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IMPLEMENTATION OF TRAUMA-PROTECTING TECHNOLOGICAL LINES FOR TRANSPORTATION OF GRAIN CROPS

Abstract

This article initiates the study of injury-preventive technologies for transporting grain crops. The author investigates the problem of mechanical damage to grain during post-harvest processing, which leads to loss of seed quality. The main factors affecting grain damage are identified, in particular, physical and mechanical properties, parameters of external influences and biological features of grain crops. The study is based on the analysis of recent research in the field of mechanical damage to grain and methods for its minimization. Methods of theoretical mechanics, continuum mechanics, and the Federman–Buckingham theorem are used. Structural features of transport systems that affect the level of grain injury are analyzed, and improved approaches to their design are proposed. A comprehensive analysis highlights injury-prone areas of technological lines, including points of grain entry into a bucket elevator, chain or belt conveyor, and grain bunker. Dimensional theory is used to assess grain damage, which allows determining the most significant impact criteria and optimizing equipment operating modes. Measures to increase the efficiency of the transport system and reduce grain losses by synchronizing grain movement with the working bodies of the equipment are considered. The results of the research can be used to develop new technologies for grain transportation and improve existing systems, taking into account modern trends in automation and energy efficiency. The final conclusions of the study will contribute to improving the quality of seed material and increasing the efficiency of the agro-industrial complex. Prospects for further research aimed at developing mathematical models of grain movement in technological systems are outlined. The implementation of the proposed solutions will contribute to increasing the competitiveness of the agricultural sector. This emphasizes the importance of an integrated approach to the design of transport systems, combining technical, economic and technological aspects.

Keywords: trauma-saving technology, grain injury, grain damage, seed quality improvement, the dimensional theory

Introduction

The importance of the agro-industrial complex in Ukraine's economy makes increasing grain production volumes a highly relevant and even vital issue for the country. One of the key factors influencing the increase in grain production and yield is the reduction of losses at all stages of its production. Grain losses can be divided into two types: direct and indirect. Direct losses are associated with the physical loss of grain, while indirect losses involve the deterioration of its qualitative characteristics. Damage and injury to grain during post-harvest processing due to multiple mechanical impacts are one of the main reasons for the deterioration of grain quality and subsequent reduction in germination and growth strength of seed material. Mechanical damage causes physical and physiological changes, making injured grain more difficult to store. Moisture and air penetrate cracks, fractures, and microcracks, negatively affecting the grain's shelf life. During storage, such grain experiences increased segregation, impacting product safety. Segregation occurs during gravitational loading of storage containers in a compact stream. Grain actively respires, increasing its temperature and promoting the spread of fungal diseases and microorganisms. In some years, grain damage due to certain weather, climatic, mechanical-technological, biological, soil, and varietal characteristics can reach 55-65% of the total production volume [1, 2, 3].

In our era of innovation, the technical level of machinery, aggregates, and complexes for post-harvest grain processing is rapidly evolving. New mechanisms and technologies for manufacturing equipment and its components are emerging, used both for the production of new and the modernization of existing traditional technological equipment. New materials are being developed, and high-quality materials for manufacturing working elements of equipment are becoming more accessible. Reducing grain injury during post-harvest processing is a crucial task of our time.

However, as general practice shows, little attention is paid to reducing mechanical damage to grain under industrial conditions. Although reducing the force interaction between the grain kernel and the working element of equipment is one of the indicators of a high technological level of the manufacturer, most attention is still directed towards increasing mechanization, boosting equipment productivity, enhancing equipment reliability, and reducing operational costs. The efficiency of existing measures affecting grain damage remains very low. During processing, grain is subjected to complex loads comprising various combinations of impact, compression, and shear forces. According to scientific studies, loading, unloading, and cleaning machines can damage up to 52% of the grain [2].

For this reason, the application of trauma-protecting technologies and new or existing (but with the use of new methods) equipment elements can increase the percentage of intact seeds during post-harvest grain processing and extend the working life of equipment components.

