THERMOMETRIC DIAGNOSTICS OF ELEMENTS OF REAPER DRIVE FOR SUNFLOWER HARVESTING

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Abstract. Ensuring failure-free operation of agricultural machinery in seasonal operation conditions is based on a maintenance system including diagnostics. A promising method of diagnosing the technical condition of mechanical transmission units is contactless thermometry based on measuring the intensity of infrared radiation of friction pairs. The purpose of the work is to verify the thermometric diagnostic method for mechanical transmission units of agricultural machinery. The results of experimental development of technology of thermometric nondestructive testing of the cardan joint of ZAFFRANI 940N reaper drive CLAAS TUCANO 570 grain harvester are presented in the work. The method of conducting the experiment included monitoring the temperature of parts and ambient air, the dynamic parameters of the reaper drive and the level of solar radiation. In order to implement the system approach, evaluation of the thermal state of the object of research was carried out at three hierarchical levels. The first level is represented by an analytical equation for determining the temperature in the friction zone. The second hierarchical level is implemented using CAE-technology, which makes it possible to establish the relationship of temperature in the friction zone and diagnostic temperature on the surface of the part. The influence of external heating factors at the third hierarchical level is due to solar radiation, which causes heating of the surfaces of the parts. To take this factor into account and compensate for the measured temperature values, a mathematical model of the thermal balance for the studied unit was developed, which includes thermal energy from solar radiation and energy supplied to the environment through convection and radiation. A summary of the results of the study confirms the effectiveness of thermometric nondestructive testing for mechanical transmission units using the example of bearing assemblies of the cardan joint of the reaper drive.

Keywords: harvester, nondestructive testing, thermal diagnostics, cardan joint, system approach, reliability.

Introduction

Ensuring the reliability of mechanical transmission elements is based on the planned preventive maintenance system and the reliable-centered maintenance system, an integral part of which is technical diagnostics [1-4]. Earlier, the authors on the basis of the system approach proposed a method of estimating thermal load for mechanical transmission units [5]. The method implementation procedure is shown on the example of monitoring reliability of agricultural machines by parameters of thermal diagnostics of drive lines [6]. Interpretation of the method is shown in studies of working capacity of bearing units taking into account thermal characteristics of the contact of rollers and rings of bearings during operation in the presence of lubricant [7]. The implementation of thermometric nondestructive testing is based on the development of a temperature model of the object to be diagnosed, which, after checking adequacy, is introduced into the diagnostic algorithm. The most effective tool for developing temperature models of technical objects is the finite element method, which allows both modeling and predicting the behaviour of the studied models, which is confirmed in studies in relation to rolling bearings [8]. The authors developed an adaptive temperature model of the cardan joint, including a mathematical model of the first hierarchical level and finite-element models for the second and third levels [9]. The results of bench tests showed the adequacy of the developed mathematical model, so it is necessary to carry out operational testing of the thermometric control technology.

Materials and methods

The research is based on a systematic approach, which forms a temperature model at three interconnected hierarchical levels: the temperature of the elementary heat-generating connection (temperature in the friction zone Θ_F); temperature of the unit to be diagnosed; temperature of the unit to be diagnosed, taking into account the influence of external heat generation (diagnostic temperature Θ_D). Algorithm of thermometric diagnostics application is shown in Fig. 1. The main task is to establish the dependence of the diagnostic temperature Θ_D on the temperature of the elemental fuel connection Θ_F, the ambient temperature Θ_0. The obtained dependence makes it possible to determine the value Θ_F, and compare it with the maximum allowable temperature of Θ_L = 250 ºC by the value of the measured diagnostic temperature Θ_D. The results of bench tests [9] made it possible to establish such dependence, however, in real operation, the temperature model is inevitably influenced by more factors, which include the intensity of solar radiation.

