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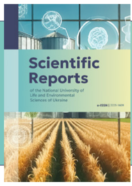

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Justification of the suspension type of a single-axle fruit transport trailer

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Abstract. The relevance of the study is due to the importance of preserving fruit products, the quality of which is affected by mechanical damage to fruits during transportation, associated with specific difficulties due to their substantial sensitivity to mechanical influences, so reducing the dynamic impact on fruits requires improving the design parameters of special vehicles and recommendations for their use. The purpose of the study was to conduct a comparative examination of the level of vertical

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accelerations of a trailer with balanced and unbalanced suspensions and prove the feasibility of using the latter for fruit transportation. The influence of design parameters and operational factors of single-axle trailers on vertical accelerations and their distribution in the energy spectrum of vehicle vibrations during fruit transportation was assessed. Theoretical and experimental studies were conducted, and a comparative analysis of vertical accelerations of two types of suspensions was performed. In the course of theoretical research, a differential equation for estimating the level of vertical accelerations was solved, considering the following factors: suspension type; balancer parameters; road profile irregularities; radial deformation and tire stiffness; speed of the vehicle. An experimental evaluation of vertical accelerations of a single-axle trailer with balanced and unbalanced suspensions was conducted when transporting fruits in a garden on a dirt Inter-block road to confirm the results of theoretical studies. The results showed that the RMS values of vertical accelerations in the operating speed range that occur in trailers with unbalanced suspension are higher than in trailers with balanced suspension. The dominance of harmonics of vertical vibrations in the range of 1.75-2 Hz was established, which accounted for more than 55% of the power of the acceleration spectrum, which is crucial for assessing fruit damage. It was experimentally proven that at an average transportation speed (about 20 km/h), the level of vertical accelerations of a trailer with both suspensions did not exceed the permissible level. The practical value of the work lies in the possibility of applying the results obtained in the design and improvement of single-axle trailers for fruit transportation, which will help reduce product losses and increase the efficiency of horticultural farms

Keywords: soil irregularities; vibrations; mechanical damage to fruits; differential equations; vertical accelerations; amplitude-frequency characteristics

Introduction

The process of harvesting and transporting fruits is one of the most labour-intensive processes in horticulture, which accounts for more than 30% of all costs for growing fruit products, and at the same time, more than 15-20% of products are lost. The causes of losses are known, but not fully understood (Khalid *et al*., 2024). A substantial part of scientists in their publications focus on logistics research, timely execution and productivity of vehicles (Lozova, 2019), and other studies are aimed at reducing the loss of fruit products in the process of logistics transportation (Słupska *et al*., 2022). One of the most difficult tasks is to reduce losses due to mechanical damage to fruits, where an important role belongs to vehicles. Reduced marketability and even spoilage of apples are most often the result of incorrect choice of packaging, type, and design of vehicles and transportation conditions.

In many cases, the absence of roads with hard and smooth surfaces and the tendency to increase the performance of vehicles lead to insufficient smoothness and leads to an increase in the level of mechanical damage to products. M. Al-Dairia *et al.* (2021) investigated the mechanisms of mechanical damage to apples during harvesting and transportation, and proposed the design of an experimental platform for testing, accounting for dynamic load parameters. The authors demonstrated that uneven movement of cars on rough terrain is one of the key factors of fruit damage. The study determined the relationship between the intensity of vibrations and the frequency of damage and also confirmed the need to develop adaptive collection and transportation systems that consider mechanical loads. B. Suleimani & E. Ahmadi (2021) analysed the effect of road conditions, suspension, and transport speed on the level of vibrations transmitted to fruits during transportation. It is established that the parameters of the road surface, in particular, bumps, and the type of suspension of the vehicle are the main factors determining the amplitude and frequency of vibrations. This study confirmed that insufficient smoothness when transporting products on irregular roads substantially increases the risk of mechanical damage to the fruit. Insufficient smoothness of vehicles is associated with a large number of external influences from roads and their nature.

Damage to products is mainly affected by two components: the characteristics of the cargo (physical and mechanical properties of the transported product, the method of its packaging and wrapping), and the characteristics of the vehicle (body type and suspension). Thus, in the study by D. Cigdem & M.S. Aday (2022), indicators that characterise the smoothness of the vehicle were evaluated depending on the speed of movement, active accelerations, but their frequency distribution was not researched. Mechanical damage to the fruit during transportation is caused by three factors: co-impacts, compressive force, and vibration. In the paper of F. Han *et al.* (2023), the authors presented that vibration accounts for half to two-thirds of the total amount of fruit damage during transport, but did not reveal the structure of vibrations, nor did they perform frequency analysis of the distribution of vertical accelerations. Similar examination of the vehicles is given in a publication of X. Liu *et al.* (2022), where it was confirmed that one of the most important factors is difficult road conditions, when vehicles make vibrations with accelerations, the value of which reaches the limit of 3.5g (g – acceleration of gravity), not specifying the type and parameters of the suspension.

