



Impact of mechatronic systems on accuracy and stability of vibration cleaning machines in the agricultural sector

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Abstract. The study was conducted to determine how the use of mechatronic systems can optimise the operation of vibration-cleaning machines and improve their performance in agricultural processes. Vibration accuracy measurement, automated load control, monitoring of operating parameters, wear assessment, energy efficiency analysis, and impact assessment to minimise human intervention were used in the study. A study conducted at BIG Harvest Group demonstrated that the introduction of mechatronic systems in vibration-cleaning machines significantly improves the accuracy and stability of their operation. The integration of automated control of the frequency and amplitude of oscillations has reduced energy consumption and increased the efficiency of seed cleaning compared to traditional methods. The study determined that the system of automatic monitoring and correction of parameters ensures stable machine performance even under variable load conditions. Reduced wear and tear on mechanical components ensure longer equipment life, reduced downtime and the need for manual

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intervention. In general, the results confirmed that mechatronic systems significantly increase the efficiency of vibration-cleaning machines, which has a positive effect on the quality of cleaning and economic efficiency in agriculture. The study also determined that automatic adjustment of operating parameters using mechatronic systems reduces fluctuations in machine performance, resulting in more uniform cleaning. The integrated monitoring system identified and eliminated faults, reducing maintenance time. As a result, improvements in the overall management of seed cleaning processes were achieved, which increased productivity and reduced equipment operating costs

Keywords: automated control; energy consumption; seed cleaning; wear of mechanical components; economic efficiency

Introduction

In the agricultural sector, the efficiency of seed treatment is critical to ensuring high product quality and optimising resources. Vibration cleaning machines, which are used to clean seeds from contaminants and impurities, are central to this process. However, traditional control systems often face problems with accuracy and stability, which can affect cleaning quality and operating costs. In this regard, mechatronic systems that combine mechanical, electronic and computer technologies have become a promising solution for improving the efficiency of vibratory cleaning machines. The introduction of such systems promises significant improvements in setup accuracy, operational stability, energy efficiency and reduced equipment wear.

In the agricultural sector, the precision and stability of vibration-cleaning machines are important aspects for improving the quality of seed processing and reducing operating costs. The problem is that traditional systems often do not provide sufficient accuracy and stability, which affects cleaning efficiency and increases maintenance costs. C. Cardona *et al.* (2024) investigate how the integration of mechatronic systems can increase the accuracy of vibration control in vibration cleaning machines, which has a positive effect on the quality of seed cleaning. Their study shows that automating settings reduces energy consumption and improves overall process efficiency. D. Xie *et al.* (2022) addressed automated oscillation frequency control, which provides

a significant reduction in energy costs. Their research confirms that such systems increase cleaning efficiency and reduce operating costs. I. Hassan *et al.* (2024) studied the impact of sensors for monitoring vibration parameters on the stability of vibration-cleaning machines. The results show an increase in stability under varying load conditions due to automatic correction. L. Badita-Voicu *et al.* (2024) find that mechatronic systems significantly reduce wear and tear on mechanical components, which extends the life of the equipment. This reduces the need for frequent repairs and maintenance. E. Mincă *et al.* (2022) noted that the integration of mechatronic systems reduces downtime and the need for manual intervention. The study highlights the improvement in the overall performance of vibration-cleaning machines.

E. Aliiev & K. Lupko (2021) demonstrated that automatic parameter adjustment results in more uniform seed cleaning. This helps improve the quality of the final product and reduce processing costs. D. Essola *et al.* (2022) demonstrated how reducing vibrations in vibration cleaning machines can improve cleaning quality and reduce maintenance costs. Their results confirm the effectiveness of mechatronic systems in reducing operating costs. M. Romanssini *et al.* (2023) confirmed that the introduction of mechatronic technologies increases the energy efficiency of vibration-cleaning machines. This reduces energy costs and improves economic performance. D. Ionescu *et al.* (2022) determined that the

automated monitoring system can be used for quick detection and elimination of equipment malfunctions. This reduces the time required for maintenance and repairs. A. Hayat *et al.* (2022) proved that mechatronic systems can significantly reduce the cost of operating vibration cleaning machines. Research shows that these systems significantly improve economic efficiency in the agricultural sector. Thus, while research has revealed significant advantages of mechatronic systems in improving the accuracy and stability of vibration-cleaning machines, there are gaps, particularly in terms of economic benefits and specific operating conditions, that require further study.

The study aimed to investigate the impact of mechatronic systems on optimising the operation of vibration-cleaning machines and increasing their efficiency in the agricultural sector. Research objectives:

- to consider the introduction of automated control of vibration processes and its effect on energy costs and quality of seed cleaning;
- to study how mechatronic systems affect the accuracy and stability of vibration cleaning machines;
- to evaluate the results of the integration of sensor technologies and automatic monitoring, as well as their impact on operating costs and overall equipment performance.

