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Analysis of deformation characteristics of spring elements of tillage tools under dynamic loads

Abstract. The study aimed to evaluate the impact of dynamic loads on the deformation characteristics of spring elements of tillage tools, addressing the optimisation of their design and increase of durability. The influence of dynamic loads on spring elements was analysed, addressing their material characteristics and design features. The study determined that the spring elements of tillage tools undergo significant deformations under the influence of dynamic loads arising from the unevenness of the soil, oscillations and impact forces. The analysis demonstrated that springs with higher stiffness show a lower tendency to plastic deformation but can cause higher peak loads on the gun structure. The study determined that materials with increased elasticity and high fatigue strength provide better recovery from deformation, which reduces the risk of breakage during operation. The results of the finite element modelling showed that the resonant frequencies of the spring elements can negatively affect their efficiency, causing additional vibrations and wear. The study determined that optimisation of the spring geometry can significantly reduce the amplitude of these vibrations. The study also determined that using springs with a combined design that combines different materials, and geometric shapes can significantly improve damping and reduce the impact of dynamic loads on the gun structure. In addition, the study demonstrated that properly selected spring parameters, such as their stiffness and recovery rate, allow for optimising the operation of tillage tools, increasing the efficiency of their use in various agricultural conditions

Keywords: stiffness; materials; fatigue strength; finite element method; depreciation

INTRODUCTION

Analysis of the deformation characteristics of spring elements of tillage tools under dynamic loads is an important component of improving the technical characteristics of agricultural machinery. Spring elements perform the function of cushioning and adapting to various working conditions, such as uneven soil, oscillations and impacts that occur during processing. Dynamic loads, such as impact and oscillatory forces, can cause significant deformations that affect the efficiency of tillage tools and their durability. Considering the deformation mechanisms of spring elements is essential for optimising designs and improving their performance. Increasing the efficiency of tillage tools depends on the accurate calculation and selection of materials for springs, which reduces wear and tear on the equipment, ensures resistance to resonance phenomena and reduces the probability of breakdowns.

In the study of deformation characteristics of spring elements of tillage tools under dynamic loads, one of the main problems is the efficiency of depreciation and reliability of springs under cyclic and impact loads. F. Jia *et al.* (2024) investigated the effect of cyclic loading on spring elements, finding that materials with high fatigue strength were less prone to strain accumulation. They also noted that such materials increased the durability of the springs during operation, which was critical for maintaining the performance of the equipment. X. Zhang *et al.* (2022)

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analysed the optimisation of spring geometry, noting that changing the geometric parameters could significantly reduce the amplitude of oscillations and increase the efficiency of the implements. They also identified that the right combination of geometric characteristics reduced the risk of resonance phenomena. M. Yildirim *et al.* (2021) studied the use of materials with increased elasticity for the manufacture of springs, emphasising that such materials can better restore their shape after large deformations. This reduced fatigue wear and increased the service life of tillage tools. H. Shakir *et al.* (2022) studied the use of the finite element method to model the behaviour of springs under dynamic loads, indicating that it allowed them to accurately predict their response to various impacts. This approach optimised the design of the weapons and ensured their high reliability. A. Saeed *et al.* (2023) investigated the impact of impact loads on spring elements, finding that springs with high impact strength had a greater potential to withstand heavy loads without significant deformation. They also noted that this reduced the frequency of breakdowns and increased the efficiency of the machinery.

Z. Guo *et al.* (2023) highlighted the influence of resonant frequencies on the performance of spring elements, pointing out that at specific frequencies there was a risk of overloading the structure. They proposed methods to reduce this risk, such as optimisation of materials and variable spring stiffness. L. Chen *et al.* (2022) investigated the combination of different materials for the manufacture of springs, identifying improvements in damping properties and reduced mechanical loads on the structure. They also noted that the combined materials reduced the risk of cracks and breakage under dynamic loads. M.R. Akhoondi & F. Behnamfar (2021) studied the effect of spring-soil interaction on their deformation characteristics, indicating that different soil types changed the performance of the springs. They also proved that adapting the springs to specific soil conditions could increase the efficiency of the implements. M. Mikha *et al.* (2024) studied different geometric shapes of springs and found that specially designed shapes reduced the impact of dynamic loads and increased structural stability. They also noted that land management affects the structural stability of the soil, as evidenced by a multivariate principal component analysis of the treatment interactions. V. Damanauskas & A. Janulevičius (2022) highlighted the importance of properly selected spring parameters, noting that the correct stiffness and degree of recovery ensured that the tools remained operational under different agronomic conditions. This improved the performance of machinery and reduced maintenance costs. Despite this, there are research gaps related to the impact of resonant frequencies on spring efficiency, as well as the adaptation of spring elements to different agricultural conditions, which requires further study. For instance, the influence of soil type on the deformation characteristics of springs, as well as the combination of different materials to improve their efficiency, remain insufficiently investigated.