Transportation of fruits from the garden is conducted by both general-purpose vehicles (cars, tractor trailers) and special ones. I. Hazbavi (2013) found that the disadvantages of general-purpose vehicles include excessive platform height and insufficient smoothness, which affects the increase in mechanical damage and deterioration of fruit quality. For the most part, special vehicles are single-axle trolleys with or without balanced suspension, with low-pressure tires and a wide profile. Their use allows increasing the yield of standard products, fully mechanising loading and unloading operations, substantially improving labour productivity, reducing material costs for containers, and preserving the quality of fruit products. Trailers with tandem axles are widely used. Their advantage is evident in the case of heavy-duty vehicles. In a study by B. Jarimopas *et al.* (2005), the use of balanced suspension was explained by the high permissible loads on running systems and the fact that it absorbs various shocks well and, as a result, provides for moving at an increased speed on uneven roads. It remains unclear how the use of a balancing suspension affects the level of vertical accelerations and their frequency distribution compared to an unbalanced one.

The study aimed to investigate the influence of the efficiency of using the balanced suspension of a single-axle trailer with fruits on the level of vertical accelerations and the feasibility of using an unbalanced suspension in the process of on-farm transportation. The goal of the paper is to prove the feasibility of using a single-axle trailer with an unbalanced suspension for on-farm transportation of fruits with acceptable oscillation modes.

Materials and Methods

In this paper, theoretical and experimental studies of vertical vibrations of a single-axle trailer with an unbalanced or balanced tandem suspension are conducted. It is customary for a trailer loaded with fruit to move along a dirt road at a constant speed. Given that the trailer is a complex oscillatory system, vertical accelerations were taken as the main indicator of vibrations, which most affect the mechanical damage to fruits during their transportation (Khodaei *et al*., 2019). For theoretical studies of vertical vibrations of vehicles, a model with one degree of freedom for moving over randomly located road bumps is adopted, considering non-sprung masses, the impact of cargo, and tire stiffness (Martyshko & Volyansky, 2018). An equivalent oscillatory system of a uniaxial container ship was used (Fig. 1) with unbalanced and balanced suspensions to determine and analyse vertical accelerations.

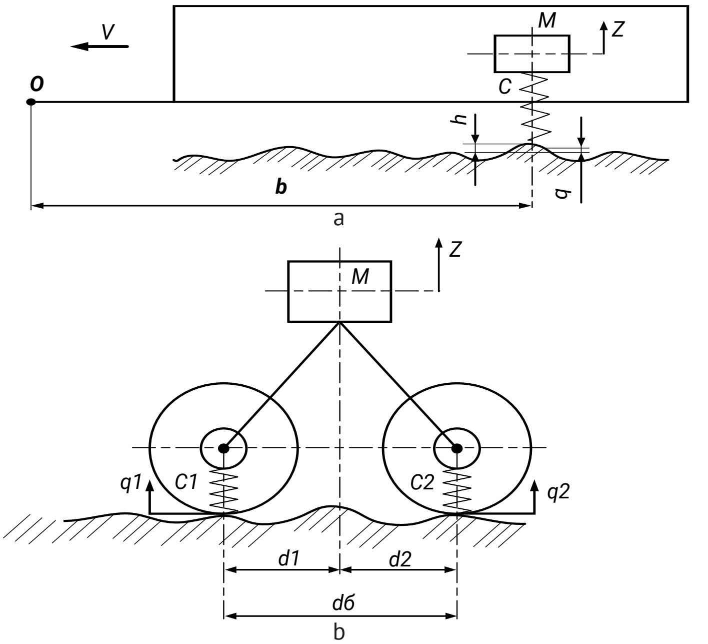

Figure 1. *Equivalent single-axle trailer oscillation system*
Note: a – unbalanced suspension; b – tandem balanced suspension: *M* – trailer weight shown; *V* – speed of movement; *Z* – vertical movement of the reduced mass; *c*– total tire stiffness; q_1 and q_2 – value of the height of unevenness under the front and rear wheels; d_1, d_2, d_b – balancer parameters
Source: compiled by the authors

An experimental test of the dependence of vertical accelerations on the speed of a container ship with balancing and unbalanced suspensions was conducted when transporting fruits along a dirt road along the edge of the block in the garden of the Institute of Horticulture of the National Academy of Agrarian Sciences to confirm the results of theoretical research. Measurement and analysis of vertical vibrations of the fruit trailer was conducted using vibration measuring equipment of the company "Brüel & Kjær", Denmark (Fig. 2) according to the methodology developed by the Forecasting and Testing of Equipment and Technologies for Agricultural Production named after Leonid Pohorily.

