ASSESSMENT OF OPERATIONAL RELIABILITY OF MIXER-FEEDER MACHINES UNDER CONDITIONS OF LIVESTOCK ENTERPRISES

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Abstract. Current development trends in modern livestock production within the structure of agricultural output involve the use of equipment for feed preparation and distribution. However, due to factors characteristic of the operating conditions of agricultural enterprises in Ukraine, mixer-feeder machines exhibit the occurrence of fault and failure flows, which reduce their operational reliability indicators. This article presents the results of an assessment of the operational reliability of mixer-feeder machines used at livestock enterprises. The purpose of the study is to provide a quantitative assessment of individual indicators of reliability and maintainability, as well as to determine the availability coefficient of the machines while taking into account real operating conditions. The study was conducted in accordance with a reliability test plan of the [NMT] type for PROFILE 12.2 DS and PROFILE 14.2 DS mixer-feeder machines manufactured by KUHN, under the operating conditions of livestock enterprises. Data collection and statistical processing of information on mean time to failure and restoration time during operation were carried out. It was established that during the initial and warranty periods of operation, the inoperative condition of the machines is mainly caused by failures of the second group of complexity, among which failures of the chopping-mixing mechanism are the limiting factors for the reliability of mixer-feeder machines. Based on the results of the statistical analysis, individual reliability indicators were determined: the mean time to failure is 3152.0 operating hours; the standard deviation is 902.6 operating hours; and the coefficient of variation is 0.40. It has been demonstrated that the time to failure follows a normal distribution law, as confirmed by the Kolmogorov goodness-of-fit test. Confidence intervals for the mean time to failure were established as 1964.2-4339.8 operating hours. Maintainability indicators were also evaluated: the mean restoration time is 24.0 h; the standard deviation is 12.93 h; the coefficient of variation is 0.49; the theoretical distribution law is the normal distribution; and the confidence limits for the mean restoration time are 6.98-41.02 h. A comprehensive reliability indicator – the availability coefficient of the mixer-feeder machines – was determined as K_c = 0.992, indicating a high level of operational availability of the equipment. The obtained results can be used to improve the operational reliability of mixer-feeder machines, enhance maintenance and repair systems, and justify optimal inventories of spare parts at livestock farms.

Keywords: mixer-feeder, failure-free operation, maintainability, operational reliability.

Introduction

One of the fundamental branches of the agricultural sector is livestock production, the efficiency of which is largely determined by the level of mechanization of feed preparation and distribution processes. The quality of feeding directly affects animal productivity, production cost, and stability of livestock enterprises. Modern feeding concepts involve the formulation of total mixed rations balanced in terms of nutritional and physicomechanical parameters, taking into account the physiological needs of animals of different age and production groups [1]. The implementation of these technologies is possible only with the use of highly efficient equipment for feed grinding, mixing, and controlled distribution.

Over recent decades, countries with developed livestock sectors have actively conducted research aimed at improving technological processes of feed mixture preparation and increasing the efficiency of mixer-feed distributors [2; 3]. At the same time, the operation of mixer-feed distributors occurs under conditions of variable loads, aggressive dust environments, fluctuations in operating modes, and the influence of the human factor. This leads to significant variability in the parameters of techno-economic efficiency and reliability indicators of the machines [4].

On modern farms, mixer-feed distributors from leading manufacturers are widely used, including Seko, KUHN, Siloking, Strautmann, Roto-Mix, Trioliet, and DeLaval. In Ukraine, a significant share of the market is occupied by the PROFILE 12.2 DS and PROFILE 14.2 DS machines produced by KUHN, which are used for feeding cattle on livestock farms of various forms of ownership.

Particular importance under modern conditions is attached to the integration of approaches to reliability indicators such as failure-free operation and maintainability as components of operational reliability. The failure of an individual mechanism of a mixer-feed distributor leads to disruption of the

entire set of feeding operations, increased downtime, feed losses, and reduced productivity of livestock enterprises.