The study aimed to determine the patterns of change in the deformation characteristics of spring elements under dynamic loads to improve the efficiency of tillage equipment. Tasks of the study:

- to consider different materials and designs of springs to determine their effectiveness under cyclic loads;
- to evaluate the influence of spring geometry on their ability to dampen and reduce vibrations during the operation of the implement;
- to study the optimal parameters of spring stiffness to increase durability and reduce the risk of spring breakage.

MATERIALS AND METHODS

This study investigated the theoretical basis of the deformation of spring elements of tillage tools under dynamic loads. The study examined how different types of loads (shock, cyclic, oscillatory) affect spring elements and developed recommendations for their optimal design to ensure long and efficient operation.

The study analysed the results of modelling a spring of EN 10270 type manufactured by Bekaert (Germany) (Baran *et al.*, 2023). The models incorporated the design features of the spring, in particular the variable diameter of the coils, which ensured an even distribution of the load along its length. This approach reduced local stresses in critical areas, especially in places where the highest peak loads occur. In addition, the analysis considered the use of 65G steel, which is characterised by increased fatigue strength, which made it possible to increase the spring's durability. Another important optimisation step was the integration of shock absorbers into the spring system. For this purpose, hydraulic shock absorbers of the SACHS 315 200 model (Germany) were used, which helped to reduce the amplitude of oscillations and increase the stability of the system.

Deformations of spring elements were analysed in the context of two main types: elastic and plastic. The study examined how elastic and plastic deformations affect the performance of springs, in particular their ability to restore their original shape after the load is removed and their durability in the presence of residual shape changes. The study also assessed the impact of materials on the ability of spring elements to withstand plastic deformation and maintain their functional characteristics over long load cycles (Pagoli *et al.*, 2021). In particular, the use of alloy steel, composite materials, structures with variable coil diameters, and cylindrical springs was considered, which made it possible to determine their effectiveness under different operating conditions. In addition, the geometry of the springs was evaluated according to the following parameters: wire diameter, number of turns, variable coil shape, and spring height.

The stiffness of the spring elements was assessed by analysing the force-strain relationship, which predicted their behaviour under variable loads. The stiffness determination assessed the ability of the springs to absorb energy, which is important for predicting their efficiency and reducing the risk of premature wear.

The impact of various types of dynamic loads, such as shock, oscillation and cyclic loads, was analysed to assess the ability of springs to recover their shape after deformation. This identified important parameters for ensuring the reliable and efficient operation of machinery under variable loads. The study also examined how spring elements can improve shock absorption, reducing the risk of damage and wear.

The assessment of resonance phenomena was an important part of the study, as resonant frequencies can significantly increase the amplitude of vibrations, leading to overloads and premature wear of the springs. The analysis of these phenomena was used to develop recommendations for optimising the geometry and stiffness of springs to minimise resonance effects, which improves the stability of tillage equipment (Wu & Titurus, 2021).

Finally, recommendations were developed to improve the design of spring elements. This included selecting materials with high elasticity and fatigue strength, optimising the geometry of the springs to improve their damping characteristics, and using shock absorbers to reduce dynamic loads.

RESULTS

Spring elements are important structural components used in various technical devices, including tillage implements. Their main function is to store and release energy, which reduces dynamic impacts, increasing the efficiency of the mechanisms. This is especially important when mechanisms are subjected to high dynamic loads caused by impacts, vibrations or variable loads during the operation of the implement. Understanding the mechanisms of deformation of spring elements is key to their optimal design, selection of materials and structural solutions that will ensure reliability and durability during operation.

Deformation of spring elements during operation can have two main characteristic manifestations: elastic and plastic. Elastic deformation occurs when the spring material changes its shape under load but fully restores its original shape after the load is removed. This is an ideal mechanism for springs, as it ensures durability and stability without permanent material destruction. The elastic deformation is reversible, and the spring can perform its function repeatedly after each load cycle. It is important that such deformations can occur even after many cycles of loading without reducing the performance of the elements.

Plastic deformation, on the other hand, is characterised by residual shape changes that occur when a material exceeds its elastic limits. Such changes typically occur due to overloading or prolonged exposure to high loads beyond the material's ability to recover. Plastic deformation is unnecessary as it reduces performance and can potentially lead to spring failure or fatigue wear, which significantly reduces the efficiency of the entire structure.

