TEMPERATURE CONDITIONS AND DIAGNOSTICS OF BEARINGS

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Abstract:
The purpose of this work is to prove the effectiveness of a practical study of the temperature regime for diagnosing bearing assemblies of mechanical transmissions. Using the example of a two-row roller bearing of the rear support of the intermediate shaft of the vehicle transmission, the temperature in the friction zone under different transmission operating modes on a KAMAZ-5320 was calculated. Finite element analysis of temperature fields made it possible to determine the relationship between the temperature on the outer surface of the bearing assembly and the temperature in the friction zone through the coefficient k=0.327. The zone for temperature measurement - the bearing cover is determined and the maximum temperature of its heating is set. Thermal imaging observations confirmed the effectiveness of the developed method of technical diagnostics of bearings.

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1. INTRODUCTION

During the operation of mechanical transmission units, part of mechanical energy is converted into thermal energy [1-3]. The size of the heat loss is an indirect feature characterizing the technical state of the friction pair, therefore, the thermal mode of the mechanical transmission unit can be used to diagnose its state. In addition, the result of exceeding the limit temperatures will be a violation of the normal lubrication mode and the transmission unit will enter the limit state [4-8].

The most common elements of mechanical transmissions are bearing assemblies. Thermal diagnostics accuracy of bearing assemblies is affected by heating factors from ambient air, adjacent heat sources and solar radiation [9]. Therefore, diagnostics by the temperature measured on the outer surface of the bearing assembly has no practical application [10-15]. Modern technologies and technical means of temperature measurement make it possible to perform thermal diagnostics automatically, without manual labour, but only when measuring the temperature of the outer surface of the bearing assembly [16-19].

The diagnostic criterion for the limit state of bearings is the excess of the temperature in the friction zone of more than 215-250 °C (RTM 23.2.74-79 Procedure for accelerated testing of drive lines of agricultural machines). However, direct temperature measurement in the friction zone is practically difficult, therefore, methods of calculating heat flows are used to determine the relationship between the temperature on the outer surface of the bearing assembly and the temperature in the friction zone [14].

A more efficient adaptation of different bearing assemblies to thermal diagnostics is possible using the finite element analysis method under stationary thermal conductivity conditions. The use of this method will ensure effective thermal diagnostics of bearings in automatic mode.

The purpose of this study is the practical application of the study of temperature conditions

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for the diagnosis of bearing assemblies of mechanical transmissions.

The practical implementation of the method of technical diagnostics based on the measurement of the temperature of bearing units provides wide prospects for the digitalization of monitoring the technical condition of the equipment. Automatic temperature measurement and processing of the received information by integrated diagnostic systems in combination with telematic means will ensure timely prevention of pre-failure state, as well as accumulation of statistical information on the reliability of equipment for its further improvement by manufacturers [16].

This – study aims to prove the practical applicability and effectiveness of the developed method of digital thermal diagnostics of bearing assemblies of mechanical transmissions.

2. MATERIALS AND METHODS

The object of the study is a two-row roller bearing 53610 GOST 520-2011 (22310CC/W33 ISO DIN 630, 22310EAW33 SNR), installed in the rear support of the intermediate shaft of the gearbox of the KAMAZ-5320 truck. Data from operation [20] weas used to calculate bearing load modes. When creating a 3D-model of the bearing assembly, KOMPAS-3D software (ZAO ASCON, Russia) was used, and for finite element analysis - APM FEM (SCIENTIFIC AND TECHNICAL CENTER "APM," Russia). During thermal imaging observations, a Testo 865 thermal imager was used.

The theoretical friction zone temperature calculation is based on the conventional bearing model shown in Fig. 1. Here are the geometric parameters used in the analytical model (1).

