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ПРАВИЛО ЗАМЕНЫ АГРЕГАТА ПО ТЕХНИЧЕСКОМУ СОСТОЯНИЮ С УЧЕТОМ ИНКУБАЦИОННОГО ЭТАПА РАЗВИТИЯ ДЕФЕКТА

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В статье исследуется задача оптимизации правила обслуживания для стохастически деградирующей системы с длительным инкубационным этапом развития дефекта (например, питтинга). Порог превентивной замены определяется для агрегата сельскохозяйственной машины, диагностирование которого осуществляется перед выполнением технологической операции. Оптимизация порога превентивной замены выполняется по критерию минимума суммарных производственных издержек, которые состоят из потерь части урожая вследствие отказа и затрат на диагностирование и замену агрегата.

Ключевые слова: обслуживание по техническому состоянию, отказ, lинкубационный этап, диагностирование, порог замены, питтинг, сельское хозяйство.

Introduction. Failures of tractors and farm machinery lead to untimely performance of crop production process operations. As a result, the part of the harvest is lost [1]. The main factors limiting units' operating life of tractors and agricultural machinery transmission is oxidational wear, abrasive wear (when abrasives from the air contaminate the grease) and surface fatigue of the bearing and gears. A promising way to reduce crop losses and operating costs is a condition-based maintenance of machines [2].

Analysis of recent research and publications. In [3] an overview of the functions used to approximate the machine parts wear is given. The linear, exponential and power approximation of the wear and gap increasing from the operating time are mainly used [3]. In [4] the wear is approximated by elementary power random function. The random parameter characterizing the deterioration rate is considered as distributed by the normal or Weibull distribution. Review of the optimizing methods of the preventive replacement threshold during the periodic inspection of the worn parts are given in [4,5].

The main differences in the kinetics of deterioration processes with wear [3] and a surface fatigue [6], essential for optimizing the preventive replacement threshold, are the following:

– wear begins when commissioning, and a surface fatigue is characterized by long latent stage (hence the duration of the defect progress, that is measured from the end of the latent stage till inspection, is unknown);

– when a surface fatigue, the initial defect size is unknown (size at the exit of microcracks on the surface of the part at the end of the latent stage);

– a surface fatigue is developing much faster than the wear is, nonlinearly in time, with repeatedly increasing rate.

The condition-based maintenance effect depends essentially on the preventive replacement threshold, the optimal choice of which is the subject of this paper. Further we consider the optimization of the condition-based maintenance of units, failed due to the defects with the long latent stage, such as surface fatigue. Depending on whether one takes into account prior states of the unit when deciding to replace, the following ways of the inspection and the preventive replacement of units are possible.

First, these are repeated regular measurements of the defect feature, the accumulation of their results, the determination of the defect feature trend and residual life prediction. If the residual life of the unit is smaller than the inspection interval, it has to be replaced . Such techniques are given in [7].

At second, this unit inspection (periodic or before production tasks performance) and arriving at the decision about the preventive replacement or continued operation of the unit, depending on the result of the comparison of the defect feature and the preventive replacement threshold.

In such case the defect feature trend is not determined. The advantage of this method is simplified requirements for the organization of services and technical equipment (data collection tools, computer systems of decision support, etc.). In this paper, we consider the decision-making process of the unit preventive replacement by the result of a single defect feature measurement before the process operation of crop production.

The analysis of recent researches and publications. We'll consider the ways of the mechanical systems deterioration simulating used in the optimization of a condition-based maintenance. Depending on the type of realizations of the deterioration process they can be divided into models based on an elementary random function (smooth function upon time, in which, as a parameter, a random variable, independent of time, is included), and models using stochastic increments.

In [8] power function used to approximate deterioration process. With regard to the application of the processes with the stochastic increments in the deterioration simulation for maintenance optimization, stationary gamma process (process with independent nonnegative stationary increments) are mainly used. In [9] the systems modeling with decreasing resistance (viewed as a process with independent stationary increments) under random loading) is done. In [10] to generate a random increment of the system parameter the semi-Markov process is used, to each state of which a certain parameter increment corresponds. The deteriorating process, increment states of which have non-stationary character, is considered more seldom. In [11] an external factor affects on the increment value of the system parameter. Random changes of this factor allow modeling the deterioration rate variation due to changes in operating conditions (load, etc.). Multiple transitions to high and low deterioration rate are possible over one realization of a random process. In [12] while investigation of the system adaptability to a particular mode of operation, stochastic process with systematically decreasing deterioration rate is applied. It was noticed that some objects deterioration may occur with increasing rate. As in [11], the influence of external factors on the deterioration rate is taken into account. In [8] a process with the systematically increasing increments (power function from operating time) is applied.