Literary review

Research is being conducted on the dependence of grain injury at different stages of post-harvest processing. Studies [5, 6, 7, 8, 9, 10] analyze various stages of grain processing, identifying causes and factors influencing seed injury and quality during harvesting, processing at elevators, and sowing. Improvements in technological processes at elevator complexes occur through refining and optimizing grain quality enhancement processes using cleaning, drying, and storage methods, often through full or partial automation and the introduction of additional equipment elements. These include sensors that monitor product parameters during processing and relevant technological processes (such as rotational speed of working components, moisture levels, and energy efficiency), providing information to operators and reducing human error. To perform typical tasks of controlling the executive bodies, frequency-controlled drives of the working bodies, sensors, programmable logic controllers and specialized software for performing typical tasks of controlling the executive bodies are installed [11, 12].

The studies [7, 13, 14, 15, 16, 17] examine the geometry of the bucket and the material from which it is made, as well as their relationship with the stresses arising during operation. The drive configuration has been studied. A modal analysis of the elevator's operation has been conducted, existing dynamic characteristics have been determined, and stress-strain states of the belt elevator have been calculated. The dynamic properties of the equipment structure under oscillatory excitation have been studied. The unloading of bulk materials at various belt speeds has been analyzed using discrete data analysis methods, and the design methods and mechanics work of the elevator and buckets have been reviewed, including the relationship between bucket geometry, stresses, and deflections arising in the processes. Examples of optimal bucket shapes have been provided depending on the type and condition of the transported material and the speed of the elevator belt.

Many scientific studies confirm the dependence of grain's physical and mechanical properties on biological and quality characteristics. A significant number of these properties depend on the moisture content of the initial product [18, 19].

In the study [3], the dependence of the grain damage coefficient on the angle of impact of the wheat grain on the surface, the impact velocity (similar to the friction coefficient) and the surface material was established. The optimal moisture content of wheat was experimentally determined at the levels of 12.7-15.3%. In this case, the number of damaged grains increased both with a decrease in the percentage of moisture and with its increase from the optimal. First, this is due to disturbances in the internal system of the starch-protein network due to an increase or decrease in moisture content. The water absorption capacity of protein is stronger than that of starch. Therefore, when deviations from optimal indicators, the starch-protein network system becomes irregular, which weakens the mechanical properties of the grain [19].

Objective and Tasks.

The purpose of this study is to conduct a comprehensive analysis of a typical grain transportation technological line (excluding the drying process), identify its injury-prone areas and elements that directly interact with the grain. Formation of factors influencing grain damage in these zones. Determination of the most influential criteria affecting grain damage.

Materials and methods

The research methods used in this study include analytical studies based on continuum mechanics, physical laws, and theoretical mechanics. The material for the study is a grain mass moving along a technological transport line during one of its main actions - movement (transportation). During this process, various changes in speed and motion vector occur, introducing new dynamic loads that increase the likelihood of product quality deterioration.

Results of the study and their discussion

The degree of grain injury during post-harvest processes depends on many factors, starting from the application of mineral fertilizers during plant growth, varietal characteristics, and ending with the quality of the grain mass (moisture content, impurities) and the mechanical-physical properties of the grain kernel. However, the greatest mechanical impact of a shock-cyclic nature is exerted by the structures, mechanisms, and working elements used for grain transportation and processing (cleaning, treatment). This includes grain kernel collisions, friction between kernels, and contact with working elements. The effect of such impact interactions may be intensified by the presence of heavy abrasive particles in the grain flow, which are harder than the grain itself. These may include weed seeds or small stones picked up by the combine harvester. A significant number of technological processes occur under conditions of high-speed gravitational material movement. The conditions of rapid grain flow include the presence of linear and angular velocities in the seeds and their chaotic movement in the grain layer. As a result of such fast gravitational flows, individual grains interact with each other, leading to technological effects such as mixing or separation [20].