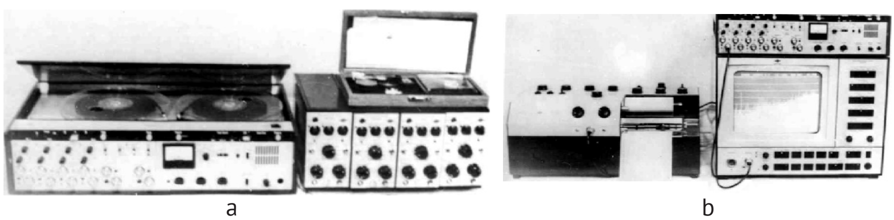

Figure 2. *Measuring equipment "Brüel & Kjær"*
Note: a – for recording; b – frequency analysis
Source: compiled by the authors

The frequency spectrum and vertical accelerations were analysed at the centre of mass of the fruit trailer. A block diagram of the experiments is shown in Figure 3.

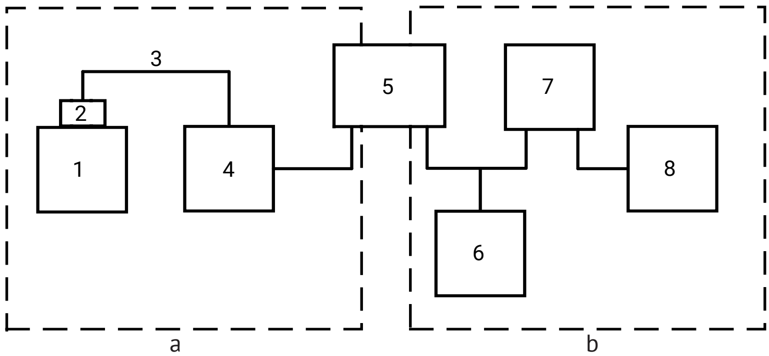

Figure 3. *Experiment flowchart: for recording and frequency analysis of container ship vibrations*

Note: a – to record results; b – for frequency analysis; 1 – object of the experiment; 2 – accelerometer; 3 – cable; 4 – amplifier; 5 – tape recorder; 6 – RMS measurement device; 7 – frequency analyser; 8 – recorder

Source: compiled by the authors

The root-mean-square value was taken as the indicator for estimating vertical accelerations, from a known dependency (Kalchenko *et al.*, 2017):

$$a = \sqrt{\frac{1}{T_0}\int_0^{T_0} a^2(t)\, dt}, \qquad (1)$$

where $a(t)$ – acceleration from time t; T_0 – time averaging.

Accelerometers 4370 were used, the sensitivity of which was 10 pC/m.s^2 to measure the oscillation parameters. Oscillation signals from the accelerometer were sent to the frequency amplifier, the lower filter limit of which was 0.25 Hz, and the upper limit –1000 Hz. After amplification, the signals were recorded on a 4-channel tape recorder and then fed to an RMS amplifier. The oscillation level was recorded in the maximum value saving mode. The spectral distribution of accelerations in the frequency spectrum was measured using a frequency analyser in the frequency range 0...100 Hz. The filter bandwidth is 0.25 Hz. The averaged frequency spectra were recorded by a frequency analyser and recorded on frequency-granular paper, where accelerations were denoted in decibels relative to the conditional zero acceleration level $a_0 = 3 \times x10^{-4}\ m/s^2$.

Results and Discussion

Given that road bumps are random in nature, they were considered one-dimensional: in the longitudinal direction, ignoring the probability of movement of the left and right wheels in different profiles. With this assumption, there are no lateral vibrations of the trailer since the change in the micro-profile of the cross-section of the field is usually insignificant, and the track of the unit is not wide. The correlation function for the height of road surface irregularities was taken from the study by M.I. Karbovanets & V.Y. Lazur (2019) according to the formula:

$$K(l) = Дe^{-\alpha|l|}, \qquad (2)$$

where Д – variance of inequalities; α – coefficient that characterises the attenuation of the function; l – correlation interval. The field profile is defined by the equation:

$$q = h(1 - e^{-\alpha|l|}), \qquad (3)$$

where q – flow value of the inequality height; h – the limit to which the height of the inequality is directed. It is assumed that the ordinates of the heights of inequalities are distributed according to the normal law, then the largest of them are directed to the value 6σ, where σ – the mean square of the heights of inequalities (Martynenko & Yuryk, 2008). The considered movement of the system (Fig. 1a) around the point O, with the assumption that the displacement of the reduced mass M of the oscillation system occurs in a vertical straight line since the longitudinal base of the trailer B is substantially higher than the height of the bump h. In this case, the motion of the system is described by the differential equation in general form:

$$M\ddot{Z} + c(Z - q) = 0, \quad (4)$$

where Z – vertical movement of the reduced mass; c – total tire stiffness. Inelastic resistance forces in tires were disregarded.

If the possibility of lifting the wheels from the support surface is not accounted for, it can be assumed that there is a condition:

$$f = (Z - q), \quad (5)$$

where f – flow value of the radial strain of the tire.

Then, the equation of motion can be written in terms of the radial deformation of the tire:

$$M\ddot{f} + cf = -M\ddot{q}. \quad (6)$$

It is considered that:

$$\omega = \sqrt{\frac{c}{M}}, \quad (7)$$

where ω – the natural frequency of vibrations of the system, then the equation of motion will acquire a more convenient form for analysis:

$$\ddot{f} + \omega^2 f = -\ddot{q}. \quad (8)$$

After double differentiation of equation (3) over time t, given that $l = vt$, and substituting the result in expression (8), the forced motion equation of the system will have the form:

$$\ddot{f} + \omega^2 f = h\alpha^2 v^2 e^{-\alpha vt}. \quad (9)$$

Equation (9) was solved for the steady-state oscillation process, yielding:

$$f = \frac{h\alpha^2 v^2}{\omega^2 + \alpha^2 v^2}\left(\frac{av}{\omega} sin\omega t - cos\omega t\right). \quad (10)$$

Considering condition (8), the vertical acceleration of the system (trailer at the driving point) was found at the known values of its components:

$$\ddot{Z} = \frac{h\alpha^2 v^2 \omega^2}{\omega^2 + \alpha^2 v^2}\left(cos\omega t - \frac{av}{\omega} sin\omega t\right). \quad (11)$$

Thus, from expression (11), the vertical accelerations of a trailer depend on the size of road irregularities, the speed of movement, and the natural frequency of vibrations. Further, the features of vertical vibrations of vehicles with balanced suspension were considered (Fig. 1b). The parameters and assumptions were the same as without it, with the difference that the signals from the wheel are different, and therefore their effect on the overall axis of the balancers is not the same. The moment of inertia of the balancers relative to the suspension oscillation axis was not considered. The effect of road bumps on the axle of a car with a balanced suspension can be recorded as follows:

$$q = \frac{d_2}{d_1 + d_2} q_1 + \frac{d_1}{d_1 + d_2} q_2, \quad (12)$$

where d_1, d_2 – balancer parameters; q_1, q_2 – value of the height of unevenness under the front and rear wheels. If the balance beam arms are the same, then:

$$d_1 = d_2 = \frac{1}{2} d_б, \quad (13)$$

The road roughness function that affects the car's axle will look like:

$$q(t) = \frac{1}{2}[q_1(t) + q_2(t)]. \quad (14)$$

The equation of motion of the system, written in terms of radial deformation of the tire, has the same form as for unbalanced suspension (8). Considering the symmetry of the suspension scheme, including the fact that the speed of the trailer remains constant during overcoming the bumps, the road profile can be set by the expression:

$$q = h\left\{1 - \frac{1}{2}\left[e^{-\alpha|l|} + e^{-\alpha|l^*|}\right]\right\}. \quad (15)$$

After double differentiation of equation (9) over time, and also considering that $l^* = v(t - t_0)$, where t^0 – difference in time when the wheels hit a given bump (q), and substituting the obtained value into the equation of motion of the system written through the radial deformation of the tire, the following is obtained:

$$f + \omega^2 f = \frac{h\alpha^2 v^2}{2}\left[e^{-\alpha v t} + e^{-\alpha v(t-t_0)}\right]. \quad (16)$$