Deterioration models [3,4,8–12] have a number of limitations that do not allow fully consideration of the defects features, to which the latent stage is peculiar. In particular, in these models the initial value of the defect feature and the start of deterioration are assumed known.

Vibrational diagnostics: and acoustic emission [13] analysis are increasingly used to detect a surface fatigue. However, the task of the preventive replacement threshold grounding needs further investigation.

Objectives. The purpose of this study is to develop technique of optimizing the preventive replacement threshold for the unit that has failed due to the defect with the long latent stage. We consider a single unit, which condition is characterized by the only feature defect. The technique is intended to inspect machinery units used in the crop production before the process operation performing.

To achieve this goal it is necessary to solve the following problems:

- to determine the effect of the preventive replacement threshold to change of the parameter of failure flow of the units over time;
- to determine the average total production costs of the corrective maintenance of the unit and condition-based maintenance;
- to determine the effect of the transition from the corrective maintenance to the condition-based maintenance and formulate the problem of optimizing the preventive replacement threshold

Modeling of the preventive replacement threshold impact for a change of the unit failure intensity over time. The overview of deterioration models used in the optimization of condition-based maintenance, showed that they are based on an elementary random function [4] or on the process with stochastic increments [8–12]. Let us analyze these models in relation to the purpose of the study. The advantage of models on the basis of an random function of the unit is the simplicity of the structure and the opportunity to perform analytically much of the research. Model based on the process with stochastic increments are more difficult to analyze, since they require multiple use of random number generator in the simulation of each implementation of the deterioration process.

In this case, the entire set of the random process implementations is divided into subsets, in each of which elementary random function is a kind of mathematical expectation for implementations included in this subset. Using a process with the stochastic increments allows simulating the objects resource dispersion due to the changes in load and other operating conditions during the implementation. However, such dispersion can largely be accounted for in the model based on an elementary random function by increasing the variation coefficient of the deterioration rate. It should be noted that the use of stochastic increments does not preclude the need of an elementary random function application. This function should be used to change the increment average value over time in accordance with the kinetics of the deterioration process.

The preventive replacement threshold can be determined either for all units of this type, either individually for each of the units taking into account the operating time before an inspection. Let us analyze the feasibility of using the dependence of the failure probability on the operating life before an inspection (for example, using proportional hazard model [14]). Using this dependence will reduce the failure probability and make better use of the unit operating life, but the magnitude of the resulting effect will depend on a priori knowledge of the distribution of the operating life and the variation of the operating life. However, the condition-based maintenance becomes more difficult and expensive because of the accounting of the unit operating time before an inspection and individual calculation of preventive replacement threshold.

Considerable resource variation of parts that are failed due to the surface fatigue, has negative impact on the effect of individual calculation of the preventive replacement threshold. Therefore, at this stage of the study the technique for determining of the preventive replacement threshold without accounting of the unit running time before an inspection is developed. In view of the above stated, in this study the deterioration model is implemented on the basis of an elementary random function.

Statistical analysis of the rolling bearings tests results [15] showed that the dependence of the mass wear due to the operating time can be approximated by an exponential function. Therefore, in describing the deterioration an exponential elementary random function is used.

We assume that the inspection allows determining the size of the defect. Therefore, subsequently we'll consider the change in the size of defects over time and not mention that the size of the defect is calculated on the basis of the defect feature measured in the inspection. The completion of the latent phase and the beginning of the rapid visible development of the defect we'll call, for short, the moment of the defect occurrence.

Under these assumptions, the defect will be characterized by a dimensionless value, since the obtained results apply to both the defect size and the characteristic value of the defect feature:

$$D(t) = D(t_0)\exp(V(t - t_0)) \ , \qquad (1)$$

where D is the size of the defect; t is the time, s; t_0 is the time of the defect occurrence, s; V is the deterioration rate, 1/s.

In the modeling of the condition-based maintenance we will be based on the following assumptions:

– the defect may occur before or after the inspection;

– upon the occurrence the defect has a random size that does not exceed the preventive replacement threshold;

– the inspection is made before the operating process; if in the inspection the defect size exceeds the preventive replacement threshold the unit is replaced with a new one;

– if the size of the defect has reached the correction replacement threshold during the operating process, the failure occurs, after which the unit is replaced with a new one;

– the duration of the latent phase of the defect exceeds the duration of the operating process (hence, if the unit has been replaced before the process or when it is executed, until the completion of this operation, the unit will not fail);

– it is assumed that previously only the corrective maintenance of units was performed, so the failure flow before the inspection is considered as stationary.