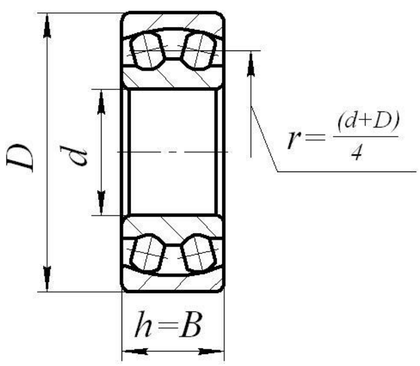


Fig. 1. Bearing Design Diagram

The friction zone temperature analytical model is based on structural, process and operational factors [13]:

$$\Theta_F = \frac{\delta f F \omega}{2h\left(\lambda\sqrt{\frac{2\alpha(h+\pi r)}{\lambda h \pi r}} + k'\rho c \cdot 2{,}6\sqrt{\frac{a\omega r}{\lambda_R}}\right)}, \quad (1)$$

where values are:
Θ_F – friction zone temperature, *°C*;
δ – coefficient of heat distribution between rubbing bodies;
f – friction coefficient;
F – bearing load, *N*;
ω – angular speed, s^{-1};
h – length of the spike, *m*;
r – spike radius, *m*;
λ – heat conductivity, *W/m°C*;
α – surface heat transfer coefficient, $W/m^2 °C$;
k' – coefficient of proportionality;
ρ – material density, kg/m^3;
c – specific heat, *J/kg°C*;
a – thermal diffusivity, m^2/s;
λ_R – the wavelength of irregularities on the rubbing surface, *m*.

3. RESULTS AND DISCUSSION

The gearbox of the KAMAZ-5320 truck is a five-speed, with the fifth gear having a gear ratio of 1; that is, the bearings of the intermediate shaft are under during operation when transmitting torque on gears 1-4 gears. Initial data - rotation speed and torque at different gears [20], diameters of division circles of gears (Table. 1).

The Eq. 2 determines the force acting on the intermediate shaft from the gear engagement:

$$F_2 = \frac{2T_2}{d_2 \cos \alpha_W}, \quad (2)$$

where values are:
F_2 – force from gearing, *N*;
T_2 – output shaft torque, *Nm*;
d_2 – diameter of the pitch circumference of the output shaft gear, *m*;
α_W – angle of engagement, *deg*.

The calculation uses the diameters of the pitch circumference of the output shaft gear at I-IV gears: d_2=0.252 *m*; 0.208 *m*; 0.185 *m*; 0.150 *m*.

The force acting on the intermediate shaft from the primary shaft is determined by the Eq. 3:

$$F_1 = \frac{2F_2 d_1}{d_0}, \quad (3)$$

where values are:
F_1 – force acting on the intermediate shaft from the primary shaft, *N*;
d_1 – diameter of the pitch circle of the gear wheel of the intermediate shaft in each gear, *Nm*;

d_0 – diameter of the dividing circle of the driven gear of the intermediate shaft, *m*.

The calculation uses the diameters of the pitch circle of the gear wheel of the intermediate shaft at I-IV gears: d_1=0.070 *m*; 0.108 *m*; 0.140 *m*; 0.180 *m*. Diameter of the dividing circle of the driven gear of the intermediate shaft: d_0=0,208 *m*.

Results of calculation of forces F_2, F_1 are given in Table 1. To calculate the force acting on the bearing, design diagrams for each transmission are compiled, shown in Fig. 2: a) – I gear, b) – II gear, c) – III gear, d) – IV gear.