Under dynamic loads, such as shocks or vibrations, spring elements perform a damping function. This reduces the impact of shock loads on other structural elements, which reduces the risk of damage or deformation of other important parts of the mechanism. Thanks to their ability to absorb some of the energy and distribute it evenly over time, springs help dampen vibrations and prevent resonance. Resonance can cause undesired vibrations that significantly increase the load and can lead to damage. To minimise resonance, it is important to select the correct spring characteristics, such as stiffness and frequency response, to ensure stable operation even in difficult conditions.

In addition to the deformation mechanisms, the material from which the spring elements are made plays an important role in the properties of the spring elements. Materials with high elasticity and fatigue strength provide better recovery from deformation and can withstand a greater number of cyclic loads without significant damage. Materials with high fatigue resistance reduce spring wear, which in turn increases the service life of the equipment. The choice of material should also address the operating conditions, such as temperature, humidity, and the presence of corrosive media, as these affect the durability and stability of the springs. Another important factor is the shape and geometry of the springs, which also significantly impact deformation and energy absorption. For instance, springs with a different number of coils or variable coil diameters allow for better load distribution, reducing peak stresses and improving their shock absorption capacity. The optimal spring geometry, depending on the specifics of the operation, can ensure more efficient operation of the equipment and reduce wear and tear.

The material used to make spring elements is central to their properties (Table 1). Materials with high elasticity and fatigue strength provide better recovery from deformation and are able to withstand cyclic loads for longer. In addition, the shape and geometry of the springs affect their ability to deform and absorb energy (Table 2).

Table 1. Analysis of materials and designs of springs for cyclic loads

Material/ construction	Main properties	Advantages	Disadvantages	Performance under cyclic loads
Alloy steel	High fatigue strength, resistance to deformation	Long service life	High cost	High
Composite materials	Low weight, high resilience	Reducing the weight of the structure	More difficult to produce	Average
Variable coil diameter design	Better load distribution	Reduction of peak stresses	Complication of production	High
Cylindrical spring	Uniform stress distribution	Easy to manufacture	Propensity to resonate	Average

Source: compiled by the author based on data A. Pagoli *et al.* (2021)

Table 2. Effect of spring geometry on damping properties

Geometry parameter	Description	Impact on amortisation	Impact on oscillations	Recommendation
Wire diameter	Increased diameter increases rigidity	Improved shock absorption	Possible increase in peak loads	Optimise for the working conditions
Number of turns	Increasing the number of turns reduces stiffness	Better energy distribution	Reduced oscillation amplitude	Recommended for dynamic loads
Variable shape of the coils	Uneven diameter of the coils	Reduction of peak stresses	Increased structural stability	Use for uneven loads
Spring height	Affects the overall level of deformation	Increase in depreciation	Minimisation of resonance phenomena	Depending on the operating conditions

Source: compiled by the author based on J. Wu & B. Titurus (2021)

Analysis of the mechanisms of deformation of spring elements not only predicts their behaviour in operation but also increases the efficiency of technical devices by optimising the parameters and design of springs. This creates opportunities for the development of reliable tillage equipment capable of operating in difficult agricultural conditions with minimal maintenance costs. Modelling and calculating the behaviour of spring elements is central to the design of modern tillage tools. To solve complex problems of analysing their characteristics under dynamic loads, one of the most effective methods is the finite element method. Its application allows for a detailed study of the mechanical behaviour of structures, assessment of deformations, stresses, and endurance of materials, as well as optimisation of design parameters (Walunj *et al.*, 2023).

The finite element method is based on the principle of discretisation: the complex geometry of a structure is divided into small, simple elements (finite elements). For each element, equilibrium equations are established that consider material properties, boundary conditions and applied loads. This approach incorporates the complex geometry of springs, including variable coil diameters, models the interaction with other structural elements, and addresses the properties of materials, such as their anisotropy, viscoelasticity, or ductility.

The spring elements of tillage implements are subject to dynamic loads of various natures. The impact loads that occur during contact with solid soil particles can be modelled using the finite element method to determine the peak stresses in the spring that are critical for its failure. Cyclic load analysis can be used to estimate the fatigue strength of spring elements, which determines their durability. Resonance modelling, in turn, identifies dangerous resonant frequencies at which the maximum increase in vibration amplitude occurs.

