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Using Digital Twins of Bearing Units for Their Automatic Diagnostics

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Abstract:
Diagnostics of bearing assemblies during operation are essential for maintaining operational reliability. The study focused on the bearing assemblies of the rear axle gearbox of a KAMAZ 6x4 vehicle. Finite element modeling of temperature distribution was performed using APM FEM. An INSTRUMAX PIRO-330 pyrometer and a UTi260B thermal imager were used to measure temperatures. Digital twins of the bearing assemblies were developed to obtain friction zone temperatures and proportionality coefficients for the finite element models, based on the nominal load criterion and lubricant properties. Thermal imaging demonstrated the practical applicability of digital thermal diagnostics technology and the developed digital twins. Practical recommendations are proposed for technical diagnostics of bearings using infrared pyrometers, thermal imagers, temperature indicator stickers, and a transmission fault recorder.

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1. INTRODUCTION

Rolling bearings used in various machine designs significantly impact the reliability of the equipment. Rolling bearings can be used as shaft supports for mechanical transmissions and as power components, such as needle bearings in universal joints.

Most rolling bearings are standard products, so their design reliability is constant. Process and operational reliability may be lower due to imperfections in bearing manufacturing and equipment operation. Therefore, timely diagnostics of bearing assemblies during operation are essential for maintaining operational reliability, making this research topic relevant.

It has been established that rolling bearing failures primarily result from plastic deformation and corrosive wear. Therefore, it is recommended to use a fault tree when determining the requirements for purchasing new bearings [1]. Also, high-power bearing assemblies, such as universal joint needle bearings, operate under challenging conditions and are subject to significant loads [2-5].

The operational reliability of rolling bearings depends on a variety of factors, including lubricant properties, the nature and direction of applied loads, temperature, humidity, and environmental dustiness, vibration, and dynamic loads [5-9].

Many researchers propose vibration diagnostic methods to automatically monitor the technical condition of bearings during operation [10-13]. A significant drawback of this method is the need for complex processing of the vibration signal, resulting in low diagnostic accuracy. A significant drawback of the vibration diagnostic method is the free propagation of mechanical vibrations from various sources throughout the machine's structural elements. Furthermore, filtering the diagnostic signal from a specific bearing—the object under diagnosis—is particularly challenging.

Another diagnostic method is temperature, which allows the bearing assembly's technical condition to be assessed based on its heat generation [14-16]. Temperature diagnostics, like vibration diagnostics, are based on measuring the

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level of energy loss in the bearing due to friction. The advantage of temperature diagnostics lies in the simplicity of temperature measurement and the ability to automate the technical diagnostic process. The temperature of the bearings being diagnosed is affected by ambient temperature and by the temperatures of other heat sources in the immediate vicinity of the bearings. The influence of these factors must be taken into account when developing digital twins.

Developing a model of the relationship between the operating processes of the bearing under diagnosis and its thermal state can enable the application of digital thermal diagnostics, and such models can further serve as digital twins of the actual bearings being diagnosed.

The aim of the study is to justify the use of digital twins of bearing assemblies for their automatic diagnostics.

2. MATERIALS AND METHODS

The bearing assemblies of a KAMAZ 6x4 vehicle, installed in the mid- and rear-axle gearboxes, were used as the study subjects.

The temperature distribution in the bearing assembly was analyzed using the APM FEM application in KOMPAS-3D V 18.1 software. An INSTRUMAX PIRO-330 non-contact infrared pyrometer (emission coefficient of 0.95, measurement accuracy of ±2°C) and a UTi260B thermal imager (infrared emissivity of 0.95, measurement accuracy of ±2°C) were used to measure temperature. The calculations utilized methods of theoretical mechanics and thermodynamics.

3. RESULTS AND DISCUSSION

When implementing digital thermal diagnostics technology, automatic temperature-measurement and fault-signalling devices operate on a digital twin of the unit under diagnosis. Fig. 1 shows the structural diagram of the digital twin.

In the structure of the digital twin of a bearing assembly, the initial elements are design factors (material, shape, dimensions), process factors (lubricant properties), and operational factors (nominal loads). Based on the nominal loads, the friction zone temperature Θ_F^{min} can be determined using analytical relationships presented in some sources [17-19]. The maximum permissible temperature of the lubricant used corresponds to the friction zone temperature Θ_F^{max}. Based on the design factors, a three-dimensional finite element model of the bearing assembly is created and loaded with the friction zone temperature (Θ_F^{min}; Θ_F^{max}), as well as the ambient air temperature Θ_0, and temperature loads from other sources Θ_N. As a result of calculating the temperature distribution in the finite element model, the value of the proportionality coefficient of the finite element model, *k*, is obtained.