Based on the research results, parameters that contribute to the negative effect of grain breakage were identified. These parameters were divided into several types and illustrated in Figure 1. In research, these parameters can be used to compare similar grain transportation processes, as well as individual nodes and elements of the system.

Young's modulus (elasticity modulus, longitudinal elasticity modulus) E characterizes the ability of the grain to undergo elastic deformation under tensile or compressive forces. Essentially, it is an indicator of stress in the grain kernel caused by externally applied forces in relation to the contact area of this force. This parameter reflects the influence of molecular bonding forces in the kernel during interaction with external forces. If E is greater than F, the system returns to its original state before the force was applied. In this case, molecular bonds are restored, and the architecture of the grain kernel is maintained. If E is less than F, molecular bonds break, leading to irreversible destruction of the kernel.

The maturity of the grain affects its density ρ, shell stiffness k, Young's modulus E, Poisson's ratio μ_p,

Parameters determining grain damage

Physical and mechanical properties of grain

Parameters	Designation	Dimension
Young's modulus	E, N/m²	$L^{-1}MT^{-2}$
Bran density	ρ, kg/m3	ML^{-3}
Relative elongation	δ, m	L
Coefficient of friction	f	Dimensionless quantities
Poisson's ratio	μp	Dimensionless quantities
Hardness of the grain	μ, kgf/mm²	MFL^{-2}
Shell stiffness	k, kg*m/s²	MLT^{-2}
Surface roughness	Rz, m	L

External influence parameters

Parameters	Designation	Dimension
Temperature	t	Tc
Gravity	Fg, кг*m/s²	MLT^{-2}
Contact surface area	S,m²	L²
Dynamic impact force	F, кг*m/s²	MLT^{-2}
Impulse	P, кг*m/s	MLT^{-1}
Impact duration	T, sec	T
Hardness of the contact surface	μ_{sf} ,kgf/mm²	MFL^{-2}

Biological, anatomical, morphological properties of grain

Parameters	Designation	Dimension
Size	R, м	L
Shape	C	Dimensionless quantities
Weight	M, кг	M
Grain moisture	W, %	W
Grain maturity	Z	Dimensionless quantities
Quality (amount of protein)	Q, %	Dimensionless quantities
Quality (amount of starch)	Q, %	Dimensionless quantities

Fig. 1. Structural model of parameters determining grain damage

and relative elongation δ. The physical and mechanical properties characterize the ability of the grain kernel to resist deformation and destruction, as well as its ability to elastically and plastically deform under external mechanical loads. Depending on the nature and magnitude of the force applied to the grain kernel, its dimensions and shape may change. External force parameters cause deformations, which can be elastic (reversible) or plastic (irreversible). Overcoming elastic and plastic deformation in the kernel under external forces leads to its destruction. Destruction occurs when the applied force exceeds a certain threshold, known as the strength limit.

The density of the grain depends on its chemical composition and the ratio of organic components. Note that the grain should be considered as a composite material consisting of layers with different strength characteristics. The shell and endosperm contribute to different mechanical properties [19, 21, 22]. An increase in the thickness of the shell leads to an increase in grain deformation, which increases the likelihood of crack formation and propagation. This, in turn, reduces the hardness of the kernel μ. The endosperm is a mixture of protein and starch cells. A higher endosperm content increases the strength and hardness of the grain due to the compact structure of the starch granules, which form the glassy endosperm. The mass fraction of protein in the endosperm also affects the hardness of the kernel. The more protein cells, the greater the hardness of the kernel. There is a relationship between the internal structure of the grain and its mechanical properties [16].

Grain temperature also influences storage properties, including physical and mechanical characteristics of seed. As is known, decreasing temperature increases the brittleness of the grain kernel.