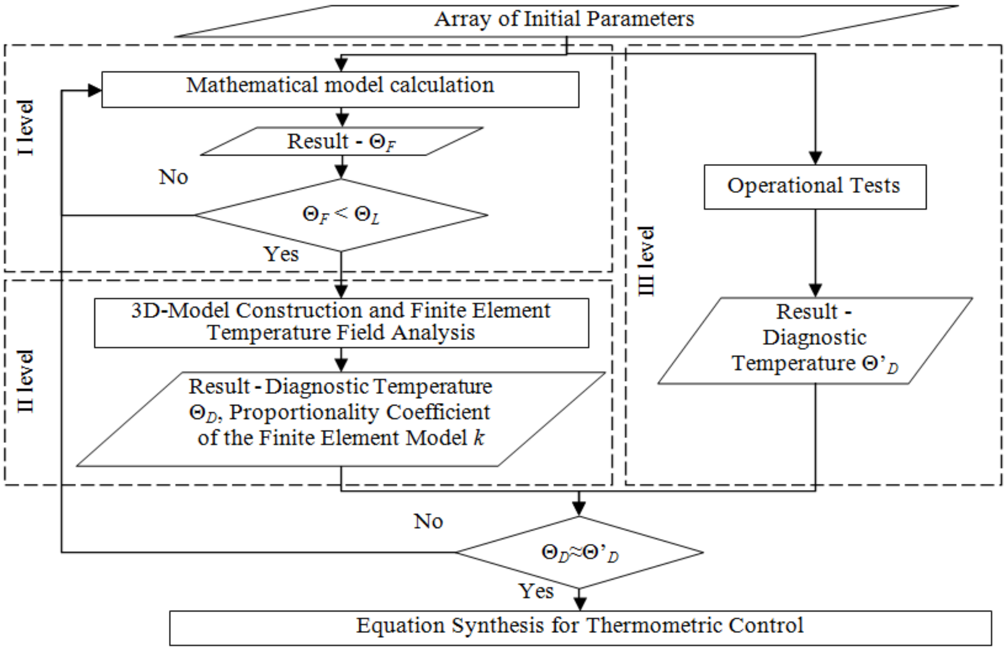

Fig. 1. **Thermometric diagnostic algorithm**

Temperature fields were simulated using the finite element method in the COMPAS-3D V18 program using the APM FEM application library. As the object of the study, a cardan joint manufactured by EUROCARDAN was chosen, which serves to drive the reaper ZAFFRANI 940N of the CLAAS TUCANO 570 combine harvester. The measurement of the diagnostic temperature Θ'_D was carried out by a contactless method using the digital infrared pyrometer INSTRUMUMAX PIRO-330. The distance of the contactless measurement was selected in accordance with the operating manual: for measuring an area with a diameter of 30 mm the required distance was 360 mm.

The purpose of the study is to test the thermometric control technology for cardan joints and study the influence of climatic factors.

Results and discussion

The dependence obtained in the study [9] is used to calculate the temperature of the first hierarchical level Θ_F. The design parameters for the EUROCARDAN cardan joint were determined by measuring the dimensions of its parts, as well as studying the manufacturer's catalogs on the website www.eurocardan.it. To determine the operational factors (speed, angle of break, torque), a kinematic scheme was used (Fig. 2). The reaper drive ZAFFRANI 940N is designed and operated as follows. The power flow from the inclined chamber is transmitted through the drive line 1 being examined. Further, through two chain transmissions, power is transmitted to the screw 2, after which, also through the chain transmission, to the motor 3. Mechanism of swinging washer 4 is driven through the chain and belt gear. Kinematic characteristics are shown in the diagram (Fig. 2): the power transmitted by the cardan joint is 25.7...29.1 kW, the angular velocity is 59.7 s^{-1}, the torque is 430...487 Nm, the angle of fracture in the joint is determined in fact and amounted to $\gamma = 16^o$.

The preliminary design estimate showed a temperature value of Θ_F = 135.5...153.5 ºC. These values are less than the limit temperature Θ_L = 250 ºC, therefore, in accordance with the study algorithm, we construct a 3D-model of a cardan joint for studying temperature fields using the finite element method. Figure 3 shows the results of 3D-modeling and temperature field calculation.

By changing the value of the temperature Θ_F for the finite element model, the value of the proportionality coefficient of the finite element model $k = 0.225$ is obtained (Fig. 4). Taking into account the obtained coefficient, and having Θ_F = 135.5...153.5 ºC, the value of the diagnostic temperature, determined theoretically, will be Θ_D = 30.5...34.5 ºC, and on average – 32.5 ºC.