The finite element model's proportionality coefficient *k* characterizes the relationship between the friction zone temperature and the diagnostic temperature Θ_D.

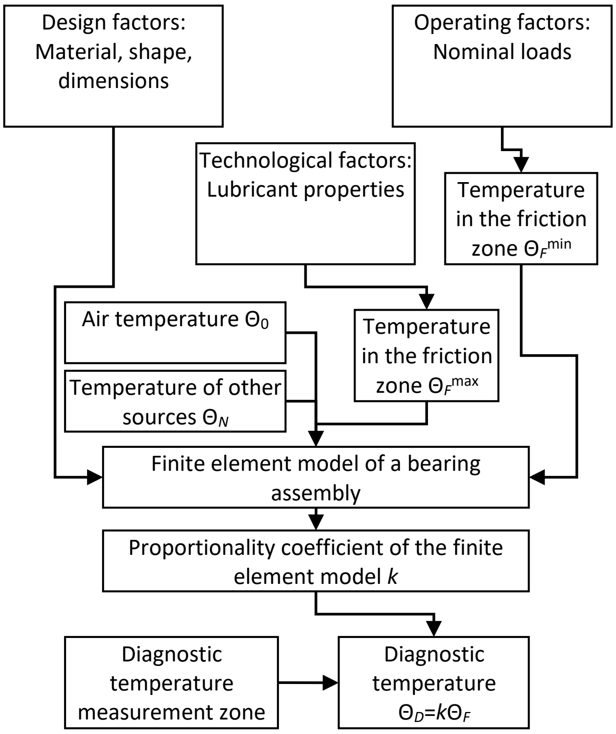


Fig. 1. Structural diagram of a digital twin

Fig. 2 shows an example of the relative positions of the diagnostic temperature Θ_D and the friction zone temperature Θ_F as functions of the design factors F_K, process factors F_T, and operational factors F_E.

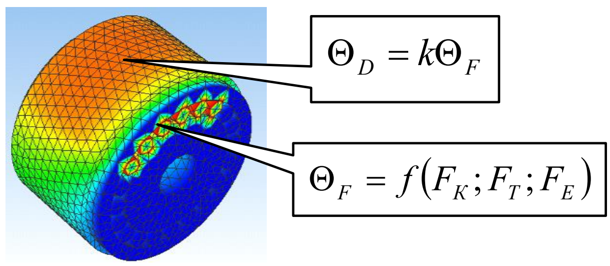


Fig. 2. Location of temperature zones in the friction zone and diagnostic temperature

The diagnostic temperature had to be measured in a special zone, the selection of which is based on maximizing diagnostic accuracy. The diagnostic zone is selected based on an analysis of the surface thermogram of the operating bearing assembly, based on three criteria: 1) maximum proximity to the bearing's loaded zone; 2) maximum temperature in the diagnostic zone; 3) maximum distance from other heat sources.

For diagnostic purposes, temperature was measured using contact thermometers, infrared pyrometers, and thermal imagers, as well as a specially designed device – a transmission fault recorder. A block diagram of this device's operation is shown in Fig. 3.

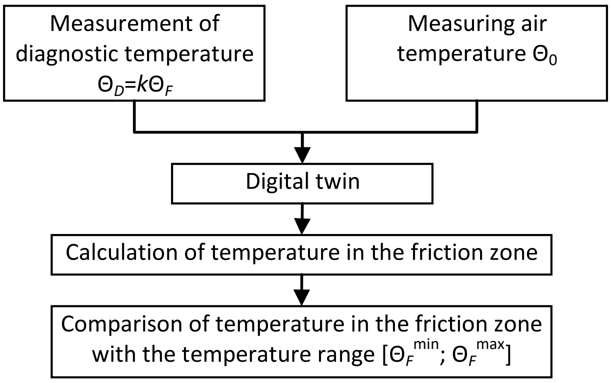


Fig. 3. Structural diagram of the transmission fault recorder operation

Thus, the transmission fault recorder automatically measures the diagnostic temperature and the friction zone temperature. Then, based on the digital twin data, the recorder calculates the friction zone temperature of the bearing being tested and compares the resulting value against a preset temperature range, from the minimum to the maximum friction zone temperature. If the calculated value falls within this range, the recorder triggers an alarm, indicating that the bearing is in a critical condition. If the calculated friction zone temperature exceeds the maximum temperature determined by the lubricant properties, this indicates an emergency operating mode for the bearing and impending failure.

Existing automatic temperature-based diagnostic devices use only one measured value—temperature. The use of programmable microcontrollers allows for measuring and monitoring not only the temperature but also the rate of its increase.