We assume that the inspection is performed at the beginning of the reference time. We perform the logarithm function (1) and move from the sizes of the defects to their logarithms. Since the deterioration rate depends on the various factors, the combined effect of which is typically expressed with their product [3], we believe that the deterioration rate is distributed according to a log-normal distribution:

$$\ln D(t) = \ln D(t_0) + V(t - t_0) \quad , \tag{2}$$

$$f_V(V) = \frac{1}{\sqrt{2\pi}\,\sigma_V V} \exp\left(-\frac{(\ln V - \ln M_V)^2}{2\sigma_V^2} \right) , \tag{3}$$

where f_V is the probability density function of the deterioration rate; M_V is the mode of the deterioration rate, 1/s; σ_V is the shape parameter of the deterioration rate distribution.

We can use the results obtained in [16] when considering the linear defects increase due to operating time, for changing the failure intensity after the inspection and the units replacement, in which the defect size exceeds the preventive replacement threshold – Fig.1.

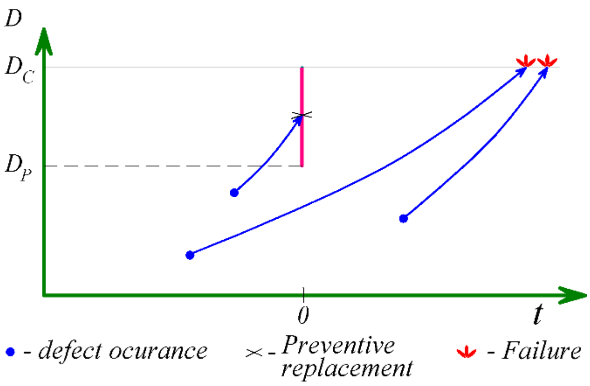

Fig. 1 – Diagram of defect growth.

Thus,

$$w(t) = k_W(t)\, w_0 \quad , \tag{4}$$

$$k_W(t) = \Phi\left(\ln\left(\frac{M_V\, t}{\ln D_C - \ln D_P} \right) / \sqrt{\ln(1 + c_v^2)} \right) , \tag{5}$$

where w is failure intensity, 1/s; w_0 is occurring defects intensity, 1/s. k_W is the decrease coefficient of the failure intensity; D_C is the corrective replacement threshold; D_P is the preventive replacement threshold; c_v is the variance of the deterioration rate.

From the deterioration rate we move to the deterioration time constant – a random variable that is inversely proportional to the deterioration rate. We determine the distribution of deterioration time constant and its expected value from (3, 6):

$$\tau = 1/V \quad , \tag{6}$$

$$f_\tau(\tau) = f_V\left(\frac{1}{\tau}\right)\left|\left(\frac{1}{\tau}\right)'\right| = \frac{1}{\sqrt{2\pi}\sigma_V\tau}\exp\left(-(\ln\frac{1}{\tau} - \ln M_V)^2 / 2\sigma_V{}^2\right) \quad , \tag{7}$$

$$\mathbf{E}[\tau] = \int_0^\infty \tau \; f_\tau(\tau)\, d\tau = \frac{1}{M_V(1-c_v^2)} \quad , \tag{8}$$

where τ - the deterioration time constant, s; f_τ is the probability density function of the deterioration time constant 1/s.

We transform (5), taking into account the properties of the log-normal distribution, and move from time to portion of the treated field area:

$$\varphi = t / T \quad , \tag{9}$$

$$k_W(\varphi) = \Phi\left(\ln\left(\frac{\varphi T}{(1-c_v^2)\,\mathbf{E}[\tau]\ln(D_C/D_P)}\right) \bigg/ \sqrt{\ln(1+c_v^2)}\right) , \tag{10}$$

where φ is the portion of the treated field area; T is the duration of the process, s.

We simplify the function (10). The ratio of the corrective replacement and the preventive replacement thresholds we characterize by the corresponding coefficient. Also, we introduce the notation for the average value of the defect growth duration after exceeding the preventive replacement threshold:

$$K_D = D_C/D_P \quad , \tag{11}$$

$$\tau^* = \mathbf{E}[\tau]\ln K_D \; , \tag{12}$$

where K_D is the ratio of the corrective and the preventive replacement threshold; τ^* is the average value of the defect growth duration from the corrective replacement threshold to the preventive replacement threshold, s.