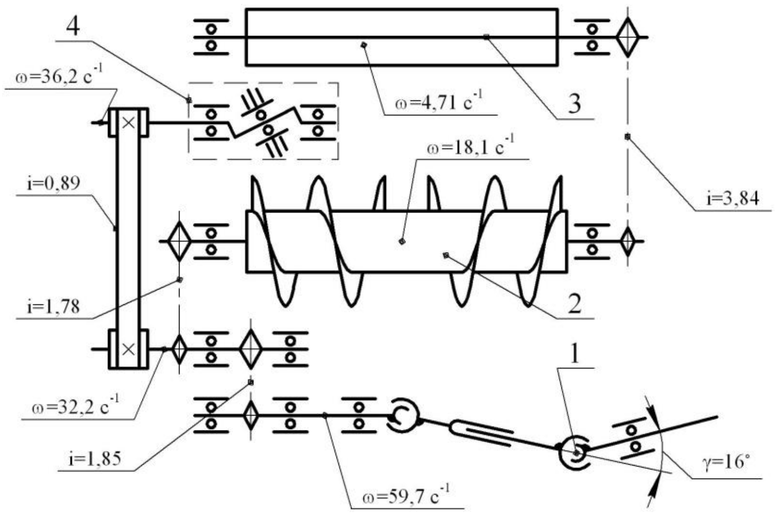

Fig. 2. **Kinematic diagram of the reaper drive ZAFFRANI 940N**

In the course of operational observations, the temperature of the cardan joint Θ'_D, operating time, as well as the temperature of the ambient air Θ_0 were monitored. The average value of the measured diagnostic temperature is Θ'_D = 29.5 ºC. Comparison of the received values shows their approximate equality Θ_D = 32.5 ºC ≈ Θ'_D = 29.5 ºC that allows to complete the next stage of an algorithm – synthesis of the equation for thermometric control.

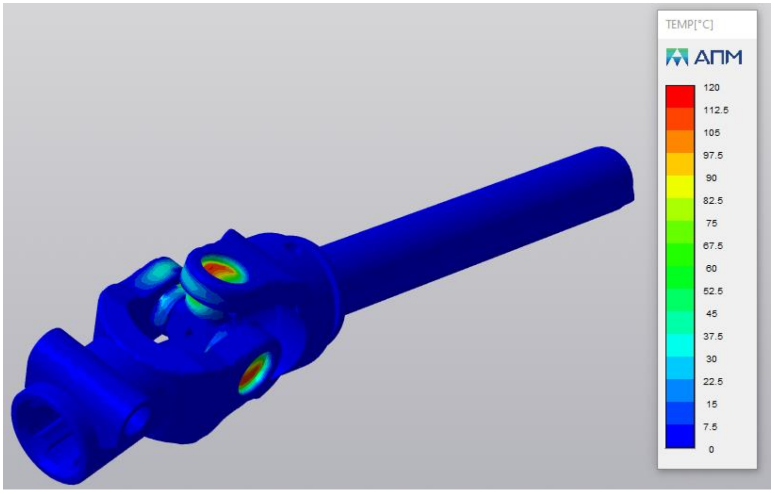

Fig. 3. **Results of simulation of temperature fields of reaper drive cardan joint ZAFFRANI 940N**

Based on the measured value, the temperature in the friction zone is calculated taking into account the ambient air temperature Θ_0 and the proportionality coefficient of the finite element model k = 0.225 according to formula (1).

$$\Theta_F = \frac{\Theta'_D - \Theta_0}{k}, \tag{1}$$

where Θ_F – temperature in friction zone, ºC;
Θ'_D – diagnostic temperature, ºC;
Θ_0 – ambient temperature, ºC;
k – coefficient of proportionality of finite-element model.

The results of the observation of the temperature in the friction zone Θ_F are shown in Fig. 5. Obviously, the obtained data are poorly approximated (R^2 = 0.00004), and the temperature value in the friction zone is significantly different from the theoretically calculated one. Earlier bench tests showed convergence of results [9]. Obviously, the results of the measured diagnostic temperature are influenced by an unaccounted factor, which is probably solar radiation.