Size, shape, weight, and geometry also significantly impact the degree of kernel damage. Information about the technical and technological properties of the grain kernel is an essential requirement when designing and constructing working elements, configuring technological lines in production processes during post-harvest grain processing, and preparing seed material. The dimensions of the grain kernel are determined by linear parameters—length, width, and thickness—which vary significantly due to many objective and subjective factors during growth.

After conducting a comprehensive analysis of the operation of a typical grain transportation technological line (excluding the drying process), discrepancies between the movement of grain and the working parts of the equipment were identified. Injury-prone areas and elements of the working parts of the equipment that directly interact with the grain were identified.

1. This is a node: gravity pipe (gravity flow node) - bucket elevator. This refers to the point where grain enters the boot of the bucket elevator. In this case, grain damage occurs due to the impulse received from the difference in the vectors of the kinetic energy of the grain entering the elevator and the elevator buckets, which collide with the grain as they pass through the drum. The parametric model of this system's operation is shown in Fig. 2.

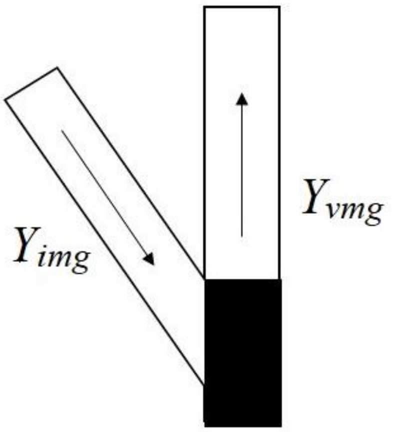

Fig. 2. Parametric model of the work system gravity pipe (gravity flow node) - bucket elevator

Y_{img} - conditions of inclined movement of grain material in gravity flow. This includes physical and geometric parameters of the gravity pipe: length, cross-section, inclination angle, type of material, and lining (external influence parameters), and the physical-mechanical, biological, anatomical, and morphological properties of the grain.

Y_{vmg} - conditions for vertical movement of grain material. These are the geometric parameters of the buckets and elevator shoe, the belt speed, and the physical and mechanical, biological, anatomical, and morphological properties of grain materials.

2. Gravity pipe (gravity flow node)- Chain Conveyor. This refers to the point where grain enters the conveyor from gravity flow. From a technical and technological standpoint, as well as in terms of reliability, the chain conveyor is the most optimal and widely used in the elevator industry. In this case, grain damage occurs due to the impulse received from the difference in the vectors of the kinetic energy of the grain entering the conveyor and the working elements of the conveyor, which collide with the grain. The parametric model of this system's operation is shown in Fig. 3.

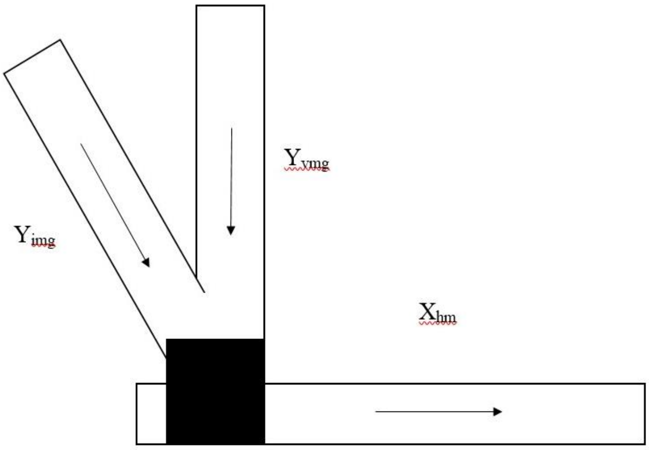

Fig. 3. Parametric model of the work system Gravity pipe (gravity flow node)- Chain Conveyor

Y_{vmg} - conditions of vertical movement of grain material in gravity flow. $Y_{vmg} = Y_{img}$ *cos α

X_{hm}- conditions of horizontal movement of grain material. This includes the geometric parameters of the working elements, their movement speed, the material they are made of the presence of direct contact between the working element and the conveyor casing (external influence parameters), physical-mechanical, biological, anatomical, and morphological properties of grain materials.