We distinguish in the formula (10) the dimensionless complex, which is defined as the ratio of the average value of the defect growth duration after exceeding the preventive replacement threshold to the duration of the operational process:

$$\Theta = \frac{\tau^*}{T} = \frac{\mathbf{E}[\tau]\ln(D_C/D_P)}{T} \quad , \tag{13}$$

$$k_W(\varphi, \Theta, c_v) = \Phi\left(\ln\left(\frac{\varphi}{\Theta(1-c_v^2)}\right) \bigg/ \sqrt{\ln(1+c_v^2)}\right), \tag{14}$$

where Θ is the relative value of the defect growth duration after exceeding the preventive replacement threshold.

Determination of the average total production costs in the case of the corrective maintenance of a unit and the condition-based maintenance. We will take into account the average crop losses and the costs of machine efficiency recovery, which includes the cost of the unit and the cost of doing the replacement, as well as the costs of the inspection.

When analyzing the impact of production equipment downtime due to the failure to the production loss, the cost is considered to be dependent only on the recovery duration [17]. In [18] a technique of the optimization of a condition-based maintenance taking into account the time-dependent downtime cost is given. However, in the optimization process of the condition-based maintenance of agricultural machines, it should be considered that the crop loss depends both on the recovery duration and on the proportion of the field area treated before the failure [19]. For a large number of crops the linear approximation of crop losses due to the time is used [20]. In this case, the average value of the loss can be determined by the following formula [19]:

$$\mathbf{E}[\Delta k] = k_1\mathbf{E}[T_R](1-\mathbf{E}[\psi]) \; , \tag{15}$$

where Δk is the crop reduction due to the failure of the unit; k_1 is the proportionality factor, 1/s; T_R is the duration of the repair, s; ψ is the field area part treated before the failure.

We determine the average costs of the corrective maintenance. We take into account the crop losses due to the unit failure and the cost of the unit replacement after the failure:

$$Z_C = Z_{CC} + Z_{CU} \quad , \tag{16}$$

$$Z_{CC} = P_C\, C_C\, \mathbf{E}[\Delta k_C] \quad , \tag{17}$$

$$Z_{CU} = P_C\, C_U\, k_{CU} \ , \tag{18}$$

where Z_C is the average costs upon the corrective maintenance; Z_{CC} is the average crop losses upon the corrective maintenance; Z_{CU} is the costs of the unit replacement upon corrective maintenance; P_C is the unit failure probability upon the corrective maintenance; C_C is the crop cost in the absence of losses; Δk_C is the crop loss portion due to the unit failure upon the corrective maintenance; C_U is the cost of the unit; k_{CU} is the coefficient which takes into account the cost of the work on the unit replacement upon the corrective maintenance.

Upon the corrective maintenance the failure moment is uniformly distributed on the interval of operational process doing. Consequently,

$$P_C \approx 1 - \exp(-w_0 T) \approx w_0 T \quad , \tag{19}$$

$$\mathbf{E}[\psi] = 1/2 \quad , \tag{20}$$

$$\mathbf{E}[\Delta k_C] = k_1 \mathbf{E}[T_R]/2 \quad . \tag{21}$$

We now define the average production costs upon the condition-based unit maintenance. We take into account crop losses due to a unit failure, the inspection costs and two types of the unit replacement costs (replacement after a failure and the preventive replacement):

$$Z_P(\Theta) = Z_{PC}(\Theta) + Z_{PU}(\Theta) + Z_I \ , \tag{22}$$

$$Z_{PC}(\Theta) = C_C\, P_{PF}(\Theta)\, \mathbf{E}[\Delta k(\Theta)] \ , \tag{23}$$

$$Z_{PU}(\Theta) = P_{PR}(\Theta)\, C_U\, k_{PU} + P_{PF}(\Theta)\,(1 - P_{PR}(\Theta))\, C_U\, k_{PU} \ , \tag{24}$$

where Z_P - the average costs upon the condition-based operating; Z_{PC} is the average crop losses upon the condition-based maintenance; Z_{PU} is the average costs of the unit replacement upon the condition-based maintenance; Z_I is inspection costs; P_{PR} is the preventive replacement unit probability; P_{PF} is the failure probability upon the condition-based maintenance; k_{PU} is the coefficient taking into account the cost of works upon the preventive replacement of the unit.