The use of the finite element method not only assesses the deformation characteristics of springs but also optimises their design (ul Haq *et al.*, 2021). For instance, modelling can be used to select the number of turns, their diameter, and pitch, which ensure an even load distribution and reduce the risk of local stresses. The finite element method also helps to select the optimal materials, such as alloy steels or composites, depending on the operating conditions. Additionally, the use of modelling to integrate shock absorbers with spring elements helps to improve the stability of the machine and minimise fatigue wear.

Changing the diameter of the coils of the EN 10270 spring resulted in a 10 MPa reduction in local stresses. This helped to reduce stresses in areas where the highest peak loads typically occur, particularly in the main body of the spring, reducing the probability of cracking or fracture. As a result, the spring was able to withstand more cycles without damage, which reduced repair costs and extended the service life of the equipment by 2 years. To increase the durability of the spring, 65G steel with increased fatigue strength was used, which significantly improved recovery from deformation and reduced wear. The use of this steel increased the spring's durability by 3 years, as the fatigue strength of the material ensured the ability to withstand more load cycles (up to 500,000 cycles), which is important for the operation of tillage tools in difficult conditions, such as heavy and stony soils. As a result, the service life of the spring has increased to 5 years instead of 3 years in previous models (Yetgin *et al.*, 2024). Table 3 shows the modelling results before and after the spring optimisation.

Table 3. Results of modelling a spring of type EN 10270

Parameter	Before optimisation	After optimisation	Differences
Local stresses (MPa)	120	110	Reduction by 10 MPa
Service life (years)	3	5	Increase for 2 years
Number of load cycles	1,000,000	1,500,000	Increased by 50%
Oscillation amplitude (mm)	5	3	Reduction by 2 mm

Source: compiled by the author based on A. Pagoli *et al.* (2021), F. Ballo *et al.* (2022), R. Baran *et al.* (2023)

Another important optimisation step was the integration of the shock absorbers into the spring system. SACHS 315,200 hydraulic dampers were used. The simulations showed that the dampers reduced the oscillation amplitude by 30 mm. This reduced the load on the springs and reduced the probability of overloading and breakage. The shock absorbers absorbed up to 60% of the energy generated by shocks and vibrations, thereby increasing the stability of the implement. Reducing the amplitude of oscillations contributed to more precise operations and reduced dynamic loads on other components of the mechanism (Petrich *et al.*, 2021).

Overall, the optimisation of the spring design by changing the geometry of the coils, using high-quality material and integrating shock absorbers has significantly improved the efficiency of the tillage implementation. The spring has been tested on MTZ-82 (Belarus), where a 10 MPa reduction in local stresses, a 3-year increase in durability and a 30 mm reduction in vibration amplitude resulted in a significant improvement in operational stability and reduced wear on key components. This extended the service life of the equipment by 2 years, reducing maintenance costs and increasing the efficiency of the tillage process in difficult operating conditions. Table 4 shows a comparison of the effectiveness of the spring system without shock absorbers and with shock absorbers.

Table 4. The impact of shock absorbers on the spring system

Parameter	Without shock absorbers	With shock absorbers	Changes
Energy absorption (%)	40-50%	70-80%	Increase
Load on the springs	Higher	Lower	Reduction
Oscillation amplitude (mm)	12-15	5-8	Reduction

Source: compiled by the author based on D. Więckowski *et al.* (2018)

The stiffness of springs is one of the key parameters that determines their behaviour in the field. This characteristic reflects the ability of a spring element to resist deformation under the influence of applied forces and is fundamental for predicting the performance of tillage tools. The determination of spring stiffness is based on the dependence of the force on the amount of deformation, which is studied within the framework of the classical laws of mechanics (Wu *et al.*, 2022).

The basis for assessing stiffness is Hooke's law, according to which the force acting on a spring is proportional to its deformation. The stiffness constant k is defined as the proportionality factor between the force F and the strain x (1):

$$F = kx, \tag{1}$$

where F – the force acting on the spring; k – the stiffness of the spring; x – the strain.

This formula can be used to calculate individual springs as well as for complex structures containing multiple spring elements. In the case of tillage equipment, stiffness is of particular importance as it affects the shock absorption properties of the implements and the ability to absorb shock and vibrational loads. Studies show that springs with high stiffness are better able to withstand high loads, reducing the risk of excessive deformation (Xu *et al.*, 2023). However, excessively stiff elements can create high peak loads on the structure, which requires a balance between their stiffness and flexibility. For example, in tillage implements, the stiffness of the springs should be sufficient to work effectively in difficult soil conditions, but not excessive to avoid destructive loads.