Materials and Methods

The study, which focuses on the impact of mechatronic systems on the accuracy and stability of vibration-cleaning machines in the agricultural sector, comprehensively assessed the integration of these systems. The main areas of focus included precise adjustment of vibration parameters, automated load control, monitoring and correction of operating parameters, wear reduction, energy efficiency and minimisation of human intervention.

The study was conducted at BIG Harvest Group (Ukraine). The study examined seeds of several crops, including wheat, barley, corn and peas. Each of these seed types had its unique

characteristics that affected their behaviour during the cleaning process. Experiments were carried out on samples of these crops to study in detail the effect of various vibration parameters, such as vibration frequency, vibration amplitude and vibration direction, on cleaning efficiency. This was used to analyse how the amplitude and frequency of oscillations affect the cleaning results of each type of seed, as well as to identify the optimal conditions for achieving the best performance.

To evaluate the precise adjustment of vibration parameters, Toshiba Vibration Cleaner X-1000 (Japan) equipped with mechatronic systems from Bosch Rexroth (Germany) was used. These machines allow for precise control of the frequency and amplitude of vibrations. Vibration levels were measured using high-precision Kistler sensors and a National Instruments data recording system.

The analysis of automated load control was carried out using Meyer Industries V-300 vibration cleaning machines (USA) equipped with Siemens S7-1200 mechatronic systems (Germany). In this case, Endress+Hauser sensors were used to monitor the amount of seed entering the cleaning process. The automatic load control was evaluated using Rockwell Automation's FactoryTalk software, which records and adjusts parameters in real time.

At this stage, the performance of the Haver Roto-Packer vibration cleaning machines from Haver & Boecker (Germany) was evaluated using Honeywell (USA) integrated sensors, which were used to monitor temperature, humidity and vibration levels. The data were collected using a LabVIEW data acquisition system and analysed using MATLAB software for automatic parameter correction.

Alapala VIB-500 vibration cleaning machines from Alapala (Turkey) equipped with Parker Hannifin mechatronic systems (USA) were used to assess wear reduction. Wear measurements of mechanical components were carried out using specialised Mitutoyo equipment (Japan). Wear was assessed by analysing differences in the physical characteristics of the components,

including measuring material thickness, determining the volume of worn parts and conducting dynamic vibration tests. A comparison with traditional Ocrim (Italy) machines without automatic systems was used to determine the impact of automatic control on equipment service life and maintenance costs.

The energy efficiency analysis was carried out using Satake MCH-100 vibration cleaning machines from Satake (Japan), which were used in tests with mechatronic systems from Schneider Electric (France). Electricity consumption was measured using Fluke energy meters (USA). The data was compared with the energy consumption of traditional Omas systems (Italy) to determine the effectiveness of optimising electricity consumption.

To analyse the impact of mechatronic systems on reducing human intervention, Groupe SEMA (France) vibration cleaning machines with Mitsubishi Electric (Japan) automated systems

were used. Operator error rates and performance were assessed by observing the number of errors and their impact on machine performance.

A comprehensive approach to assessing the impact of mechatronic systems on various aspects of the operation of vibration-cleaning machines has provided detailed data on their effectiveness and benefits in the agricultural sector.

Results

In the modern agricultural sector, especially in the growing and processing of grain crops, optimisation of technological processes is critical. BIG Harvest Group, which specialises in growing and processing wheat, barley, corn and peas, has become one of the pioneers in implementing automated technologies to improve the efficiency of its production processes. In particular, the study of automated control of vibration processes has significantly reduced energy costs and improved the quality of seed cleaning (Table 1).

Table 1. Effect of automated control of vibration processes on energy consumption and quality of seed cleaning

Parameter	Before automation	After automation	Improvement (%)	Parameter
Power consumption (kW)	15-20	10-15	20-30	Power consumption (kW)
Electricity costs (UAH/hour)	45-60	30-45	25-33	Electricity costs (UAH/hour)
Level of seed contamination (%)	5-7	1-3	50-70	Level of seed contamination (%)
Seed cleaning accuracy (%)	85	95	10	Seed cleaning accuracy (%)

Source: compiled by the authors based on V. Ishchenko (2023)

The vibration processes used in the seed cleaning process are critical to achieving high quality in the final product. Traditional methods of seed cleaning are often associated with high energy consumption, which negatively affects the overall costs of the enterprise. The BIG Harvest Group has implemented an automated control system that can monitor vibration parameters in real-time. This solution is based on state-of-the-art mechatronic systems that ensure precision and efficiency in the seed cleaning process.