Since the replacement probability is significantly less than one, the (24) can be simplified:

$$Z_{PU}(\Theta) = P_{PR}(\Theta)\, C_U\, k_{PU} + P_{PF}(\Theta)\, C_U\, k_{PU} \ . \tag{25}$$

We define the failure probability under the condition-based maintenance:

$$P_{PF}(\Theta) \approx 1 - \exp\left(-\int_0^1 w_0 T\, k_w(\Theta, \varphi)\, d\varphi \right) \approx w_0 T \int_0^1 k_w(\Theta, \varphi) d\varphi \quad . \tag{26}$$

Crop losses under the condition-based maintenance we determine using (15). To do this, we find the probability density of the field part treated before the unit failure, and its expectation:

$$f_\psi(\varphi, \Theta) = k_w(\varphi, \Theta) \ \Big/ \ \int_0^1 k_w(\varphi, \Theta)\, d\varphi \quad , \tag{27}$$

$$\mathbf{E}[\psi(\Theta)] = \int_0^1 \varphi\, f_\psi(\varphi, \Theta)\, d\varphi = \int_0^1 \varphi\, k_w(\varphi, \Theta)\, d\varphi \ \Big/ \ \int_0^1 k_w(\varphi, \Theta)\, d\varphi \ , \tag{28}$$

where f_ψ is the probability density function of the field part treated before the unit failure.

We determine the probability of preventive unit replacement. We believe that the inspecting moment is uniformly distributed over the unit operating life. The unit will be replaced if the defect size exceeds the preventive replacement threshold. The replacement probability is defined as the ratio of the average operating life part of the unit on which the defect exceeds the preventive replacement threshold to the unit operating life:

$$P_{PR} = \overline{T}_{PR} / \overline{T} \,, \tag{29}$$

$$\overline{T} = 1 / w_0 \,, \tag{30}$$

where P_{PR} is the probability of preventive unit replacement; $\overline{T}_{PR}$ is the average duration of the time interval between exceeding of the preventive replacement threshold and the failure, s; $\overline{T}$ is the unit operating life, s.

We determine the average duration of the time interval between exceeding of the preventive replacement threshold and the failure, averaging over the possible values of the deterioration rate:

$$T_{PR}(V) = \frac{\ln D_C / D_P}{V} \,, \tag{31}$$

$$\overline{T}_{PR} = \int_0^\infty T_{PR}(V)\, f_V(V)\, dV = \mathbf{E}[\tau] \ln \frac{D_C}{D_P} \,. \tag{32}$$

$$P_{PR}(\Theta) = \frac{\overline{T}_{PR}(\Theta)}{\overline{T}} = w_0\, \mathbf{E}[\tau] \ln \frac{D_C}{D_P} \,. \tag{33}$$

Optimization of the unit's preventive replacement threshold. We describe the effectiveness of the condition-based maintenance compared with the corrective maintenance as the ratio of the corresponding average costs. Assuming the inspection costs are relatively small, it is possible to estimate the effect limiting value of the condition-based maintenance. In this case, the actual inspectional costs it is advisable to take into account when formulating the limits of the optimization problem:

$$\begin{cases} K(\Theta) = \dfrac{Z_P(\mathit{\Theta})}{Z_C} \approx \dfrac{Z_{PC}(\mathit{\Theta}) + Z_{PU}(\mathit{\Theta})}{Z_C} \to \min => \mathit{\Theta}_{Opt} \\ K(\mathit{\Theta}_{Opt}) < 1 - \dfrac{Z_I}{Z_C} \end{cases} , \tag{34}$$

.where K is the ratio of costs upon the condition-based maintenance and the corrective maintenance excluding the inspection costs; $\mathit{\Theta}_{Opt}$ is the optimal relative duration of the defect growth after exceeding of the preventive replacement threshold.

If the limit in (34) is failed, then it is advisable to carry out a corrective maintenance of the unit. Having determined the optimal relative duration of the defect, we can calculate the optimal preventive replacement threshold from the formula (13).

We move to the relative value of the unit cost - it will be characterized by the ratio of the unit value (including the operational cost upon the preventive replacement) to the average crop losses due to the unit failure upon the corrective maintenance. The ratio of the operational cost of the unit replacement after the failure and the preventive replacement will be characterized by the corresponding factor. :

$$c_{PU} = \frac{C_U\, k_{PU}}{C_\mathrm{C} \mathrm{E}[\Delta k_\mathrm{C}]} \tag{35}$$

$$k_{CP} = k_{CU} / k_{PU} \,, \tag{36}$$

where c_{PU} is the relative unit cost; k_{CP} is the costs ratio upon replacing the unit after the failure and the replacement under the results of the inspection.