Within the framework of precision livestock farming, which is based on the principles of Industry 4.0 and IoT technologies [5], reliability and maintainability of farm machinery are considered key factors in the efficiency of production processes. An analysis of contemporary studies devoted to the improvement of design and investigation of operating processes of screw conveying mechanisms [6-8] indicates that geometric parameters [6] and design features of working elements [7; 8] significantly influence the force and energy characteristics of the conveying process, the dynamics of material movement, and the magnitude of operational loads acting on machine components. In combination with the influence of the human factor, operating conditions, and the technical level, these factors determine the patterns of functioning of mixer-feed distributors and the specific aspects of assessing and ensuring their reliability.

Thus, a relevant scientific and practical task is the comprehensive assessment of the operational reliability of mixer-feed distributors under real conditions of livestock enterprises, taking into account the indicators of failure-free operation and maintainability.

The objective of this study is to determine an integrated reliability indicator of mixer-feed distributors and to develop recommendations for improving their operational efficiency.

Materials and methods

The research methodology was based on the concept of predictive maintenance for mixer-feed distributors operating under conditions of variable technological and organizational parameters. The scientific premise was the assumption of the stochastic nature of performance degradation of mixer-feed distributors under the influence of mechanical interaction with feed components, cyclic loads, and instability of operating regimes. The mixer-feed distributor was considered as a complex technical system with functionally interconnected subsystems. The objects of the study were the mixer-feed distributors PROFILE 12.2 DS and PROFILE 14.2 DS manufactured by KUHN (France), which perform the operations of grinding, mixing, conveying, dosing, and unloading of feed mixtures (Fig. 1). A functional and structural decomposition of the machines into subsystems was carried out: the grinding-mixing mechanism, the unloading mechanism, the running gear system, the frame, and the hopper.

The empirical basis was formed from the results of observations of 25 mixer-feed distributors of the specified models, which were operated during 2016-2023 on livestock farms in seven regions of Ukraine. The territorial diversification of the sample ensured the representation of the influence of climatic, production, and organizational factors on the intensity of failure and repair flows of the machines. The research regime was defined as operational, which ensures the representativeness of the results for industrial livestock production conditions.

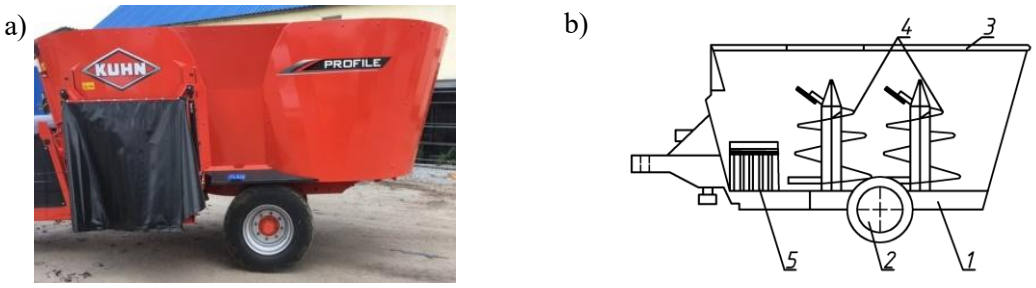

Fig. 1. **Mixer-feed distributor PROFILE 14.2 DS – photograph under operating conditions (a) and schematic diagram with subsystems (b):** 1 – frame; 2 – running gear system; 3 – hopper; 4 – grinding–mixing mechanism; 5 – feed mixture unloading mechanism

The tests were conducted according to an operational test plan of type [NMT] for repairable systems [9]. The plan included a fixed number of objects (N), their restoration after failures (M), and termination of observations upon reaching a specified operating time or duration of use (T). Such an approach made it possible to form a representative set of failures under real production conditions without removing the

equipment from the technological process. The plan parameters were aligned with the requirements for statistical reliability.