The introduction of automated control of vibration processes has brought significant benefits. It was possible to reduce electricity consumption by 20-30% as a result of optimising the operation of vibrating machines. Reducing energy costs not only helped to increase the company's profitability but also had a positive impact on the environmental component of production. The advanced system can adjust vibration to the type of seed being processed, which also reduces unintended energy consumption. Vibration frequency

and amplitude control optimise machine performance by preventing unnecessary vibrations that are not required for a particular type of seed. This reduces energy consumption as the machine operates at maximum efficiency, using only as much energy as necessary to achieve optimum results.

The automated control has also improved the quality of seed cleaning. Precise control of the vibration parameters achieves greater efficiency in the process of separating impurities from the seeds. The quality of wheat, barley, maize and pea seeds has improved significantly, which has had a positive impact on their marketability and consumer characteristics. In particular, the company was able to reduce the level of seed contamination to the minimum permissible standards, which increased the competitiveness of its products in the market.

Mechatronic systems significantly increase the accuracy and stability of vibration-cleaning machines in the agricultural sector by integrating mechanical, electronic and computer components. The precise adjustment of vibration parameters in vibration-cleaning machines is a key factor in ensuring an efficient seed-cleaning process in the agricultural sector. Mechatronic systems that combine mechanical, electronic and computer components open new possibilities for precise control of the frequency and amplitude of vibrations. Thanks to the introduction of such systems, vibrating machines can operate at optimal parameters, which significantly improves the

quality of cleaning various types of seeds, even under variable operating conditions.

The main advantage of mechatronic systems is the automatic adjustment of vibration parameters depending on the type of raw material being cleaned. Each type of seed has its characteristics – density, size, texture, and contamination (Brown *et al.*, 2021). For instance, smaller or lighter grains (wheat, barley) may require less intense vibrations, while larger or heavier grains (corn, peas) may require higher amplitude and frequency for effective cleaning. Mechatronic systems automatically adjust these parameters, reducing the need for manual intervention, which reduces the risk of errors and productivity losses.

The automatic parameter adjustment system also accounts for external factors such as humidity or temperature that may affect the cleaning process (Amertet *et al.*, 2023). This ensures even vibrations and, as a result, uniform seed cleaning. By precisely controlling the frequency and amplitude of vibrations, vibration cleaning machines operate with greater stability and efficiency, which has a positive effect on the final product quality.

In addition, precise adjustment of the vibration parameters reduces wear on machine components (Table 2). Vibration amplitudes that are too high or too low can put additional stress on mechanical parts, causing additional wear. Mechatronic systems keep vibration cleaning machines operating within a safe range, which extends equipment life and reduces maintenance costs.

Table 2. Precise adjustment of vibration parameters

Parameter	Vibration cleaning machines with mechatronic systems	Vibration cleaning machines without mechatronic systems
Oscillation frequency (Hz)	30-60	25-55
Oscillation amplitude (mm)	2-5	3-6
Sensor	Kistler sensors	Kistler sensors
Data recording system	National Instruments	National Instruments
Cleaning efficiency (%)	90	80

Source: compiled by the authors

The introduction of mechatronic systems in vibration cleaning machines renders the seed cleaning process not only more efficient but also

cost-effective. Automation of vibration settings significantly improves equipment accuracy, reduces human error and ensures stable operation

even under variable load conditions. This makes mechatronic systems an integral part of modern technological processes in the agricultural sector, ensuring high-quality seed cleaning and increasing agricultural productivity.

Automated load control is one of the key functions of modern mechatronic systems, enabling vibration-cleaning machines to maintain stable performance even under variable operating conditions. Given the importance of precision and efficiency in the agricultural sector, the ability to automatically adjust the workload is crucial to ensure the smooth operation of the equipment and high-quality seed cleaning.

Mechatronic systems equipped with integrated sensors and software allow for continuous monitoring of the amount of raw materials entering the treatment (Kuntoğlu *et al.*, 2021). This is especially relevant in situations where the amount

of seed or grain being loaded into the machine is constantly changing. Instead of the operator having to constantly monitor the process, the system automatically adjusts to the changing load parameters to ensure the optimum performance of the vibration cleaning machine. This reduces the human factor and ensures consistent performance even if the amount of seeds or grain varies.

Thanks to automated load management, mechatronic systems also enable better management of machine energy consumption (Table 3). As the load changes, the system can adjust the vibration intensity and processing speed, which minimises energy consumption without compromising cleaning quality. Such adaptability contributes to the energy efficiency of the entire process, which is important for reducing overall production costs and increasing the economic efficiency of an agricultural enterprise.