The digital transmission fault recorder is based on the DD1 microcontroller with an ATmega328 processor (Fig. 4). Temperature sensors DD2 and DD3 (TMP36) are used: one as the main sensor and the other for measuring air temperature. Capacitors C1 and C2 (0.1 µF) are included in the sensor power supply circuit. Two LEDs (VD1 and VD2) are used for indication, with 1 kOhm current-limiting resistors (R1 and R2) providing more informative indication: one LED lights when the critical temperature is reached, and the other when the critical speed is reached. An active buzzer (BF1) is used for additional indication.

Software was developed for the transmission fault recorder, and laboratory and operational testing were conducted.

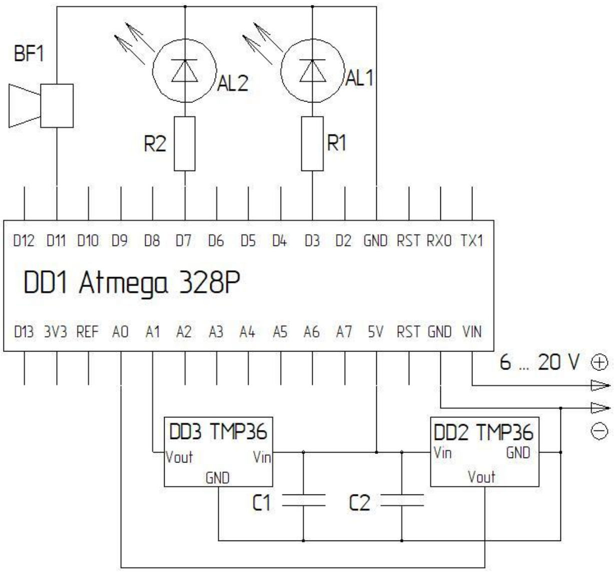


Fig. 4. Schematic diagram of the transmission fault recorder

The microcontroller board is equipped with a built-in voltage regulator, allowing operation from a direct current (DC) supply of 6 to 20 V. The recorder can be powered from the on-board electrical system of a vehicle, tractor, or combine. It can also be powered independently from a 6F22 battery. Current consumption measurements showed 16.3 mA, providing up to 30 hours of battery life with a 0.5 Ah battery.

The recorder's rate of temperature change is the derivative of temperature with respect to time. During testing, a sharp increase in the rate to 5.9°C/min was observed (Fig. 5), due to voltage drift in the device's electronic circuit and temperature sensors. The temperature sensor's measurement error is ±0.5°C, which is typical for normal operation, as observed with many similar temperature sensors.

To solve this problem, it is necessary to optimize the time interval between two measurements. When the time interval was set to 1000 seconds, speed fluctuations did not exceed 0.092°C/min, which is acceptable for practical use of the recorder and ensures the absence of false alarms.

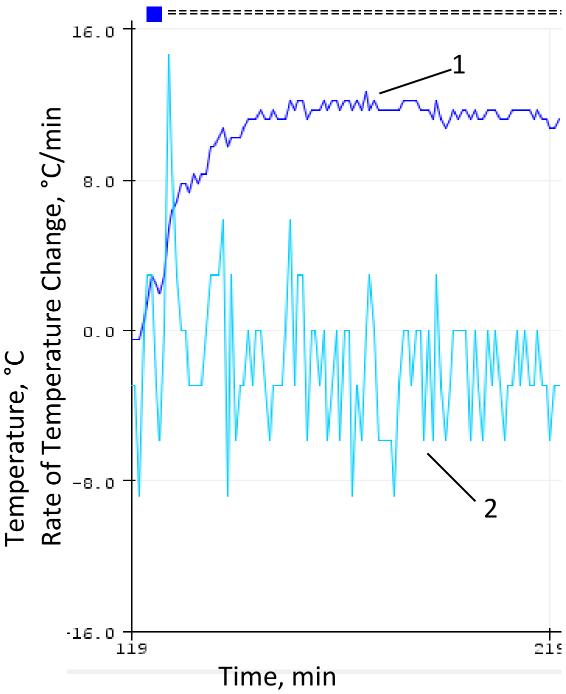


Fig. 5. Testing the recorder at a time interval of 10 s: 1 - Temperature graph; 2 - Temperature change rate graph

Fig. 6 shows a transmission component fault recorder equipped with a diagnostic temperature sensor and an air temperature sensor. The recorder is equipped with visual and audible alarms to indicate a fault condition.