These parametric models can also be applied to other typical nodes such as: gravity flow node – silo, gravity flow node –belt conveyor.

The operation of such systems is always characterized by the following functional parameters:

$\bar{X}_{hm}$ – conditions of horizontal movement of grain material and $\bar{Y}_{vmg}$ – conditions of vertical movement of grain material. Both $\bar{X}_{hm}$ and $\bar{Y}_{vmg}$ can be both vertical and inclined.

Grain damage is a complex phenomenon involving many processes. Since this process is correlated with the size of cracks and fractures, we use the size parameter **L** to characterize it. The following relationship can be established for the parameters determining grain damage:

$$\mathbf{L = f(Fm) + f(Ei) + f(Bam)} \qquad (1)$$

Table 1 - Dimensionality of the transport system operation parameters

Parameters	E	ρ	f	k	R_z	S	F	μ_{sf}	R	V	W
M	1	1	0	1	0	0	1	1	1	1	0
L	-1	-3	0	1	1	2	1	-2	0	0	0
T	0	0	0	-2	0	0	-2	0	0	0	0

We will apply dimensional theory (Buckingham's π-theorem) to characterize the grain damage process. The application of the methods of this theory [23] is based on the idea that the solution of a system of differential equations can be expressed as a function of the similarity criteria of the given system. Analyzing theoretical studies and comparing them with experimental ones, we can conclude that the determination of process parameters is a key factor in the application of this theory. The general relationship between the variables Fm, Ei and Bam, which characterize the process with the basic units of measurement r_i can be represented as a dependence between dimensionless complexes (similarity criteria) consisting of these variables. These criteria will correspond to certain dependencies. To determine the necessary number of influencing factors, the preferred method is to reduce the number of criteria by eliminating those that are less significant. Therefore, some parameters that do not significantly affect the dependent criterion and are negligible in terms of their functional characteristics were not considered. Additionally, factors such as grain kernel cohesion, the coefficient of friction between the grain and the equipment walls, and the angles of internal friction between grain kernels were disregarded. The dependence of each criterion can be expressed by the following relationships:

$$\mathbf{Fm = f\,(E, \rho, f, k, Rz),} \quad \mathbf{(2)}$$

$$\mathbf{Ei = f\,(S, F, \mu_{sf}),} \quad \mathbf{(3)}$$

$$\mathbf{Bam = f\,(R, M, W).} \quad \mathbf{(4)}$$

In the form of a criterial equation, the following can be written:

$$\mathbf{f\,(E, \rho, f, k, Rz, S, F, \mu_{sf}, R, M, W) = L} \quad \mathbf{(5)}$$

It is important to note that for this model to accurately reflect the key dependencies and characteristics of the process under study, each parameter must represent differentiation, diversity, and flexibility in terms of its impact on L.

Dimensional theory simplifies and facilitates a convenient and appropriate method of information processing, preserving the connection between entire complexes of quantities. To simplify the problem, we will use the method of dimensional analysis based on the π-theorem. The essence of this method is that the entire set of factors can be grouped into dimensionless similarity criteria π_1, π_2, etc. The essence of π-criteria is that they are dimensionless variables that help simplify and facilitate the analysis of complex processes and connect them with the main parameters. With their help, you can study the influence of various factors on the process, generalize the results, and draw conclusions. To determine these values, it is necessary to select the fundamental measurement units and express the dimensions of all other quantities in terms of them.

[N/m²] [kg/m3] [kg*m/s²] [m][m²] [kg*m/s²][kgf/mm²][kg] = [m]

In our case, with n=11quantities, we obtain n−r=8n - r = 8n−r=8 similarity criteria.

After determining all dimensions (Fig. 1), we adopt three fundamental dimensions: Mass M (kg); Length L (m); Time T (s). The dimensions of all criteria are compiled in Table 1.