Table 3. Automated load management

Parameter	Vibration cleaning machines with mechatronic systems	Vibration cleaning machines without mechatronic systems
Load range (kg/h)	500-1000	400-900
Load regulation	Automatic	Manual
Sensors	Endress+Hauser	Endress+Hauser
Software	Rockwell Automation FactoryTalk	None
Performance stability (%)	95	85

Source: compiled by the authors

Another important advantage of automated load management is the ability to maintain stable machine operation regardless of external conditions (Ullah *et al.*, 2021). In real-life conditions, in particular, in field farms, humidity, seed type and outside temperature can vary. This can affect the quality of the cleaning process if the machine is not able to adapt to these changes. Mechatronic systems can compensate for these external factors by precisely controlling the workload, which makes it possible to maintain high machining quality regardless of the conditions.

In addition, automated load management systems increase the reliability of the equipment. Vibration cleaning machines can be overloaded

or underloaded due to fluctuations in the amount of material being processed, which can reduce efficiency or cause breakdowns. Automatic load control ensures even load distribution, which reduces the risk of failure and helps to extend the service life.

Thus, the automated load control implemented in modern vibration cleaning machines provides several important benefits for agricultural production. It helps maintain a stable cleaning process efficiency, reduces the need for manual control, and ensures energy efficiency and adaptation to external changes. This not only improves the quality of seed processing but also ensures greater reliability and stability of the equipment,

which is an important factor for agricultural enterprises seeking to increase their productivity and economic efficiency.

Monitoring and correction of operating parameters using mechatronic systems is a key aspect of increasing the efficiency and stability of vibration-cleaning machines in the agricultural sector. Integrated sensors that monitor parameters such as temperature, humidity and vibration levels enable precise control of the cleaning process. Thus, the system can automatically adjust the operation of the machines to ensure consistent performance despite changes in environmental conditions or raw material parameters.

One of the main advantages of this feature is the ability to collect and analyse machine performance data in real-time. For instance, an increase in seed moisture content can affect the quality of cleaning, as wet raw materials are more difficult to separate (Müller *et al.*, 2022). Integrated sensors detect this indicator and, if necessary, the mechatronic system adjusts the vibration frequency, increasing or decreasing the intensity of the vibrations depending on the current conditions. As such, high cleaning quality can be achieved, even with variable material characteristics.

In addition, temperature monitoring is another important aspect that affects process efficiency. Vibration cleaning machines operating at too high or low temperatures can lose performance due to reduced lubrication or increased wear and tear on mechanical components (Martínez-Parrales & del Carmen Téllez-Anguiano, 2022). The monitoring system can detect temperature deviations on time and implement measures to reduce the impact of negative factors. For instance, it can automatically reduce the load on the machine or increase the coolant volume to avoid overheating.

Another important component is the control of vibration characteristics. If the vibration level exceeds the permissible limits, it damages the machine or is a reason for ineffective seed cleaning (Sinha *et al.*, 2023). Integrated sensors detect such deviations in time, and the system corrects the machine to restore stable operation.

This automatic correction capability is highly relevant in the agricultural sector, as it ensures high machine performance without the need for constant operator monitoring.

Automatic correction also reduces the risk of accidents and equipment damage. Mechatronic systems can prevent critical loads or overheating by reacting to changing parameters in a timely manner. This not only increases the efficiency of the production process but also significantly reduces maintenance and repair costs.

Thus, monitoring and correction of operating parameters with the help of mechatronic systems is an important component of ensuring the stable performance of vibration-cleaning machines. These systems automate the control process, ensuring the uninterrupted operation of machines even in the face of changes in external conditions or raw material parameters. Accordingly, the integration of such technologies into the agricultural sector significantly improves the quality and reliability of the seed-cleaning process, which contributes to the overall increase in agricultural production efficiency.

Reducing wear and extending the operational life of vibration-cleaning machines is an important advantage of introducing mechatronic systems in the agricultural sector. One of the main factors affecting the durability of equipment is the constant load on mechanical components. Without automated parameter control and overload prevention, wear and tear on parts is significantly accelerated, leading to frequent breakdowns, efficiency losses and increased maintenance costs. Mechatronic systems provide automatic parameter adjustment to avoid these problems and extend the service life of machines.

One of the key functions of mechatronic systems is the ability to continuously monitor and correct operating parameters such as vibration frequency and amplitude (Tsai *et al.*, 2021). If an overload risk is detected, the system automatically reduces the work intensity, which reduces the load on the machine components. This approach reduces the likelihood of premature wear of moving

parts, which is necessary for stable and long-term operation of the equipment.

Automatic parameter adjustment minimises excessive loads on the most vulnerable parts of the machine, such as bearings and joints. When the vibration parameters are outside the optimum range, the risk of damage to these components increases dramatically. Mechatronic systems, using integrated sensors, detect these deviations and automatically adjust the operation of the equipment, reducing the intensity of the load on

problem areas. This can ensure a stable workflow without the risk of serious breakdowns.