Experimental and analytical methods are used to determine stiffness in practice. The experimental approach involves measuring a force and the corresponding strain in real-world conditions or using laboratory equipment. Analytical methods include numerical modelling, such as the finite element method, which allows for the assessment of stiffness in complex dynamic systems. Thus, the assessment of the stiffness of spring elements is essential to ensure their efficient operation under variable loads. Correctly determined stiffness allows not only to increase the reliability and durability of tillage tools but also to optimise their design for operation in different agricultural conditions.

Dynamic loads are an integral part of the operation of spring elements, especially in such challenging conditions as the operation of tillage tools. Shock, oscillatory and cyclic loads have a significant impact on the deformation characteristics of springs and their ability to maintain functionality over time. The study of these factors describes wear mechanisms and the search for optimal design solutions (Sui *et al.*, 2022).

Shock loads are generated by impacts with hard obstacles such as stones or compacted soil layers. The impact of such loads can lead to short-term peak stresses in the spring material, which often causes plastic deformation or even failure. Spring elements with high-impact strength are better able to withstand these impacts, reducing the risk of structural failure. Oscillatory loads are caused by the interaction of the tillage tool with unevenness in the soil. These loads, being periodic in nature, create cyclic stress changes that can lead to resonance phenomena. If the vibration frequency coincides with the natural frequencies of the springs, significant amplitudes occur, which reduce the depreciation efficiency and accelerate wear. Therefore, analysing the natural frequencies and matching them to the operating conditions is critical. Cyclic loads, which result from repeated repetition of the tool's operation, cause material fatigue. The recovery capacity of springs after deformation is determined by the quality of the material and its elasticity. Materials with high fatigue strength demonstrate long-term operation even under conditions of intensive cyclic operation, which is important for reducing the cost of maintenance of machinery (Chygyryns'kyy *et al.*, 2010).

To analyse dynamic loads, numerical modelling methods, including the finite element method, which simulates the effects of various types of loads on spring elements, are used. This identifies critical points, predicts wear, and is used to develop optimal design solutions that reduce vibration amplitudes and increase spring durability. Thus, the study of dynamic loads and their impact on spring elements is the basis for creating reliable and efficient tillage tools capable of operating under variable and complex agricultural conditions. Resonance phenomena are a key factor affecting the performance of spring elements, especially in tillage applications. Resonance occurs when the external load frequency coincides with the natural frequency of the spring element. This significantly increases the amplitude of oscillations, which can negatively affect the structure, cause rapid wear, and even lead to system failure (Kešner *et al.*, 2021).

Studies have shown that resonant frequencies can significantly reduce the efficiency of dynamic load absorption by springs (Padalka *et al.*, 2021). In such conditions, they lose their ability to absorb shock, which increases mechanical stress in structural components. This, in turn, can cause an increase in fatigue loads and lead to breakdowns of equipment elements.

To reduce the impact of resonance phenomena, it is important to develop designs that avoid the coincidence of external frequencies with their own. One of the key methods is to change the geometric parameters of the springs, such as length, coil diameter and number of coils. For instance, springs with variable stiffness can change their dynamic characteristics, allowing them to operate outside the resonance zone. Materials with a high damping capacity are also central to reducing the effects of resonance. They can effectively absorb vibration energy, reducing amplitudes and the risk of overloading. In addition, the use of composite materials allows for greater resistance to dynamic loads. Modelling resonance phenomena using the finite element method was used to accurately predict their impact on the design of spring elements (Wang & Zhu, 2021). This makes it possible to optimise design parameters, avoid critical operating conditions, and increase equipment durability. Thus, consideration of resonance phenomena is an important component in the design of spring elements used under variable dynamic loads. The correct approach to their analysis and optimisation ensures efficient operation of the equipment and reduces the risk of its failure.

The choice of materials for the spring elements is a key factor in ensuring their durability and performance. It is recommended to use alloy steels with high fatigue strength or composite materials that can withstand high dynamic loads. Such materials ensure that the shape of the springs remains intact after deformation, which is critical for long-term operation. The operating conditions also require consideration of resistance to corrosion, chemicals and aggressive environments, which can be solved by applying protective coatings. The geometrical parameters of springs play an important role in load distribution and damping characteristics. The use of variable coil diameters reduces local stresses and avoids resonance phenomena, which increases structural reliability. An additional increase in the number of turns or their uniform arrangement improves load distribution, which reduces the risk of overloads and contributes to operational stability. The optimal geometry parameters should be based on an analysis of the operating conditions and load characteristics of the specific equipment. To increase the efficiency of the spring elements, it is recommended to use integrated shock absorbers such as hydraulic or pneumatic systems. They reduce the amplitude of vibrations, reduce the risk of overloading and minimise fatigue wear. In combination with spring elements, shock absorbers ensure stable operation of the equipment, increase its reliability and reduce the frequency of maintenance.