The solution of such an equation by conventional methods is quite complex. This is easier to do using operational computing. The task is simplified assuming that after hitting the first inequality after $2t_0$, the wheels of the trailer will again run over the same unevenness, after $4t_0$ – over the third, etc. Impact $q(t)$ will be periodic with a period of t_0 starting from the moment $t_0 = 0$ when the front wheels of the trailer, moving on a flat road, touch bumps. The assumption is formal in nature since the following inequality does not affect fluctuations during the first $2t_0$, when the previous bump is overcome. In this case, equation (16) has the form:

$$f + \omega^2 f = A\left[q(t) + q(t - t_0) + q(t - 2t_0) + \cdots\right], \quad (17)$$

where $q(t)$, $q(t - t_0)$, $q(t - 2t_0)$... – corresponding unit functions; $A = \frac{1}{2}h\alpha^2 v^2$. To solve equation (17), the Laplace-Carson transform and the delay theorem are applied. The function and its derivatives have the form (Massalitina, 2017):

$$f = \varphi(p), \frac{df}{dt} = p\varphi(p) - pf_0,$$

$$\frac{d^2 f}{dt} = p^2\varphi(p) - p^2 f_0 - pf_0. \quad (18)$$

Provided that at the initial moment $t = 0$, the left side of equation (16) will be as follows:

$$\ddot{f} + \omega^2 f = \varphi(p)(p^2 + \omega)^2. \quad (19)$$

To obtain the right-hand side, it is noted that, according to the delay theorem, the image of a piecewise continuous unit function takes the form:

$$q(t - t_0) = e^{-pt0}. \quad (20)$$

Therefore, the right side of equation (20) has the form:

$$A\left[q(t) + q(t - t_0) + q(t - 2t_0) + \cdots\right] =$$
$$= A(1 + e^{-pt_0} + e^{-2pt_0} + \cdots). \quad (21)$$

Thus,

$$\varphi(p)(p^2 + \omega^2) = A(1 + e^{-pt_0} + e^{-2pt_0} + \cdots). \quad (22)$$

Therefore:

$$\varphi(p) = \frac{A}{p^2 + \omega^2}(1 + e^{-pt_0} + e^{-2pt_0} + \cdots). \quad (23)$$

To return to the original expression and apply the delay theorem, the following result is obtained:

$$\frac{A}{p^2 + \omega^2}(1 + e^{-pt_0} + e^{-2pt_0} + \cdots) = \frac{A}{\omega^2 + \alpha^2 p^2} \times$$
$$\times \{1 - \cos\omega t + [1 - \cos\omega(t - t_0)] +$$
$$+ [1 - \cos\omega(t - 2t_0)] + \cdots\}. \quad (24)$$

Flow value of radial tire deformation:

$$f = \frac{h\alpha^2 v^2}{2(\omega^2 + \alpha^2 v^2)} \times$$
$$\times \{1 - \cos\omega t + [1 - \cos\omega(t - t_0)] +$$
$$+ [1 - \cos\omega(t - 2t_0)] + \cdots\}. \quad (25)$$

According to expression (5), the vertical displacement of the reduced mass has the following form:

$$Z = h^*\left\{1 - \frac{1}{2}\left[e^{-\alpha v t} + e^{-\alpha v(t-t_0)}\right]\right\} + \frac{h\alpha^2 v^2}{2(\omega^2 + \alpha^2 v^2)} \times$$
$$\times \{1 - \cos\omega t + [1 - \cos\omega(t - t_0)] +$$
$$+ [1 - \cos\omega(t - 2t_0)] + \cdots\}. \quad (26)$$

After twice differentiating the displacement by time , the vertical acceleration of the system at the driving point is obtained. For steady-state fluctuations, it has the form:

$$\ddot{Z} = \frac{h\alpha^2 v^2 \omega^2}{2(\omega^2+\alpha^2 v^2)}[cos\omega t + cos(t - t_0)]. \quad (27)$$

Based on the results of theoretical studies, it is established that the vertical vibrations of vehicles with a balanced suspension are slightly less than those with an unbalanced suspension (Fig. 4).

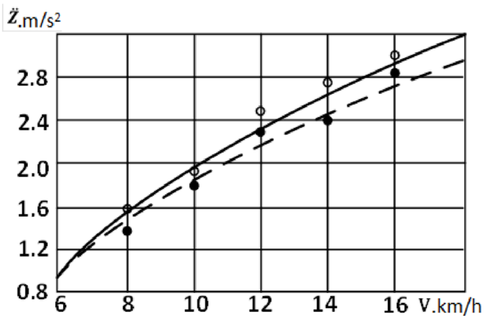

***Figure 4.** Dependence of vertical accelerations on the speed of the unit if ω = 6 rad/s, = 0.15 m, α = 1 m*

Note: ○ – with unbalanced suspension; ● – with balanced suspension

Source: compiled by the authors

The difference depends on the length of the balancer , (the larger , the smaller the vertical fluctuations will be). Since the length of the balancer is limited, the vertical vibrations differ little. The results of experimental studies and their analysis confirmed the random nature of changes in vertical accelerations over time (Fig. 5).