Data collection was carried out by timing machine operation, analyzing service documentation and maintenance logs, and monitoring the operation of feed mixers. The methodological novelty lay in the integration of reliability and maintainability indicators into a single observational information model, which formed the basis for predicting reliability based on the actual technical condition [9; 10]. Statistical data processing involved the formation of empirical data sets, analysis of variations in reliability indicators, and identification of patterns in the change of failure rates over time. The results obtained served as the basis for developing adaptive strategies for restoring the operational capability of feed mixers within the framework of the predictive maintenance concept and for establishing a repair schedule.

Results and discussion

This section summarizes the results of two applied studies [11; 12], which enabled a comprehensive interpretation of the operational reliability of equipment for feed preparation and distribution. The integrated assessment of operational reliability is carried out through the availability coefficient, which combines indicators of failure-free operation and maintainability. The quantitative value of the availability coefficient for 25 mixer-feed distributors is as follows: mean value – 0.992; standard deviation – 0.01 h; coefficient of variation – 0.47.

The results of the empirical distribution of the availability coefficient of the mixer-feed distributors PROFILE 12.2 DS and PROFILE 14.2 DS are graphically presented in Fig. 2. The intervals in Fig. 2 were formed by grouping empirical data into equal intervals of the availability coefficient (the interval width was selected considering the sample size and variability of the indicator). Their boundaries are presented as ranges, and excessive numerical precision has been eliminated by rounding to an engineeringly significant level. The value of the availability coefficient of mixer-feed distributors is significantly sensitive both to a decrease in mean time between failures and to an increase in the time required to restore operability. The dominance of the grinding–mixing mechanism in the failure structure of the mixer-feed distributor affects not only the failure and repair rates, but also the integral indicator of operational reliability.

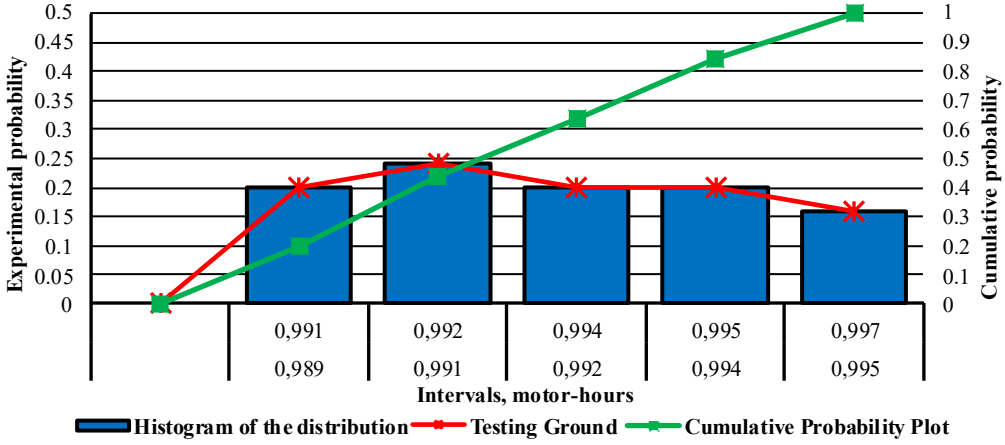

Fig. 2. **Statistical characteristics of distribution of the availability coefficient of mixer-feed distributors PROFILE 12.2 DS and PROFILE 14.2 DS (histogram, frequency polygon, and cumulative empirical probability curve)**