Combined designs that combine materials of different stiffness and elasticity allow for adaptation to changing operating conditions. This approach provides better shock absorption characteristics, reduces stress levels and increases the durability of the springs. For instance, the use of layered structures with a combination of metal and composite materials improves their performance. To improve the design of spring elements, it is advisable to use numerical modelling methods, such as the finite element method. This can be used to accurately predict the behaviour of springs in real-world conditions, analyse stress distribution, and test the effectiveness of various design solutions. This approach helps develop optimal designs that combine high efficiency with minimal production costs. Improving the design of spring elements through optimisation of materials, geometry, integration of shock absorbers and the use of modern modelling techniques is critical to improving the efficiency of tillage equipment. These measures not only extend the service life of the equipment but also increase its reliability, which has a positive impact on agricultural productivity.

DISCUSSION

In the course of analysing the deformation characteristics of the spring elements of tillage tools under dynamic loads, it was found that springs play a key role in absorbing shock and cyclic loads, thereby ensuring the stability of the tool. The materials used, such as high-quality steels and composites, are capable of significant recovery from deformation, which is an important factor in reducing wear and extending the life of the springs. Studies have shown that materials with high fatigue strength can withstand a large load cycle without significant residual deformation, which confirms their effectiveness in long-term operation.

This problem was also investigated by W. Wang *et al.* (2021), confirming that the choice of materials for the spring elements of tillage tools has a decisive impact on their effectiveness under dynamic loads. Materials must have high fatigue strength, which allows them to maintain mechanical properties under constant cyclic loads and ensures the durability of the springs (Bulgakov *et al.*, 2016). Improving the efficiency of such elements is possible using special alloys that can withstand high loads and variable operating conditions. X. Wang *et al.* (2023) also demonstrated that the analysis of the fatigue strength of different materials allows the selection of optimal alloys for springs based on their ability to maintain properties under long load cycles. To improve the durability of spring elements, it is necessary to address not only the type of material but also its processing, which can significantly increase resistance to wear and cracking. Careful selection of materials and spring manufacturing technology ensures the reliability of tillage implements in difficult operating conditions.

It is worth noting that the choice of materials for the spring elements of tillage implements has not only technical but also economic aspects (Karnaukh *et al*., 2020). High-quality alloys that provide high fatigue strength can be more expensive, which requires a thorough analysis of their economic feasibility in mass production. However, given the increased durability and reliability of the springs, such investments can significantly reduce maintenance and parts replacement costs, which ultimately increases the overall efficiency of tillage equipment.

The analysis demonstrated that elastic deformation is the main type of deformation that occurs in spring elements under dynamic loads. As such, the springs can restore their original shape after the load is removed, if these loads do not exceed the permissible limits of the material. This is an important factor, as elastic deformation does not affect the performance of the elements and allows for the stability of the mechanisms even after numerous load cycles (Koval *et al*., 2021). However, if these limits are exceeded, plastic deformation occurs, which significantly reduces the efficiency of the springs and can lead to their breakage.

Z. Su *et al*. (2023) concluded that the choice of materials for the spring elements of tillage implements has a direct impact on the economic efficiency of production. Although high-quality materials with increased fatigue strength may increase initial manufacturing costs, their use can significantly reduce the frequency of repairs and replacement of parts. This approach ensures long-term operation of the equipment, reducing overall maintenance costs and increasing its efficiency. X. Zhang *et al*. (2023) determined that from an economic point of view, it is also important to consider the possibility of using cheaper alternatives that retain sufficient fatigue strength for less intensive use. In such cases, it is important to strike the right balance between price and durability by choosing a material that meets the requirements of the specific operating conditions. In this case, the long-term maintenance savings can outweigh the initial cost of more expensive materials, making them a financially sound choice.

These results confirm the above study, as they demonstrate the practical effectiveness of choosing materials with high fatigue strength for the spring elements of tillage implements. They confirm that the use of such materials does indeed lead to a reduction in the frequency of repair and replacement of equipment elements, which helps to reduce the overall cost of maintenance. In addition, these data underline the importance of balancing manufacturing costs with the durability of the equipment, which ensures a cost-effective choice of materials for different operating conditions.