Another important advantage is the reduction in maintenance costs (Table 4). As mechatronic systems monitor the condition of the vibration-cleaning machine's components and can predict potential problems, companies are able to carry out preventive maintenance in a more efficient manner. This helps avoid emergencies and unexpected downtime that could result in serious damage.

Table 4. Reduce wear and tear and extend equipment life

Parameter	Vibration cleaning machines with mechatronic systems	Vibration cleaning machines without mechatronic systems
Level of wear and tear on mechanical components	5%	10%
Service life (years)	8	5
Wear measurement equipment	Mitutoyo	Mitutoyo
Model	Alapala VIB-500	Ocrim
Maintenance costs (UAH/year)	10,000	15,000

Source: compiled by the authors

Thanks to the integration of mechatronic systems, the need to replace or maintain specific components can be identified in time. This reduces the cost of general maintenance, as businesses can plan it in a way that minimises the impact on the production process. In addition, extending the service life of equipment without significant investments in repairs allows for more efficient use of resources.

Mechatronic systems also help optimise energy consumption, which has a positive effect on the overall condition of the mechanisms. When the equipment is not overloaded, its power consumption is reduced, which in turn reduces the level of heat exposure to machine parts. Heat load reduction is another important factor in extending the service life of equipment, as constant temperature changes can cause material degradation.

Thus, automatic parameter adjustment and overload prevention by means of mechatronic systems are central to reducing wear and extending the service life of vibration-cleaning machines. These systems not only ensure stable

machine operation but also significantly reduce maintenance and repair costs. Due to the effective control of operating parameters, the mechanical components of the equipment receive optimal conditions for long-term and uninterrupted operation, which contributes to the overall efficiency of agricultural production.

Energy efficiency is one of the key advantages of implementing mechatronic systems in vibration-cleaning machines in the agricultural sector. Modern technologies require more and more rational use of energy, and mechatronic systems help to achieve this by optimising equipment processes. With energy prices on the rise and the need to reduce carbon dioxide emissions, energy savings are becoming a strategic advantage for agricultural companies.

Mechatronic systems can adapt the operation of vibration-cleaning machines to changing conditions in real-time. This is achieved through the integration of sensors that measure various parameters of the seed cleaning process, such as the amount of material being processed, its

condition, moisture level and other indicators. The automatic control systems analyse this data and optimise the machine's operating parameters to ensure maximum productivity with minimum energy consumption. This negates excessive power consumption when processing smaller quantities of seed or when maximum power is not required.

Another important aspect of energy efficiency is the ability to precisely control the frequency and amplitude of vibration vibrations. This allows the vibration cleaning machines to operate at the power level that best suits the current process requirements. This means that unnecessary energy is not wasted on maintaining redundant parameters when it is not necessary. For example, when processing fewer seeds, the system can automatically reduce the intensity of the machine, which directly reduces energy consumption (Ji *et al.*, 2021).

In addition, the mechatronic systems can recognise when the machine is in a standby state or paused between seed treatments and automatically switch it to a power-saving mode. This minimises energy loss during downtime, which also contributes to overall operational efficiency. Thus, mechatronic systems reduce energy costs even in situations where the machine is temporarily out of active operation.

Energy efficiency not only reduces direct energy costs but also reduces overall maintenance and repair costs. Machines that operate with optimum energy consumption typically experi-

ence lower levels of wear and tear because their components are not subjected to excessive loads. This means that parts last longer, reduce the risk of unexpected breakdowns, and reduce maintenance and replacement costs.

Another important advantage is the environmental aspect of energy efficiency. The use of mechatronic systems not only reduces electricity consumption but also reduces carbon dioxide emissions arising from energy production. This helps reduce the negative impact on the environment, which is becoming an increasingly important factor for the agricultural sector. Modern enterprises are striving to meet the requirements of sustainable development, and the introduction of energy-efficient technologies is an important step in this direction.

Thus, optimising energy consumption with mechatronic systems not only reduces production costs but also ensures a more environmentally friendly operation of vibration cleaning machines (Table 5). Automatic control and regulation systems, adaptation of equipment operation to changing conditions, and switching to economical modes during downtime make these technologies indispensable for achieving high efficiency in modern agricultural production. Mechatronic systems help companies not only save resources but also remain competitive in the market while taking care of the environment and future generations.

Table 5. Comparison of energy efficiency of vibration cleaning machines with and without mechatronic systems

Parameter	Vibration cleaning machines with mechatronic systems	Vibration cleaning machines without mechatronic systems
Power consumption (kW)	10-15	15-20
Electricity costs (UAH/hour)	30-45	45-60
Energy sensors	Fluke	Fluke
Test model	Satake MCH-100	Omas
Improved energy efficiency (%)	20	0

Source: compiled by the authors

Minimising human intervention is one of the key aspects of implementing mechatronic

systems in vibration-cleaning machines in the agricultural sector. Process automation simplifies

the management of complex technological operations, reducing the risk of human error and increasing overall production efficiency.