In study [11], the failure-free operation of mixer-feed distributors PROFILE 12.2 DS and PROFILE 14.2 DS was analyzed based on real operational data. The mean time between failures of the mixer-feed distributors follows a normal distribution with the following parameters: mean operating time – 3152.0 motor-hours, standard deviation – 902.6 motor-hours, coefficient of variation – 0.40. Confidence intervals for this parameter were established in the range from 1964.2 to 4339.8 motor-hours according to the Kolmogorov goodness-of-fit test. The numerical values were obtained based on statistical

processing of operational data from the sample ($n = 25$) using methods of mathematical statistics, including testing the goodness-of-fit of empirical distributions to the normal law using the Kolmogorov criterion, as well as determining confidence intervals for the estimated parameters. The dominant subsystem in the failure structure is the grinding–mixing mechanism, which confirms the significant influence of design and technological factors on the operational stability of mixer-feed distributors. The reliability-limiting elements of the chopping–mixing mechanism are the cutting knives and screw working bodies, their failures are caused by intensive abrasive wear, cyclic dynamic loads, and stress concentrations in critical structural zones.

The obtained results are representative for both the warranty and post-warranty periods of operation, as the empirical basis of the study covers the full life cycle of the machines under real operating conditions, allowing for the variation in failure and restoration rates over time to be taken into account.

In study [12], the maintainability of the mixer-feed distributors PROFILE 12.2 DS and PROFILE 14.2 DS, which are the objects of research presented in study [11], is analyzed. It was established that the main downtime is also associated with the grinding–mixing mechanism, but from the perspective of determining the duration of restoration. The mean time to restore operability is 24.0 h, the standard deviation is 12.93 h, the coefficient of variation is 0.49, and the confidence interval ranges from 6.98 to 41.02 h, indicating significant variability in the organizational and technological conditions of technical service.

The comparative analysis shows that the variation in restoration time (coefficient of variation 0.49) is higher than the variation in time to failure (0.40), indicating greater instability of the organizational and technological conditions of technical service compared to the processes governing failure-free operation of machines.

A study was conducted on the dependence of the availability coefficient of mixer-feed distributors on the mean time between failures (Fig. 3a). The results show that with an increase in the operating time between failures of the mixer-feed distributor, the value of the availability coefficient asymptotically approaches unity, indicating the dominant influence of failure-free operation on the overall efficiency of the machines. It was established that in the range of 2000-4000 motor-hours, the availability coefficient changes most intensively. Increasing the mean time between failures through improvements in the grinding–mixing mechanism directly enhances the operational reliability of the machines.

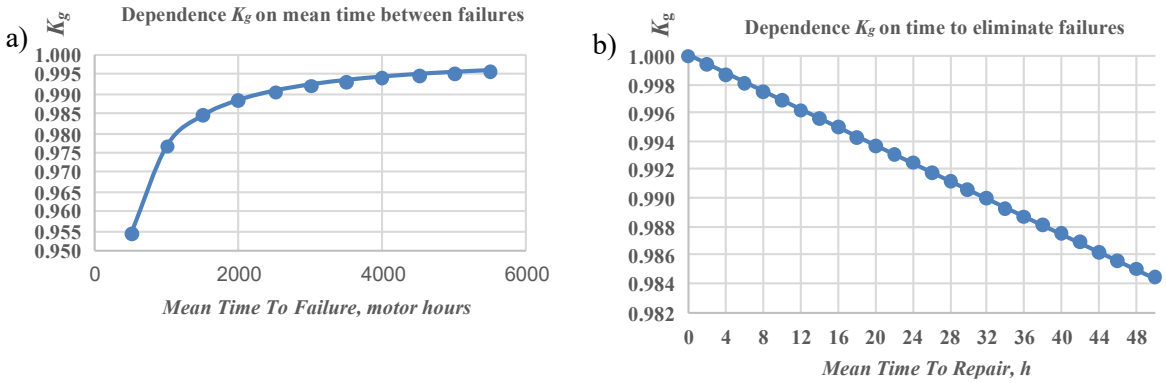

Fig. 3. **Study of variation of the availability coefficient K_g as a function of mean time between failures (a) and repair time (b)**

Fig. 3b shows the dependence of the availability coefficient on the repair time. An increase in repair duration leads to an almost linear decrease in the availability coefficient, which highlights the importance of optimizing accessibility to components and organizing technical service. Statistical analysis indicates that with an increase in the repair time of the mixer-feed distributor, the availability coefficient decreases linearly. It was established that increasing the repair time from 20 to 40 h reduces the availability coefficient by 0.3-0.4%, and that service organization has an impact on the availability coefficient comparable to that of the mean time between failures.