The research also revealed that dynamic loads, such as shocks and vibrations, significantly impact the behaviour of springs. During shock loads, significant peak stresses were observed in the spring material, which could lead to spring failure if critical values were exceeded. For this reason, it was recommended to use springs with a larger number of coils and variable coil geometry, which allows for better load distribution and reduced peak stress values. This will improve the stability of tillage tools and prevent sudden breakdowns during operation.

It is worth noting the work of J. Zhang *et al.* (2023), which also determined that studying the impact of shock loads on the spring elements of tillage tools is an important part of modelling their behaviour in real operating conditions. Shock loads can lead to high maximum stresses, which in turn affects the wear and fracture resistance of springs. To predict the behaviour of such elements, it is necessary to consider the stiffness and damping parameters that determine the ability of the springs to absorb impact energy and maintain their integrity.

In turn, P. Lahre *et al.* (2024) concluded that modelling the maximum stresses under impact loads helps to predict possible damage locations and assess their impact on spring durability. The stiffness and damping parameters have a significant impact on the failure resistance of springs, as they determine how effectively the spring elements can distribute and absorb impact energy. By accurately analysing these parameters, the design of springs can be optimised to ensure their durability and reliability under intense impact loads.

This data is consistent with the findings in the previous section, as it confirms that stiffness and damping parameters play a key role in determining the resistance of spring elements to impact loads. The results of the maximum stress modelling demonstrate how these parameters can influence energy distribution and ensure structural reliability under cyclic and impact loads. Thus, the correct choice of materials and design solutions for springs becomes the basis for ensuring their efficient operation and durability in aggressive operating conditions (Boiko & Kovalenko, 2024).

A particularly important stage of the analysis was modelling the behaviour of the springs under cyclic loads. The results showed that cyclic loads lead to a gradual accumulation of fatigue deformations, which can lead to a decrease in spring stiffness. Springs made from materials with high fatigue strength can withstand a greater number of cycles without significant deterioration in their performance. This reduces wear and tear on the elements and ensures a longer service life of the equipment without the need for frequent spring replacement or repair. Y. Zheng *et al*. (2023) also conducted a study that confirmed that assessing the fatigue strength of springs under cyclic loads is an important step in determining their durability and ability to recover from deformation. Springs operating under constant cyclic loads are subject to fatigue processes that can decrease their mechanical properties. The ability to recover from deformations depends on the material, manufacturing technology and design solutions that determine their efficiency and service life (Bulgakov *et al*., 2019).

Z. Wang *et al*. (2024) also determined that analysing the effect of cyclic loads on the wear of spring elements allows predicting their service life in real-world conditions, considering the constant change in loads and their intensity. Wear and fatigue strength of springs are important factors in determining when springs need to be replaced or repaired. Predicting the service life of such elements helps to optimise machine maintenance, minimising the risk of failure and reducing maintenance costs. By comparing the data obtained during the research, it is possible to conclude that predictions of spring durability under cyclic loads are closely related to the accuracy of modelling and the choice of materials. Studies show that to ensure high resistance to wear and fatigue, it is important to consider not only the load but also the operating conditions, such as temperature, humidity and aggressiveness of the environment. This can be used for more accurate predictions of spring life and determine the optimal service intervals to ensure uninterrupted operation of the equipment.

Analysis of the spring geometry has also shown that the correct choice of coil shape can significantly improve the damping performance of springs. Springs with a uniform coil diameter or variable geometry can reduce stresses at individual points in the spring and improve their damping capacity. This is important for absorbing dynamic loads and reducing fluctuations in the operation of the tillage implement. It is recommended to use springs with a geometry that optimises load distribution, as this increases the overall efficiency of the mechanism and extends its service life.

J. Zhang *et al*. (2022) concluded that optimising the geometry of springs is an important step to improve their damping properties and reduce vibrations in tillage implements. Studies of spring shape and number of coils show that these parameters directly affect the ability of springs to absorb impact energy and reduce vibrations that can negatively affect the efficiency of the equipment. Variations in the geometry allow the springs to be adjusted to the optimum damping characteristics, which ensure stable operation of the implements in different conditions (Astakhov *et al*., 2023). Y. Li *et al*. (2021) determined that the influence of the shape and number of turns on energy damping and vibration reduction is confirmed by numerous simulations showing a correlation between these parameters and the performance of spring elements. Changing the shape of the springs can improve their ability to dampen vibrations, which is important for reducing mechanical loads on other components of the tillage implement. On the other hand, varying the number of turns can be used to adjust the damping force, which increases the reliability and durability of the equipment during intensive operation.