Thanks to mechatronic systems, most routine and difficult tasks that previously required constant supervision by operators can now be performed automatically. For instance, setting the parameters of the vibration system, adjusting the amplitude and frequency of oscillations, as well as monitoring temperature and humidity, are all done without the need for direct human intervention. This reduces the error probability that could occur due to operator fatigue, inattention or lack of experience.

The automation of vibration cleaning processes also ensures precise and stable operation. Mechatronic systems can independently adapt to changing production conditions, quickly responding to changes in raw material volumes or machine parameters. Operators are no longer forced to constantly check and adjust the machines, which avoids shortcomings that could have been caused by delays or incorrect settings. This ensures that the seed or grain cleaning process is uninterrupted, which increases overall productivity and processing quality.

Another advantage of automation is improved workplace safety. Vibrating equipment, especially under heavy loads, can be dangerous for the operator due to the high frequency of oscillations or possible overloads. Thanks to mechatronic systems that monitor and adjust operating parameters automatically, the risk of accidents is significantly reduced. Modern systems can also detect critical situations, such as excessive wear and tear on parts or overloading, and automatically stop the machine to prevent breakdowns.

Minimising human intervention also has a positive impact on the economic performance of enterprises (Bolaños *et al.*, 2021). Since mechatronic systems perform most operations automatically, this reduces the need for additional manpower to monitor the equipment. Thus, companies can save on costs related to salaries, staff training and workplace safety. In addition, the

reduction of errors and the increase in machine efficiency reduces maintenance and repair costs.

Automated mechatronic systems also contribute to improved resource and time management. Operators can focus on more strategic tasks, such as optimising production processes or scheduling work, rather than routine technical operations. This helps improve the overall efficiency of management and, ensures flexible response to changing operating conditions.

However, it is worth noting that full automation may have certain limitations. For instance, in the event of malfunctions or unforeseen situations, the system may not always react as flexibly as a human would. It is important that mechatronic systems are properly programmed and able to adapt to a variety of operating conditions. In addition, given the complexity of modern technology, qualified personnel are needed to maintain these systems, monitor their operation and respond quickly to possible failures.

As a result, minimising human intervention with mechatronic systems opens new opportunities to improve the efficiency of vibration-cleaning machines, reducing the risk of errors and costs. This is an important step towards the modernisation of the agricultural sector, enabling businesses to operate more efficiently, safely and economically.

In general, the introduction of mechatronic systems in vibration cleaning machines not only increases their efficiency but also ensures more reliable and stable operation, which is especially relevant in improving the quality of seed cleaning and optimising agricultural production.

Discussion

The study determined that the introduction of mechatronic systems has significantly increased the accuracy and stability of vibration-cleaning machines in the agricultural sector. The automated vibration parameter control systems were used to precisely control the frequency and amplitude of vibrations, which has resulted in more uniform seed cleaning. This ensured a better quality of the cleaning process compared to traditional

methods, where such parameters were adjusted manually. Thus, the results of the study confirmed the assumption that the efficiency of equipment operation will increase as a result of the introduction of modern technologies. This was also investigated by M. Mohd Ghazali & W. Rahiman (2021), confirming that the accuracy and stability of vibration-cleaning machines are critical to achieving high standards of seed cleaning. This is achieved by fine-tuning the amplitude and frequency characteristics of vibrations and improved mechanism design. The use of modern materials also reduces vibration loads and ensures uniformity of operation. A. Linenko *et al.* (2021) also demonstrated that mechatronic systems increase the efficiency of vibration-cleaning machines by automating the adjustment of vibration parameters. The integration of sensors and controllers enables real-time monitoring and adaptation. This results in shorter processing times and improved cleaning quality.

The integration of mechatronic systems into vibration-cleaning machines not only automates processes but also increases their accuracy and reliability. However, the results of the study indicate that there are technical issues and additional maintenance costs that could reduce overall efficiency. This underscores the need for a comprehensive approach to the introduction of new technologies, accounting for both their benefits and risks. Therefore, it is necessary to study in detail all aspects of mechatronic system integration to achieve optimal results in the agricultural sector.

