partial}{\partial z_s'[t]} F = -k_k z_k'[t] + (k_k + k_s) z_s'[t]. \quad (20)$$

Taking into account the above functions, we can write a system of three equations:

$$\begin{aligned} m_t z_t''[t] &= c_t(z_k[t] - z_t[t]) - k_t(-z_k'[t] + z_t'[t]); \\ m_k z_k''[t] &= Q_i + \frac{1}{2}\left(2c_k(-z_k[t] + z_s[t]) - 2c_t(z_k[t] - z_t[t])\right) - \\ &\quad -(k_k + k_t) z_k'[t] + k_k z_s'[t] + k_t z_t'[t]; \\ m_s z_s''[t] &= \frac{1}{2}\left(-2c_s z_s[t] - 2c_k(-z_k[t] + z_s[t])\right) + k_k z_k'[t] - \\ &\quad -(k_k + k_s) z_s'[t]. \end{aligned} \quad (21)$$

Or in another form of recording:

$$\begin{aligned} m_t \ddot{z}_t &= c_t(z_k - z_t) - k_t(-\dot{z}_k + \dot{z}_t); \\ m_k \ddot{z}_k &= Q_i + \frac{1}{2}\left(2c_k(-z_k + z_s) - 2c_t(z_k - z_t)\right) - \\ &\quad -(k_k + k_t)\dot{z}_k + k_k \dot{z}_s + k_t \dot{z}_t; \\ m_s \ddot{z}_s &= \frac{1}{2}\left(-2c_s z_s - 2c_k(-z_k + z_s)\right) + k_k \dot{z}_k - (k_k + k_s)\dot{z}_s. \end{aligned} \quad (22)$$

Unfortunately, it is not possible to obtain an analytical solution of equations in the form of (21) and (22), so it can be solved only by numerical methods.

Numerical solution of the obtained equation at different geometric parameters of the support surface and wheel and at different values of mechanical properties of the support surface, modulus of elasticity and viscosity, as well as known values of reduced and defined attached masses allows to determine rational values of elastic and viscous elements c_k, c_t, k_k, k_t, which will provide the allowable amplitude-frequency characteristics of mass oscillations m_t, that is, the operator's workplace.

6. Conclusions

1. The main causes of injuries remain organizational, related to the so-called «human factor». Eliminating most of them does not require large material costs. It is only necessary to increase the level of organization of safe work. Complex mechanization and automation of production leads to a reduction in the role of man in relation to the means of production and the results of the production process; the division of labor into separate parts reduces the performers' interest in the work they perform, reduces the employee's ability to influence the end result of their work.

2. Ergonomic shortcomings in the organization of workplaces on mobile equipment are risk factors in the development of functional disorders in agricultural machine operators in the process of work. Unsatisfactory ergonomic factors of working conditions cause the development of functional disorders in mechanics in the process of work and can become risk factors in the development of occupational diseases.

3. The analysis of the system «man – machine» should include not only technical aspects, but also take into account the specifics of the material environment and external conditions in the workplace, as well as organizational aspects that are revealed only in dynamic analysis of the system.

4. Particular attention should be paid to the timely diagnosis of components and mechanisms of tractors to ensure traffic safety and safe performance of field work.

5. Theoretical and experimental studies show that with increasing geometric dimensions of the wheel, the parameters of vibrational oscillations decrease. Increasing the speed of the tractor causes an increase in the parameters of vibration oscillations. Thus, when increasing the tractor speed from 1.0 m/s to 1.5 m/s, the vibration speed also increases from 0.05 to 0.1 m/s.

6. A system of equations is obtained, which connects the parameters of the system «support surface – elastic elements – workplace». The system of equations does not have an analytical solution, so it can be solved only by numerical methods. The numerical solution of this system will allow to determine the rational values of elastic and viscous elements, which will provide the allowable amplitude-frequency characteristics of the oscillations of the operator's workplace.

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