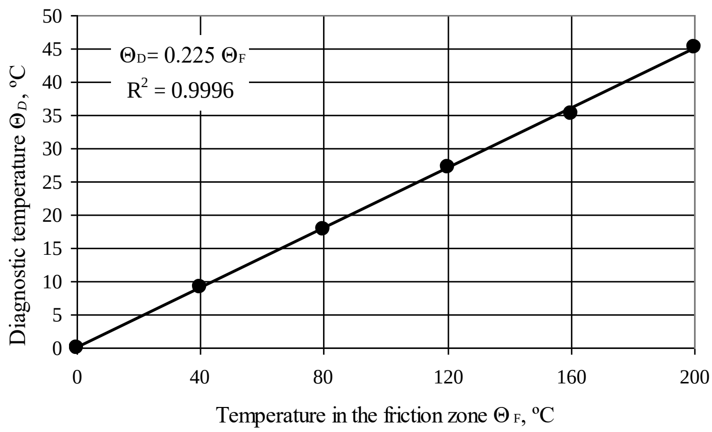

Fig. 4. **Dependence of diagnostic temperature on elemental heat-generating connection temperature in friction zone**

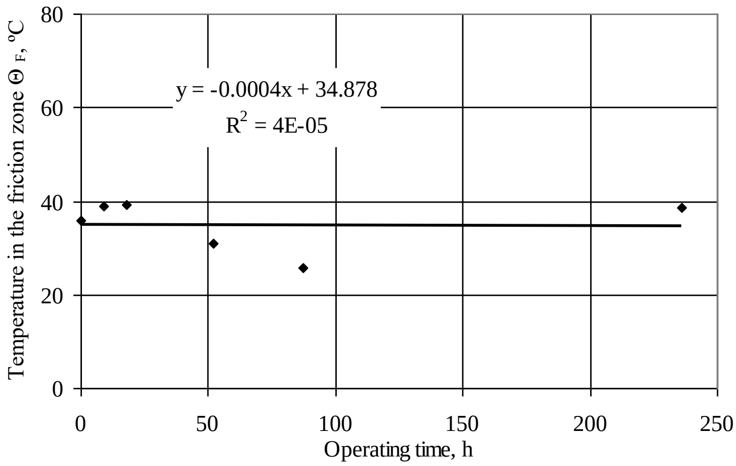

Fig. 5. **Results of measurement of temperature of bearing units of reaper drive cardan joint ZAFFRANI 940N**

To resolve this contradiction, we compose the equation (2) of the thermal balance [10].

$$Q_R = Q_{охл} = Q_{conv} + Q_{rad}\,, \tag{2}$$

where Q_R – energy from solar radiation, W;
$Q_{охл}$ – thermal energy released to the environment, W;
Q_{conv} – energy transmitted by convection, W;
Q_{rad} – energy transmitted by radiation, W.

The amount of heat (3) obtained from solar radiation is determined based on the following equation [11].

$$Q_R = Q_R^{\max} S\left(\sin\varphi_N \sin\left(\delta_0 \sin\left(360^0\,\frac{284+n}{365}\right)\right)\right) + \cos\varphi_N \cos\left(\delta_0 \sin\left(360^0\,\frac{284+n}{365}\right)\right), \tag{3}$$

where S – cardan joint surface area, m^2;
Q_R^{max} – solar constant ($Q_R^{\max} = 1367$), W·m^{-2};
φ_N – geographical latitude, grade;
δ_0 – solar declination constant (for northern hemisphere 23.45º), grade;
n – ordinal day of the year starting from January 1.

The energy transmitted by convection (4) and by radiation (5) is determined based on the following equations [10].

$$Q_{conv} = h_c S(\Theta_R - \Theta_0), \tag{4}$$

$$Q_{rad} = \varepsilon\sigma S\left(\Theta_R^4 - \Theta_0^4\right), \tag{5}$$

where h_c – convective heat transfer coefficient, W·m^{-2}·ºC^{-1};
Θ_R – heating temperature from solar radiation, ºC;
ε – object radiation constant;
σ – Stefan-Boltzmann constant ($\sigma = 5.67\times10^{-8}$), W·m^{-2}·ºC^{-4}.

By converting formulae (2), (4) and (5), we obtain a dependence for determining the heating temperature from solar radiation in the form of equation (6).

$$\Theta_R^4\varepsilon\sigma + \Theta_R h_c - \Theta_0^4\varepsilon\sigma - \Theta_0 h_c - Q_R = 0\,. \tag{6}$$

When calculating, constant values were used: the coefficient of a convective heat transfer of $h_c = 5$ W·m^{-2}·ºC^{-1}, an object radiation constant for the steel painted surface $\varepsilon = 0.8$ and the geographic latitude of the area $\varphi_N = 50.2$º NL and variable values: the ambient temperature Θ_0, data of measurements.