From Table 1, we select the fundamental measurement units for the grain transportation process. To determine the significance of the criteria, we construct third-order matrices with all parameter dimensions of the transport system's. operation and will find their determinants.

$$\Delta = \begin{array}{c} \\ M \\ L \\ T \end{array} \begin{array}{ccc} \rho & F & \mu sf \\ \end{array} \begin{vmatrix} 1 & 1 & 1 \\ -3 & 1 & -2 \\ 0 & -2 & 0 \end{vmatrix} \quad 9$$

A determinant that is not equal to zero indicates that the parameters were chosen correctly. The value of 9 is the largest determinant among all those determined and suggests that the criteria ρ, F, and μ_{sf} have the maximum impact on the system. These criteria have physical significance, meet the requirements of independence from each other, and are variable in the process of conducting further experiments.

Conclusions

After analyzing the entire transport-technological system for grain movement, critical injury-prone areas in equipment components were identified, along with parameters affecting grain damage. Based on the theory of dimensional analysis and similarity, three main independent criteria influencing grain damage were determined: grain hull density, dynamic force acting on the grain, and the hardness of the contact surface between the kernel and the equipment.

Future Research Prospects. Future research will focus on studying and analyzing processes occurring in free-fall gravitational bulk material flows in critical grain transport system areas. Mathematical modeling of changes in grain movement direction in these zones will continue. The ultimate goal of the research is to develop a methodology for evaluating dynamic loads and determining optimal equipment operating modes to synchronize grain movement with equipment components, reducing the likelihood of destructive collisions and minimizing seed injury and damage.

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ВПРОВАДЖЕННЯ ТРАВМООЩАДНИХ ТЕХНОЛОГІЧНИХ ЛІНІЙ ДЛЯ ТРАНСПОРТУВАННЯ ЗЕРНОВИХ КУЛЬТУР

Анотація

У статті розпочато дослідження травмоощадних технологій для транспортування зернових культур. Автор розглядає проблему механічного пошкодження зерна під час післязбиральної доробки, що призводить до втрат якості насіннєвого матеріалу. Визначено основні фактори, що впливають на пошкодження зерна, зокрема фізико-механічні властивості, параметри зовнішнього впливу та біологічні особливості зернових культур. Робота базується на аналізі останніх досліджень у сфері механічного пошкодження зерна та методів його мінімізації. Використано методи теоретичної механіки, механіки суцільних середовищ та теореми Федермана–Букінгема. Проведено аналіз конструкційних особливостей транспортних систем, що впливають на рівень травмування зерна, а також запропоновано удосконалені підходи до їхнього проектування. На основі комплексного аналізу виділено травмонебезпечні зони технологічних ліній, зокрема вузли входження зерна в норію, ланцюговий чи стрічковий транспортер та зерновий бункер. Для оцінки пошкодження зерна застосовано теорію розмірностей, що дозволило визначити найбільш значущі критерії впливу та оптимізації режимів роботи обладнання. Розглянуто заходи щодо підвищення ефективності транспортних систем та зменшення втрат зерна за рахунок синхронізації руху зерна з робочими органами обладнання. Результати дослідження можуть бути використані для розробки нових технологій транспортування зерна та вдосконалення існуючих систем з урахуванням сучасних тенденцій автоматизації та енергоефективності. Отримані висновки кінцевого дослідження сприятимуть покращенню якості насіннєвого матеріалу та підвищенню ефективності агропромислового комплексу. Окреслено перспективи подальших досліджень, спрямованих на розробку математичних моделей руху зерна у технологічних системах. Впровадження запропонованих рішень сприятиме підвищенню конкурентоспроможності аграрного сектору. Це підкреслює важливість комплексного підходу до проектування транспортних систем, що поєднує технічні, економічні та технологічні аспекти.

Ключові слова: травмоощадна технологія, травмування зерна, пошкодження зерна, покращення якості насіння, теорія розмірності.

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