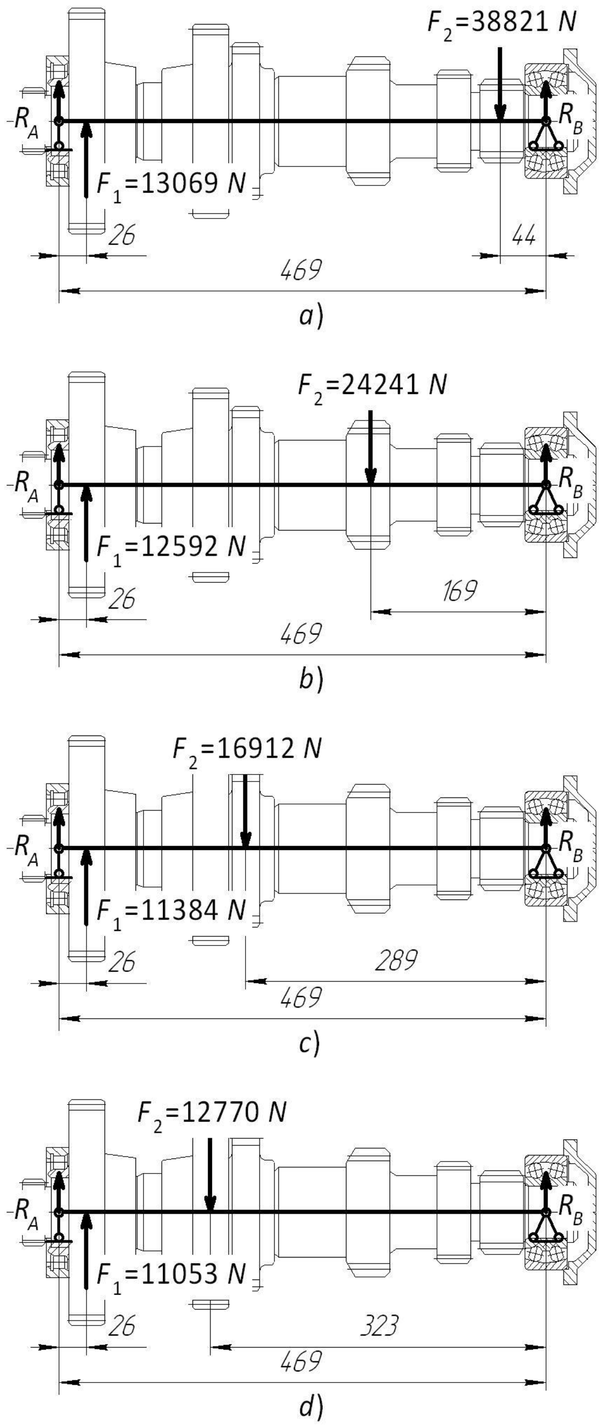


Fig. 2. Bearing load calculation

When calculating the temperature in the friction zone by the Eq. 1, the speed of rotation of the intermediate shaft n=1460 rpm was used, taking into account the thermophysical properties of the bearing material - steel. To automate calculations, the authors created a computer program - a temperature calculator in the bearing friction zone RU 2021612821 (Fig. 3). This program calculates the radius of the spike r. It uses reference data of the thermophysical properties of the materials and calculates the temperature in the friction zone (Table 1).

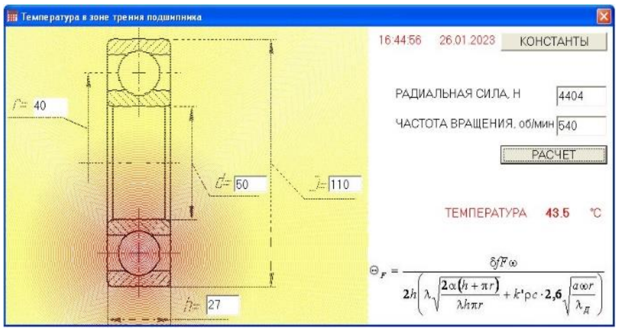


Fig. 3. Bearing Friction Temperature Calculator

To determine the relationship between the temperature on the outer surface of the bearing assembly and the temperature in the friction zone, a 3D-model of the bearing assembly is created, consisting of a bearing, a fragment of the secondary shaft, a fragment of the housing and a cover.

Preliminary studies of stationary thermal conductivity have shown that it is not necessary to use all parts in a 3D-model, since satisfactory results are obtained with the use of only adjacent bearing parts, or fragments thereof.

When setting temperature loads, temperatures in the friction zone are applied to the bearing rollers, and 0 °C to the surfaces of other parts. The surface of the lid is used as a surface for measuring the diagnostic temperature, so temperature loads were not applied to it.

As a result of the calculation, maps of temperature fields were obtained, one of which is shown in Fig. 4.

Analysis of the temperature distribution shows that the bearing cap surface has a substantially uniform temperature field and is therefore suitable for measuring the diagnostic temperature.