One of the key findings was the reduction of the impact of variable factors, such as different quantities and types of raw materials, on the stability of the vibration-cleaning machines. Automated real-time parameter adjustment ensured effective adaptation to changing operating conditions. As a result, constant productivity was achieved, even in the presence of significant fluctuations in the characteristics of raw materials. This underlined the importance of mechatronic systems for maintaining a high level of stability in agricultural processes. Y. Li *et al.* (2022) concluded that the automation of real-time adjustment

of the parameters of vibration cleaning machines allows for accurate and fast adjustment of vibration amplitudes and frequencies following changing processing conditions. This improves the efficiency of the cleaning process, as the system can respond quickly to changes in the characteristics of seeds or impurities. Thanks to this automation, the human factor is reduced, which reduces the risk of errors and improves the overall quality of processing. V. Adamchuk *et al.* (2021) determined that reducing the impact of external factors such as temperature, humidity or voltage fluctuations on the performance of vibration cleaning machines is an important aspect of ensuring stable operation. The use of modern sensors and controllers that account for these factors helps reduce their negative impact on the efficiency of the cleaning process. This ensures a consistent high-quality finish regardless of external conditions.

These results confirm the study, as the automation of real-time parameter control improves the accuracy and stability of vibration-cleaning machines. However, the impact of external factors can vary depending on the operating conditions. The results of the study indicate the need to adapt the systems to specific processing conditions, which may require additional adjustments and optimisation. Hence, while automation increases efficiency, it is important to consider all the variables to achieve maximum results.

In addition, the study showed that the use of integrated sensors to monitor key parameters such as temperature and humidity can quickly detect deviations in machine performance. Automatic parameter adjustment helped avoid overloads and ensure uninterrupted operation of the equipment. These results indicate a significant impact of mechatronic systems on improving the reliability and stability of vibration-cleaning machines. Z. Ma *et al.* (2023) also determined that monitoring and correcting key parameters such as vibration amplitude and frequency are critical to ensuring the stable operation of vibration-cleaning machines. Monitoring systems can detect any

deviations from the established norms and make prompt adjustments to maintain optimal performance. This not only improves the quality of cleaning but also reduces the risk of equipment breakdowns and malfunctions. J. Lee *et al.* (2023), in turn, concluded that integrated sensors are central in improving the reliability of vibration cleaning machines by providing continuous monitoring and accurate measurement of critical parameters. They identify and resolve problems that could affect cleaning efficiency or cause malfunctions in time. The system can automatically adjust parameters in real-time, which contributes to the durability of the equipment and its stability.

This data confirms the importance of monitoring and correcting key parameters for the stable operation of vibration-cleaning machines. The integrated sensors demonstrate the effectiveness of automated control in real-time, following the requirements. However, despite the benefits, the study results point to challenges in adapting technologies to specific working conditions. Therefore, it is necessary not only to introduce modern technologies but also to constantly adapt them to maintain high performance and reliability of the equipment.

Another important result of the study was the identification of the positive impact of mechatronic systems on reducing the wear of mechanical components of equipment. Load regulation and overload prevention have significantly extended the service life of the machines and reduced maintenance costs. This not only reduces the overall costs of agricultural enterprises but also increases the environmental sustainability of production through longer use of equipment. S. Kharchenko *et al.* (2022) also conducted a study that confirmed that reducing the wear of vibration cleaning machines is achieved using advanced technologies that ensure uniformity of vibrations and reduce the mechanical load on components. This extends the service life of the equipment and reduces the frequency of repairs and maintenance. Technical improvements contribute to greater machine reliability and lower maintenance costs.

P. Onu *et al.* (2024) also determined that mechatronic systems offer significant economic benefits, including reduced energy and maintenance costs due to increased operational efficiency. The environmental benefits include reduced waste and a lower environmental impact due to more precise process control and reduced emissions. This makes mechatronic systems a favourable choice in terms of sustainability and resource savings.

Based on the results obtained, it is possible to argue that the introduction of modern technologies, in particular mechatronic systems, significantly improves the technical, economic and environmental characteristics of vibration-cleaning machines. Reduced wear and tear and extended equipment life reduce repair and maintenance costs. In addition, economic benefits, such as reduced energy consumption, as well as environmental benefits, such as reduced emissions, underline the overall benefit of implementing these systems. Thus, the results of the study confirm the effectiveness of mechatronic systems integration for sustainable development and productivity improvement.

Energy efficiency was also central in the survey results. Mechatronic systems optimised the energy consumption of vibration cleaning machines by adapting to changing conditions. This significantly reduced electricity consumption, which is especially important for businesses seeking to reduce costs and improve environmental performance. This aspect demonstrated that mechatronic systems not only increase the efficiency of equipment but also improve the overall energy efficiency. S. Afolalu *et al.* (2021) concluded that energy efficiency is one of the key advantages of mechatronic systems, as they reduce energy consumption through optimised process control. By precisely controlling parameters and reducing energy losses, these systems help reduce energy costs and increase the overall efficiency of the equipment. This not only reduces operating costs but also has a positive impact on the environmental sustainability of production facilities. S. Ogonowski & P. Krauze (2022) determined mechatronic systems

optimise the energy consumption of vibration-cleaning machines by precisely controlling vibrations and automating processes. The integration of sensors and controllers reduced energy losses by adapting the operation of machines to real conditions and needs. This ensures more efficient use of energy, which leads to lower overall costs and an improved environmental balance.