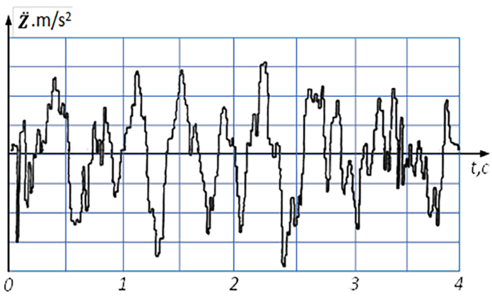

***Figure 5.** Nature of changes in vertical accelerations over time*

Source: compiled by the authors

In the process of moving a trailer with both types of suspension on a dirt road in the Garden on an inter-block road, vertical accelerations depending on changes in the speed of the unit from 6 to 24 km/h and were: balanced suspension in the range of 0.7...2.1 m/s^2, and unbalanced – 1.1...3.4 m/s^2. In both suspensions, the maximum RMS acceleration values did not exceed the permissible values of 9.8 m/s^2 (Fig. 6)

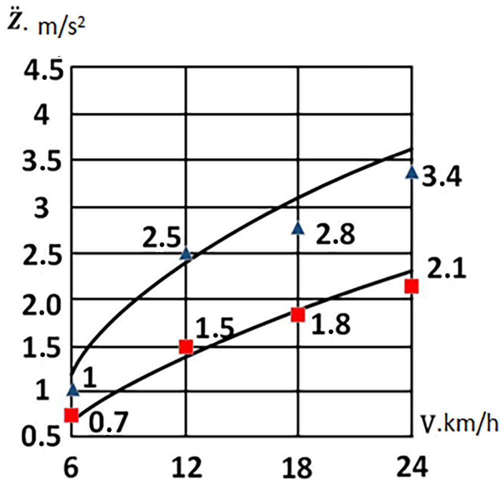

***Figure 6.** Changing the vertical accelerations of the fruit trailer while driving, depending on the speed of movement suspension type:*

Note: ▲ – unbalanced suspension; ■ – balanced suspension

Source: compiled by the authors

As a result of the analysis of the frequency spectrum, the dominance of harmonic components at low frequencies of 1.75 Hz...2 Hz, 5...5.5 Hz, and 12.5 Hz was established. At subsequent harmonics, the increase in acceleration is insubstantial, and starting from a frequency of 20 Hz or more, this phenomenon was not observed. It was established that regardless of the type of suspension and the speed of the trailer, harmonics in the range of 1.45 Hz 5 Hz predominate. (Fig. 7).

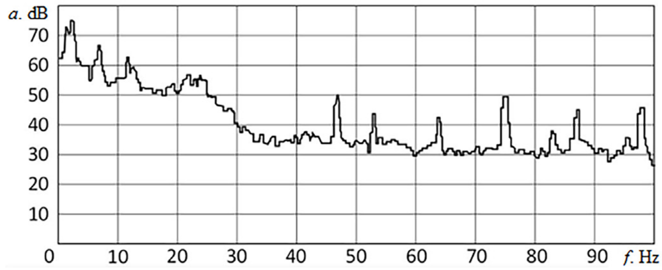

Figure 7. *Spectral distribution of vertical accelerations*

Source: compiled by the authors

The transition from the logarithmic scale in decibels (DB) to natural acceleration values was estimated by the formula:

$$N_{[dB]} = 20\, lg \frac{a}{a_0}, \quad (28)$$

where N – number of decibels; $a_0 = 3 \times \text{x}10^{-4} \frac{m}{s^2}$ – zero level; a – the numerical value of the intermediate acceleration is expressed in m/s^2.

In the energy spectrum of frequencies, the highest level of vertical accelerations is present at the harmonic of 1.75 Hz...2 Hz, while the rest have lower accelerations. When the unit with a balanced suspension is moving at a speed of V = 24 km/h, the total level of vertical acceleration is 3.4 m/s^2, and at a frequency of 2 Hz – 1.9 m/s^2. In this case, the main harmonic accounts for:

$$\frac{1.9}{3.4} 100\% = 55.8\%. \quad (29)$$

Comparing the spectra of vertical accelerations, the largest of them are at a frequency of 2 Hz and make up 55.8% of the full spectrum. When choosing the technological speed of a single-axle trailer with fruits, it is necessary to focus on the first harmonic, which accounts for approximately half of the power of the spectrum.