The search for the optimal decision variable value can only be done numerically. It is possible to determine the lowest-possible (when inspection costs are very low) costs ratio upon the condition-based maintenance and the corrective maintenance by substituting the optimal decision variable value in (38):

$$\Theta_{Opt} = f(c_{PU}, k_{CP})\Big|_{c_v=\text{const}} , \tag{37}$$

$$K_{\min}(c_{PU}, k_{CP})\Big|_{c_v=\text{const}} = K\left(\Theta_{Opt}(c_{PU}, k_{CP}, c_v), c_{PU}, k_{CP}, c_v\right), \tag{38}$$

where $K_{\min}$ - the lowest-possible costs ratio upon the condition-based maintenance and the corrective maintenance.

The graphs of the dependences (37, 38) for typical values of the arguments and $c_v = 0.5$ are shown in Fig. 2 and Fig. 3.

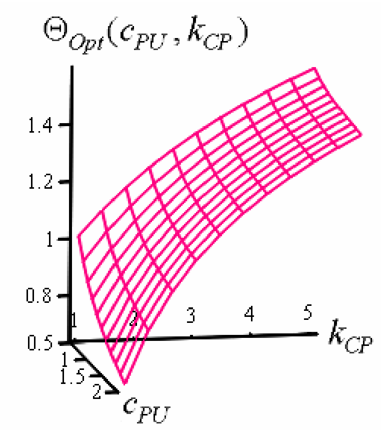

Fig. 2 The optimal decision variable upon $c_v = 0.5$

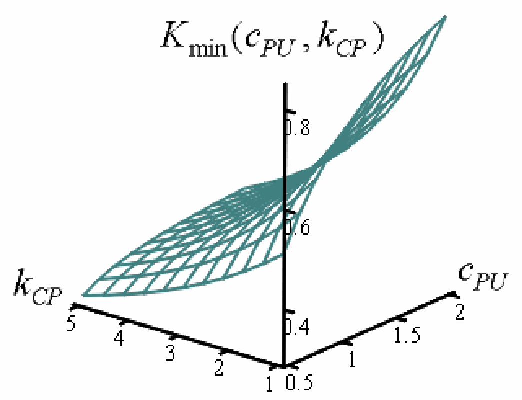

Fig. 3. The lowest-possible costs ratio upon the condition-based maintenance and the corrective maintenance at $c_v = 0.5$

Let us analyze the possibility of the developed technique applying under the subsequent process steps. We suppose using of the preventive replacement threshold value which is optimal for the former. The unit replacement probability and the unit failure probability affect on the total costs. Failure probability does not depend on the number of operations performed since the failure is caused by the defects that do not exceed the preventive replacement threshold upon the inspection. The unit replacement probability will be reduced as the repetition of process operations, as the previous inspections and preventive replacements prevent further growth of some defects. Thus, the total cost value would be less than the calculated value. Consequently, the preventive replacement threshold value, calculated by the developed technique, can be used under the process operation repeating.

Conclusions.

1. In this article, we investigate the one-time transition process from the corrective maintenance to the condition-based maintenance of an agricultural machine unit, which fails due to a defect with long latent stage (e.g., a surface fatigue). The technique of the preventive unit replacement threshold optimizing before performing the process operation is developed.

2. Thus, total production costs because of failures can be reduced by several tens of percent. Naturally, such costs ratio can be achieved only if used inspecting equipment can detect the defects whose size is equal to the optimal preventive replacement threshold.

3. The total production costs can be further reduced, considering the impact of the previous inspection and preventive replacement on the defect size probability density function under the next inspection and therefore, their effect on the replacement probability. This may be the subject of the further study.

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Shevchenko S.A. **Condition-based replacement policies of an unit taking into account the latent stage of defect development**

In this article we have focused on optimizing the service policy for stochastically deteriorating system with long latent (incubational) stage of defect development (e.g., a surface fatigue). We consider the preventive replacement threshold as a decision variable for an agricultural machine unit, which inspection is carried out before the process operation. Optimization of a preventive replacement threshold is performed on the criterion of minimum total production costs, which consist of losses of the part of the harvest due to a failure and maintenance costs.

Keywords: condition-based maintenance, failure, latent stage, diagnosis, replacement threshold, pitting, agriculture.

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