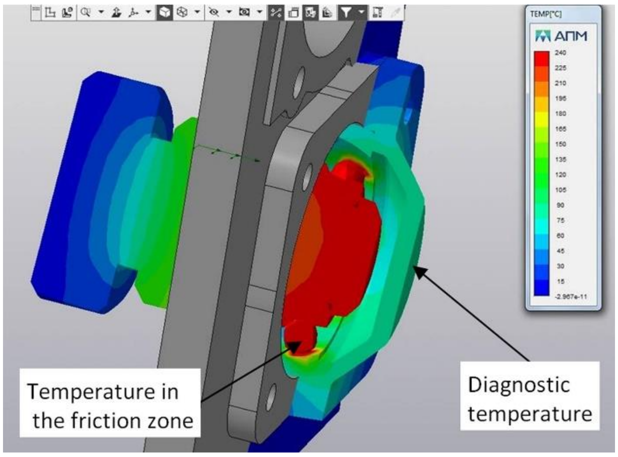


Fig. 4. Temperature Field Map

As a result of repeated repetition, direct proportional dependence of diagnostic temperature on the temperature in the friction zone is established and the coefficient of proportionality of the finite-element model of the tested bearing assembly k=0.327 is calculated, which is equal to the coefficient at the argument of the function in the straight line equation obtained after approximation of the experimental data. Based on the Eq. 4, the diagnostic temperature is determined:

$$\Theta_D = k\Theta_F, \tag{4}$$

where values are:
k – coefficient of proportionality of finite-element model;
Θ_D – diagnostic temperature in the friction zone, °*C*.

Results of calculation of diagnostic temperature values are given in Table 1.

Table 1. Friction Zone Temperature Calculation Results

Parameter	Gear			
	I	II	III	IV
Torque *T, Nm*	4598	2369	1470	900
Force from gearing F_2, *N*	38821	24241	16912	12770
Force from gearing F_1, *N*	13069	12592	11384	11053
Bearing load R_B, *N*	27952	14808	5860	3363
Friction Zone Temperature Θ_F, °*C*	313.0	165.8	127.5	37.70
Diagnostic temperature Θ_D, °*C*	102.4	54.00	41.70	12.30

The results of the temperature calculation for each transmission are shown in Fig. 5.

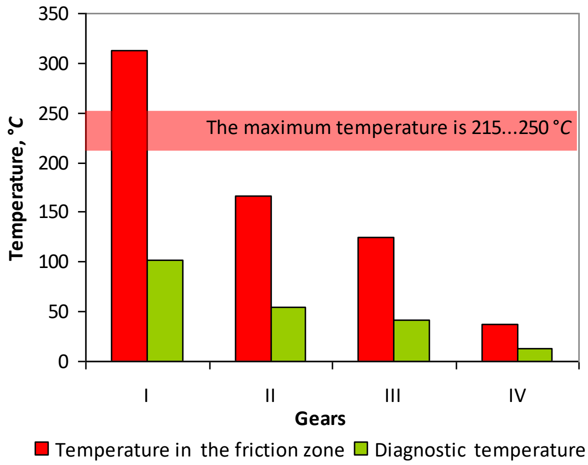


Fig. 5. Temperature calculation results

The obtained temperature value in the friction zone in the first transmission 313 °C is doubtful, since it exceeds the limit temperature 215-250 °C. This can be explained by the fact that in the operation of the truck I the gear is used only to start moving in a short period of time, the main time the transmission works on other gears. Therefore, in practice, the bearing does not have time to heat up significantly in the I gear.

For practical confirmation of the obtained results, it is necessary to measure the temperature of the cover of the bearing assembly during the operation of the truck. The truck works at different speeds, therefore the average value of the diagnostic temperature was determined by taking into account the duration according to the Eq. 5 [20]:

$$\Theta_D = \frac{100}{\frac{\alpha_I}{\Theta_D^I}+\frac{\alpha_{II}}{\Theta_D^{II}}+\frac{\alpha_{III}}{\Theta_D^{III}}+\frac{\alpha_{IV}}{\Theta_D^{IV}}}, \tag{5}$$