Analysis of the study results shows that mechatronic systems significantly improve the energy efficiency of vibration-cleaning machines. Their ability to optimise energy consumption and provide precise process control confirms significant economic and environmental benefits. The implementation of such systems not only reduces energy costs but also contributes to sustainable development and reduces environmental impact. However, to fully utilise these benefits, it is necessary to address the challenges associated with adopting new technologies.

Overall, the study results confirmed the effectiveness of mechatronic systems for the agricultural sector. They provide accuracy, stability, reduced maintenance costs and energy efficiency. This allows agricultural enterprises not only to increase productivity but also to make production processes more sustainable and cost-effective in the long term.

Conclusions

The introduction of mechatronic systems in vibration cleaning machines has significantly improved their accuracy and stability in the agricultural sector. The integration of mechatronic systems has made it possible to achieve a significant increase in the accuracy of vibration parameters, which has had a positive impact on the seed-cleaning process. Thanks to precise control of the frequency and amplitude of vibrations, automatic adjustment systems ensure uniform cleaning of different types of raw materials, which reduces product losses and improves overall quality.

Automated real-time load control ensures consistent cleaning efficiency, accounting for variable parameters such as seed or grain vol-

ume. This reduces the impact of external factors such as fluctuations in the flow of raw materials, which can negatively affect the stability of traditional machines. Monitoring and correction of operating parameters by means of integrated sensors ensures consistent machine performance even under changing operating conditions. This quickly identifies and corrects deviations, reducing the risk of malfunctions and increasing the overall reliability of the equipment. Reducing wear and tear on mechanical components by automatically adjusting parameters and preventing overloading not only extends machine life but also reduces maintenance costs, which has a positive economic impact. Energy efficiency achieved through optimising electricity consumption also reduces overall production costs. A study conducted based on the agricultural enterprise BIG Harvest Group demonstrated that the introduction of automated control of vibration processes has a significant positive impact on energy costs and seed cleaning quality. This decision not only improved the efficiency of production processes but also became an important step towards the sustainable development of the agricultural sector. Thus, automation of technological processes is the key to successful production modernisation and meeting modern market requirements.

In general, the introduction of mechatronic systems in vibration cleaning machines in the agricultural sector demonstrates significant benefits, including increased accuracy, stability and cost-effectiveness. This confirms the importance of continuing research and innovation in this area to further improve seed-cleaning technologies.

The limitation of the study is the coverage of only one type of vibration cleaning machine, which may limit the generalisability of the results for other models or designs of equipment. It is necessary to further study the impact of mechatronic systems on the long-term reliability and efficiency of vibration-cleaning machines under various operating conditions, including different types of raw materials and climatic conditions.

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Conflict of Interest

None.

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Вплив мехатронних систем на точність і стабільність роботи віброочисних машин у аграрному секторі

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Анотація. Дослідження було проведено для визначення того, як використання мехатронних систем може оптимізувати роботу віброочисних машин і покращити їх продуктивність у сільськогосподарських процесах. У цьому дослідженні застосовувалися методи вимірювання точності вібрацій, автоматизованого регулювання навантаження, моніторингу робочих параметрів, оцінки зносу, аналізу енергоефективності та оцінки впливу на мінімізацію людського втручання. Дослідження, проведене на підприємстві «BIG Harvest Group», продемонструвало, що впровадження мехатронних систем у віброочисні машини значно підвищує точність і стабільність їхньої роботи. Інтеграція автоматизованого регулювання частоти та амплітуди коливань дозволила зменшити енергоспоживання та підвищити ефективність очищення насіння порівняно з традиційними методами. Виявлено, що система автоматичного моніторингу і корекції параметрів забезпечує стабільну продуктивність машини навіть при змінних умовах навантаження. Зменшення зносу механічних компонентів вказує на подовження терміну служби обладнання, а також зниження частоти простоїв і потреби в ручному втручанні. Загалом, результати підтвердили, що мехатронні системи значно підвищують ефективність віброочисних машин, що позитивно впливає на якість очищення та економічну ефективність у сільському господарстві. Дослідження також виявило, що автоматичне коригування робочих параметрів за допомогою мехатронних систем дозволяє зменшити коливання в роботі машини, що забезпечує більш рівномірне очищення. Система інтегрованого моніторингу дозволила оперативно виявляти і усувати несправності, зменшуючи час на технічне обслуговування. В результаті, були досягнуті покращення в загальному управлінні процесами очищення насіння, що сприяє підвищенню продуктивності і зниженню витрат на експлуатацію обладнання

Ключові слова: автоматизоване регулювання; енергоспоживання; очищення насіння; знос механічних компонентів; економічна ефективність