Examinations of vibrations of a single-axle trailer confirm the random nature of the change in vertical acceleration (Fig. 5). In this paper, an analytical method for calculating vertical accelerations is developed, considering the reduced mass of the trailer (M), the speed of movement (V), vertical displacement of the reduced mass (Z), total tire stiffness (*with*), the height of irregularities (q), and the dimensions of the balancing and unbalanced suspension (d). The obtained equations for calculating vertical accelerations allow focusing on the choice of operating speeds, considering the permissible operating accelerations. This approach is fundamentally different from the model of X. Liu *et al.* (2022), in which vibration analysis was based mainly on the assessment of internal damage to fruits by the finite element method under static load conditions. In the proposed study, a system of equations is developed that allows quantifying the influence of dynamic factors already at the level of the trailer design, which allows not only assessing the risks of cargo damage but also reasonably adapting kinematic driving modes.

In real-world conditions of fruit transportation, the vertical acceleration of the trailer depends on the accepted theoretical calculations along with other factors. The paper shows that the distribution density of random factors has a spectrum either in the form of a wide band or in the form of several narrow ones (Fig. 7). Thus, to assess possible mechanical damage to the fruit, it is necessary to simulate the transportation process, considering the frequency of vibrations.

The data obtained as a result of the study confirm that the type of suspension of a single-axle trailer does not substantially affect the level of vertical vibrations, which are the main cause of mechanical damage to fruits during transportation. As demonstrated by E.J. Timm *et al.* (1996), the use of a balancing suspension can slightly reduce the intensity of fruit damage compared to an unbalanced one, as it better dampens dynamic loads that occur on uneven road surfaces. These results are also supported by the paper of Van Zeebroeck *et al.* (2007), which showed that the most critical factor in apple damage is the pulsed forces transmitted through containers as a result of vibrations and shocks during transportation. In the current study, similar conditions were modelled for different suspension types, and the acceleration level in the frequency range of 1.5-3.5 Hz was found to correspond to the highest level of vertical acceleration, regardless of the suspension type.

In addition, according to the review of M. Al-Dairi *et al.* (2022), mechanical damage received during transportation is one of the main causes of loss of presentation of products, and their number and magnitude increase more with uneven road surface and higher speed than with the type of vehicles. The present study confirms these conclusions: the level of vertical acceleration when using an unbalanced suspension exceeded 0.7 g, while when using a balancing suspension, it did not exceed 0.45 g under similar conditions. B. Suleimani & E. Ahmadi (2015) proved that the quality of the road surface, the speed of transportation, and the type of suspension form the overall oscillatory load on products. Analysis in the current study shows that at speeds up to 24 km/h, both balanced and unbalanced suspensions provide an acceptable level of acceleration. Therefore, the use of structurally simple suspensions, but with sufficient shock-absorbing properties, is an important direction for adapting vehicles to agricultural conditions.

The practical value of this study increases in the context of simplifying the design of trailers for on-farm use. The data show that when driving at speeds of up to 20-24 km/h, even an unbalanced suspension can provide an acceptable level of vertical acceleration that does not exceed the thresholds specified in works S.J. Pretorius & W.J. Steyn (2012). This enables the reduction of the cost of technical means without compromising the quality of fruits during transportation, which is also confirmed by V.M. Martyshko *et al.* (2012) on the feasibility of simplified suspension designs. The results obtained are logically confirmed in previous studies with a similar subject focus. Researchers A. Harrison & R. Van Houck (2008), in the context of transport logistics of agricultural products, noted that reducing the intensity of vibration loads in systems with adaptive or air suspension not only reduces the risk of fruit damage, but also increases the overall efficiency of logistics chains, especially at the stage of primary transportation from the producer to sorting points. A similar pattern was demonstrated by an experiment of T. Acican *et al.* (2007), which shows that when transporting apples in wooden boxes, the amplitude of vibrations on uneven surfaces causes substantial mechanical damage due to resonant effects, which can be mitigated by changing the stiffness of the supporting elements. B. Soleimani & E. Ahmadi (2015) stated that it is the type of vehicle suspension that is the fundamental factor determining the level of transmitted vibrations: particularly, pneumatic systems demonstrate the ability to adapt to changes in speed and type of road surface, providing a reduction in vibration intensity of up to 27% compared to their mechanical counterparts. The correlation of the above results with those obtained in this study indicates the universality of the effect of reducing vibrations due to the introduction of air suspension, which confirms the feasibility of its use in the conditions of fruit transportation on a mixed roadbed.