When discussing the results obtained in the present study, it is appropriate to compare them with the findings of other scientific works devoted to improving the operational efficiency and reliability of mixer-feed distributors. In particular, study [13] substantiates the parameters that determine the efficiency of combined feed mixers, demonstrating that the kinematic and structural characteristics of

the working elements significantly affect the energy loading of the machine and the efficiency of the grinding-mixing process. The results obtained in that study are consistent with the conclusions of the present research, according to which the grinding–mixing unit is the primary source of operational loads, leading to a reduction in the mean time between failures. The improvement of the design of the grinding-mixing mechanism [13] ensures a more uniform distribution of loads, reduction of peak dynamic forces, and increased efficiency in the use of the machine's energy resources. At the same time, the results of this study indicate that increasing the productivity of equipment without considering reliability indicators may lead to an increase in failure intensity and, consequently, to a decrease in the availability coefficient of the machines.

The obtained conclusions are consistent with the results of study [14], in which the stress–strain state of the vertical auger of a feed mixer–distributor was determined using the finite element method, and zones of stress concentration as well as critical sections of the drive structure were identified. Such a distribution of loads determines the probability of fatigue damage and, consequently, affects the frequency of repairs and the maintainability of the mechanism.

In study [15], a parametric analysis of the properties of mixer-feed distributors was carried out, within which the dependence of energy and operational performance indicators of the machines on the design parameters of the working elements, hopper volume, and operating modes was established. The authors demonstrated that the efficiency of feed mixing and distribution processes is determined by a combination of design and operational factors, among which the operator's qualification and the selection of rational operating modes of the technical system also play an important role [11].

Thus, the obtained empirical and graphical results confirm the appropriateness of using the availability coefficient as an integrated indicator that combines the properties of failure-free operation and maintainability of mixer-feed distributors.

Conclusions

1. Based on the generalization of operational data of 25 mixer-feed distributors PROFILE 12.2 DS and PROFILE 14.2 DS, it was established that the availability coefficient is characterized by a high mean value of 0.992 with a standard deviation of 0.01. It was shown that the mean time between failures follows a normal distribution with a mean value of 3152 motor-hours, a standard deviation of 902.6 motor-hours, and a coefficient of variation of 0.40. It was determined that the mean time to restore operability is 24 h, the standard deviation is 12.93 h, and the coefficient of variation is 0.49, which indicates a significant influence of organizational and technological conditions on the maintainability of the machines.
2. The analysis of graphical dependencies showed that with an increase in the mean time between failures, the availability coefficient asymptotically approached unity, whereas an increase in the repair duration led to its almost linear decrease. This confirms the necessity of simultaneously improving the failure-free performance of structural components and optimizing maintenance and repair processes.
3. A promising direction is the development of methods for predicting the availability coefficient based on statistical failure models and the use of digital tools for monitoring the technical condition of machines. It is also important to investigate the influence of technical service organization, operator qualification, and structural accessibility of components on the operational reliability indicators of mixer-feed distributors.

Author contributions

Conceptualization, A. N., I. G.; methodology, A. N.; validation, A. N., I. G., O. B. and Y. N.; formal analysis, A. N. and O. B.; data curation, O. B., Y. N.; writing–original draft preparation, O. B. and Y. N.; writing–review and editing, A. N. and I. G.; visualization, O. B.; project administration, A. N.; funding acquisition, A. N., I. G., O. B. and Y. N. All authors have read and agreed to the published version of the manuscript.

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