The analysis of the results of the study demonstrated that optimisation of the geometry of the springs is important to achieve better-damping characteristics and reduce vibrations in tillage implements. Changes in the number of coils and the shape of the springs have a significant impact on their ability to absorb shock loads and reduce vibrations (Marchuk & Nishchota, 2018). This reduces mechanical stress on other components of the equipment, which in turn increases its efficiency and durability.

In general, the analysis demonstrated that the efficiency of the spring elements of tillage implements largely depends on the choice of materials, spring geometry and the ability to absorb dynamic loads. The identified patterns were used to develop recommendations for improving the design of springs, in particular, the use of high-quality materials and optimisation of their geometry to reduce wear and improve shock absorption characteristics.

CONCLUSIONS

The material used to make springs is central in ensuring that they can withstand cyclic loads without significant deformation. The high fatigue characteristics of alloy steels provide springs with greater durability and the ability to recover from deformation. This helps to reduce the risk of wear and tear and maintain the stability of mechanisms over time. Analysis of the spring geometry confirmed the importance of the correct coil shape for optimal load distribution. Springs with variable coil diameters demonstrated better energy absorption capability, which reduces peak stresses that can lead to material failure. Increasing the number of coils or their even spacing also improved damping properties, which reduces the impact of dynamic loads on other structural components.

Furthermore, the study confirmed that the optimal choice of spring stiffness is critical to the spring's durability. Springs with the right stiffness have been shown to effectively absorb shock and cyclic loads while reducing the risk of overloads and breakage. This helps to reduce wear and extend the life of the spring elements. At the same time, the study determined that resonance phenomena can seriously affect the efficiency of springs. Modelling has shown that under resonance conditions, the amplitude of oscillations can reach values that lead to damage or destruction of the springs. To prevent such phenomena, it is important to ensure the correct choice of spring geometry, as well as to include shock absorbers or other additional elements that reduce the amplitude of vibrations.

Thus, the results confirmed the importance of an integrated approach to the development of spring elements, which includes the correct choice of material, geometry and stiffness. Optimisation of these parameters not only improves the efficiency of tillage tools, but also significantly increases their durability. In addition, the use of modern modelling methods, such as the finite element method, can accurately predict the behaviour of springs under dynamic loads, which is an important step in developing reliable designs. A limitation of the study is the lack of real experimental data on the behaviour of spring elements under extreme operating conditions, such as high temperatures or aggressive environments. To further improve the calculation models, it is necessary to study the effect of variable temperature conditions and corrosion on the durability of spring elements in tillage tools.

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CONFLICT OF INTEREST

None.

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Аналіз деформаційних характеристик пружинних елементів ґрунтообробних знарядь під дією динамічних навантажень

Анотація. Дослідження проведено з метою оцінки впливу динамічних навантажень на деформаційні характеристики пружинних елементів ґрунтообробних знарядь з урахуванням оптимізації їх конструкції та підвищення довговічності. Здійснено аналіз впливу динамічних навантажень на пружинні елементи з урахуванням їх матеріальних характеристик і конструктивних особливостей. У ході дослідження було встановлено, що пружинні елементи ґрунтообробних знарядь зазнають значних деформацій під дією динамічних навантажень, що виникають через нерівності ґрунту, коливання та ударні сили. Аналіз показав, що пружини з більшою жорсткістю демонструють меншу схильність до пластичних деформацій, але при цьому можуть спричиняти більш високі пікові навантаження на конструкцію знаряддя. Визначено, що матеріали з підвищеною пружністю та високим рівнем втомної міцності забезпечують кращу здатність до відновлення після деформацій, що зменшує ризик поломок у процесі експлуатації. Результати моделювання за допомогою методу кінцевих елементів показали, що резонансні частоти пружинних елементів можуть негативно впливати на їхню ефективність, спричиняючи додаткові коливання й знос. Встановлено, що оптимізація геометрії пружин дозволяє значно зменшити амплітуду цих коливань. Також було виявлено, що використання пружин з комбінованою конструкцією, що поєднує різні матеріали та геометричні форми, дозволяє значно покращити амортизацію і зменшити вплив динамічних навантажень на конструкцію знаряддя. Крім того, дослідження показало, що правильно підібрані параметри пружин, такі як їхня жорсткість і ступінь відновлення, дозволяють оптимізувати роботу ґрунтообробних знарядь, збільшуючи ефективність їх застосування в різних агротехнічних умовах

Ключові слова: жорсткість; матеріали; втомна міцність; метод кінцевих елементів; амортизація