For the practical application of thermometric control technology, it is necessary to obtain a temperature dependence in the friction zone Θ_F and compare it with the maximum permissible temperature $\Theta_L = 250$ ºC. The required dependence is determined on the basis of equations (2) and (6) taking into account the empirical coefficient k, as well as the amount of heat obtained from solar radiation Q_R. Significant difficulties are caused by the transformation of the equation of the fourth degree (6), however, due to the extremely small value of the coefficient $\sigma = 5.67\cdot10^{-8}$ W·m^{-2}ºC^{-4} in practice, it can be neglected, then the equation sought has the following form (7).

$$\Theta_F = \frac{h_c S\left(\Theta_D^{/} - \Theta_0\right) - Q_R}{h_c S k} < \Theta_L\,. \tag{7}$$

The calculation according to formula (7) made it possible to plot the dependence of temperature in the friction zone on the operation time of the unit, shown in Fig. 6. In this case, the determination coefficient $R^2 = 0.8074$ shows the efficiency of the obtained equation for thermometric control.

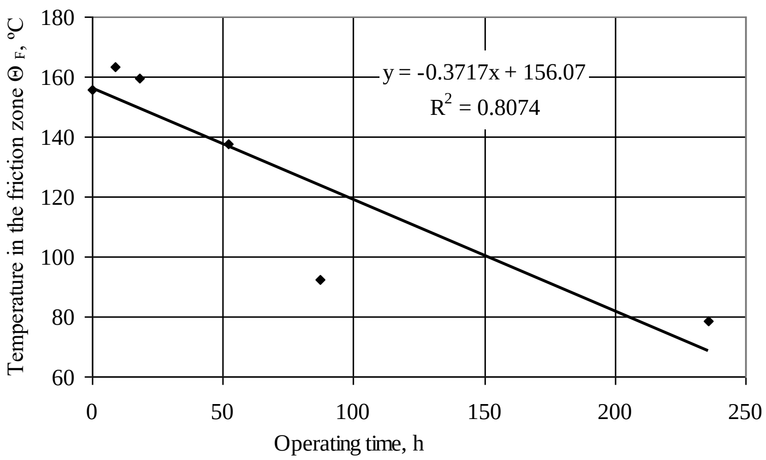

Fig. 6. **Dependence of Θ_F temperature on cardan joint operating time taking into account influence of solar radiation**

The temperature values in the friction zone using formula (7) do not exceed the maximum permissible value $\Theta_L = 250$ ºC. The obtained results show that the taken account of the influence of solar radiation on the results of temperature measurement made it possible to identify with a higher degree of reliability the dependence of diagnostic temperature on the operating time.

Similar studies were carried out by bench and full-scale tests of sliding friction units in order to increase accuracy and informational content of diagnostics of their technical condition [12-14]. However, thermal diagnostics of sliding units is performed only with consideration of a single factor of loading – the shaft rotation speed, which is not enough [12], and evaluation of temperature fields of the friction clutch disk is performed in conditions of idealization of friction and wear processes [13]. As a result of such studies is an example of optimization of structural-technological parameters of stepped shafts [14]. Thus, the conducted studies expand the factors of diagnosing the operability of mechanical transmission units by thermal load, taking into account the influence of structural, technological and, most important, operational factors.

Conclusions

1. Based on the system approach, thermometric monitoring technology is justified and implemented using the example of diagnostics of mechanical transmission elements.
2. The adequacy of the mathematical model and applicability of the results are confirmed with convergence of data Θ_D = 32.5 ºC ≈ Θ'_D = 29.5 ºC by the results of performance tests. The value of the proportionality coefficient of the finite element model k = 0.225 is determined.
3. The results of the bench tests showed the need to take into account the effect of solar radiation on the diagnostic temperature. Based on the expression of thermal balance, an equation for the practical application of the thermometric diagnostic method is obtained.
4. Prospects of thermal diagnostics studies are related to predicting reliability of friction units based on simulation by finite element method.

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