Thus, the results of the study confirm the need to consider the dynamic parameters of the suspension when designing trailers for on-farm fruit transportation. Optimisation of suspension types can be a pivotal factor in preserving the quality of agricultural products when transported from the field to primary processing or storage points. In this paper, on the example of fruit transportation by a single-axle trailer with a balanced suspension, it is proved that the spectrum of the greatest vertical accelerations falls on two lanes that require the most focus in the case of a safe speed of movement. The possibility of using an unbalanced suspension is confirmed.

Conclusions

The suspension must ensure acceptable smoothness of the vehicle at different speeds, on roads with different surfaces. Smoothness of movement is determined by the value of RMS accelerations. It was established that the vertical accelerations of vehicles with a balanced suspension are less than those with an unbalanced suspension. The difference depends on the length of the balancer, the larger it is, the smaller the vertical accelerations will be. Since the length of the balancer is limited, the vertical vibrations differ little. The spectrum of vehicle vibrations is dominated by vertical accelerations at low frequencies of 1.75...12.5 Hz, and the largest of them at frequencies of 1.75...2 Hz. The predominant harmonic components are in the range of 1.45 Hz...5 Hz. If the transport unit moves along the edge of the block at a speed of up to 24 km/h, the vertical accelerations of the container ship with balanced suspension varied in the range of 0.7...2.1 m/s^2, and with an unbalanced – 1.0...3.4 m/s^2.

Within the existing speeds at which fruits are transported during on-farm transportation, to simplify and reduce the cost of the design of a single-axle trailer, it is permissible to use an unbalanced suspension. It is advisable to use a balanced suspension only in cases where, based on the permissible loads on the axle, it is necessary to install more than two wheels. If two wheels can withstand the load, then, for reasons of simplifying the design of the vehicle, it is suggested to use an unbalanced suspension.

Further research should be aimed at selecting the speed of fruit transportation, both accounting for the characteristics of road bumps and suspension shock absorption properties, and considering the natural frequency of vehicle vibrations. It is also necessary to assess the natural frequency of vehicles with fruits to avoid the phenomenon of resonance, which occurs when the natural frequency coincides with the road caused by its roughness.

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Conflict of Interest

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Обґрунтування типу підвіски одновісного причепа для транспортування плодів

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Анотація. Актуальність дослідження обумовлена важливістю збереження плодової продукції, на якість якої впливають механічні пошкодження плодів під час транспортування, пов'язані із специфічними труднощами через їх значну чутливість до механічних впливів, тому зменшення динамічної дії на плоди вимагає удосконалення конструктивних параметрів спеціальних транспортних засобів та рекомендацій щодо їх використання. Метою роботи було провести порівняльні дослідження рівня вертикальних прискорень причепа з балансирною та безбалансирною підвісками та довести доцільність використання останньої для перевезення плодів. Досліджено вплив конструктивних параметрів та експлуатаційних факторів одновісних причепів на вертикальні прискорення та їх розподіл в енергетичному спектрі коливань транспортного засобу при перевезенні фруктів. Проведено теоретичні та експериментальні дослідження і виконано порівняльний аналіз вертикальних прискорень двох типів підвісок. В ході теоретичних досліджень розв'язано диференціальне рівняння для оцінки рівня вертикальних прискорень з урахуванням наступних факторів: типу підвіски; параметрів балансира; нерівностей профілю дороги; радіальної деформації та жорсткості шин; швидкості транспортного засобу. Для підтвердження результатів теоретичних досліджень була проведена експериментальна оцінка вертикальних прискорень одновісного причепа з балансованою та безбалансирною підвісками при перевезенні плодів у саду по ґрунтовій міжквартальній дорозі. Результати дослідження показали, що середньоквадратичні значення вертикальних прискорень у діапазоні робочих швидкостей які виникали у причепів з безбалансирною підвіскою вищі, ніж у причепів з балансирною підвіскою. Встановлено домінування гармонік вертикальних коливань в діапазоні 1,75-2 Гц, на які припадає понад 55 % потужності спектра прискорень, що є визначальним для оцінки пошкодження плодів. Експериментально доведено, що при середній швидкості транспортування (близько 20 км/год), рівень вертикальних прискорень причепа з обома підвісками не перевищував допустимий рівень. Практичне значення роботи полягає в можливості застосування отриманих результатів при проектуванні та удосконаленні одновісних причепів для перевезення плодів, що сприятиме зменшенню втрат продукції та підвищенню ефективності роботи садівничих господарств

Ключові слова: нерівності ґрунту; коливання; механічні пошкодження плодів; диференціальні рівняння; вертикальні прискорення; амплітудно-частотні характеристики