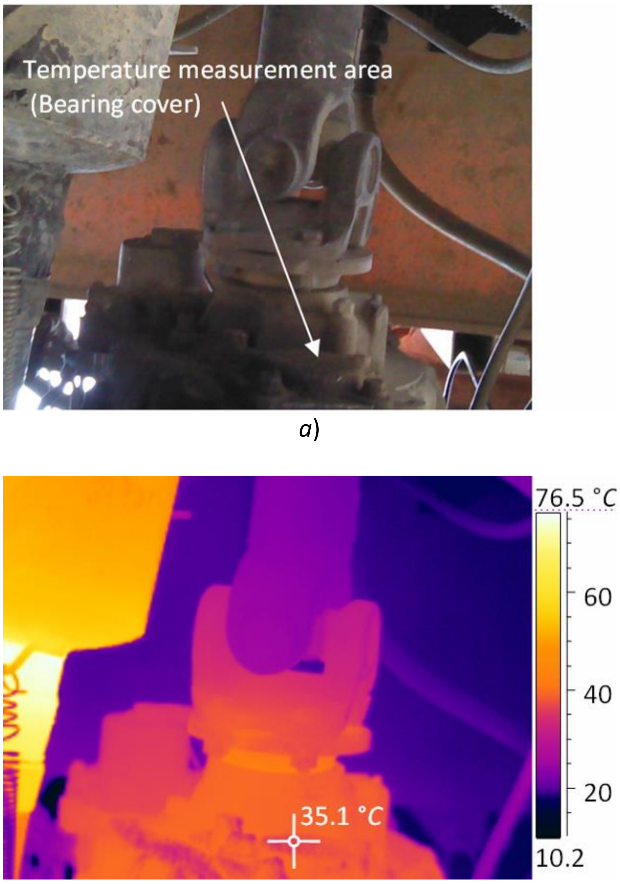
where values are:
$\alpha_I \ldots \alpha_{IV}$ – duration of work on each transmission, %;
$\Theta^I_D \ldots\ \Theta^{IV}_D$ – diagnostic temperature on each transmission.

Since work on V transmission was not considered, then for 100% of the time we will accept the total time of work on I-IV transmissions, then α_I=2%; α_{II}=6%; α_{III}=25.3%; α_{IV}=66.7% [21]. The resulting temperature of Θ_D=16.2 °C indicates how much the bearing cap surface temperature will be higher than the ambient air temperature. This value can be used as a diagnostic criterion for normal bearing operation during operation. In this case, taking into account k=0.327, the temperature in the friction zone will be Θ_F=75.8 °C.

Assuming the limit temperature in the friction zone of 215 °C, we similarly determine the diagnostic temperature of Θ_D=70.3 °C. That is, an increase in the bearing cover temperature by 70.3 °C relative to the ambient air temperature indicates a possible bearing failure.

The theoretical studies carried out require practical verification. To do this, measurements were made of the surface temperature of the bearing cover 53610 of the rear support of the intermediate shaft of the gearbox of the KAMAZ-5320 truck. The truck was operated during the shift, as usual, on hard and unpaved roads. Fig. 6a shows the general view, and Fig. 6b shows the thermogram of the gearbox with a view of the bearing cover - the temperature measurement area. Measurements were carried out at an ambient temperature of 16.7 °C.

Taking into account the measured temperature (Fig. 6b) and the ambient air temperature, the experimental value of the diagnostic temperature will be 35.1-16.7=18.4 °C, which is 11.9% different from the theoretical diagnostic temperature of 16.2 °C.



a)

b)

Fig. 6. Thermal Imaging Results

In the practical study of the bearing temperature of the conveyor drive [22,23], the value of the increase in the diagnostic temperature of 17-31 °C, characteristic of normal operation, is established, in addition, the diagnostic criterion of the limit state of 48 °C is established. The presented results are comparable to our study, but they do not take into account the temperature in the friction zone as a significant diagnostic factor. Similar results were obtained by other authors in the study of temperature conditions of bearings operation in laboratory conditions [21]. In their study, the temperature in the friction zone was measured directly by a thermal imager, which is possible in laboratory conditions, but not applicable in practice. The method developed by us allows, based on the measurement of the temperature on the surface of the unit, using the proportionality coefficient of the finite element model k, to estimate the temperature in the friction zone as an important diagnostic factor.

4. CONCLUSION

The key results of this research were:

1. Design assessment of the load of the tested bearing at various operation gears was performed.

2. A zone suitable for temperature measurement was identified and a coefficient of proportionality of the finite element model k=0.327 was obtained.

3. The average temperature in the friction zone of the bearing 53610 Θ_F=75.8 °C is determined. The diagnostic criterion of the limit state is established - an increase in the temperature of the bearing cover by 70.3 °C relative to the ambient air temperature.

4. The convergence of theoretical and actual diagnostic temperatures was revealed due to operational thermal imaging observation.

5. The practical applicability of the developed method of digital thermal diagnostics has been proven.

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