Fig. 6. In-cab transmission fault recorder for a combine harvester

A comprehensive study of the force and kinematic characteristics of the bearing loads on the transmission bearing assemblies of a KAMAZ 6x4 vehicle was conducted. A fragment of the study on creating digital twins of the vehicle's rear axle bearing assemblies is presented here. The location of the rear axle bearings is shown in Fig. 7.

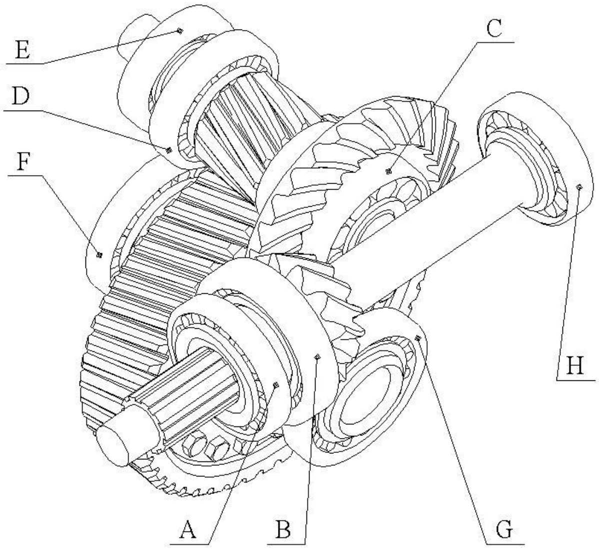


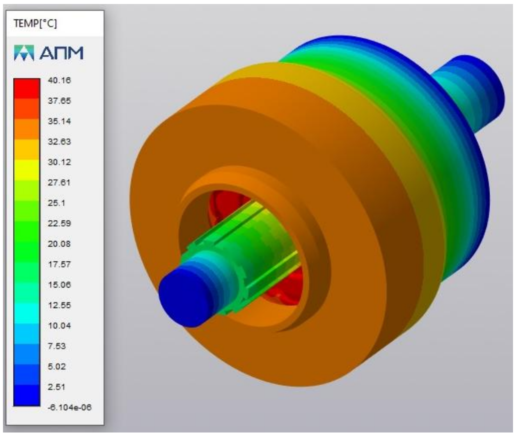
Fig. 7. Rear axle bearing arrangement

Based on the kinematic and force-load data for each bearing, taking into account the statistical share of transmission operation in each gear, and an analytical model [17], the friction zone temperatures Θ_F were calculated.

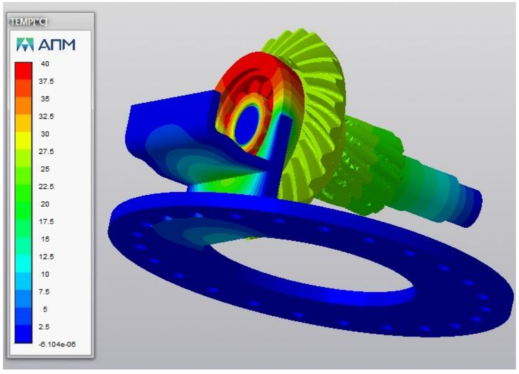
A three-dimensional finite element model was created for each bearing assembly, and, taking into account the selected diagnostic temperature measurement zone, the proportionality coefficients k of the model were determined. To calculate the k coefficients, simplified three-dimensional models of the bearing assemblies were created, and temperature loads were then applied to them. In the APM FEM application, the friction zone temperature Θ_F was applied to the bearings' rolling elements. To simulate the temperature gradient on the surfaces of the bearing assemblies, a temperature of 0°C was applied to the surfaces obtained by separating the assembly from the transmission unit. Fig. 8 shows examples of finite element models of bearing assemblies with fragments of the gearbox housing and other components.

Using computer analysis of temperature distribution maps, diagnostic zones were selected based on the three conditions described above.

The temperature field modeling was performed multiple times for each component, with the temperature in the friction zone varying from 0°C to 200°C. Fig. 9 shows the results of the research that established the relationship between the diagnostic temperature and the temperature in the friction zone.



a)



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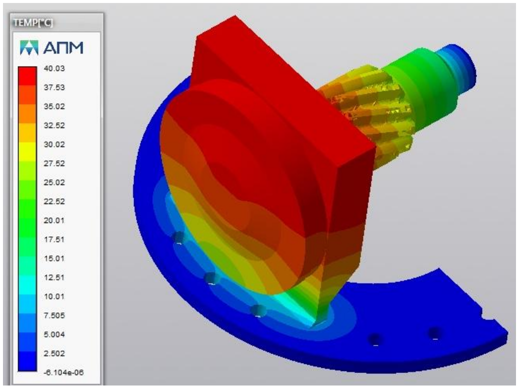

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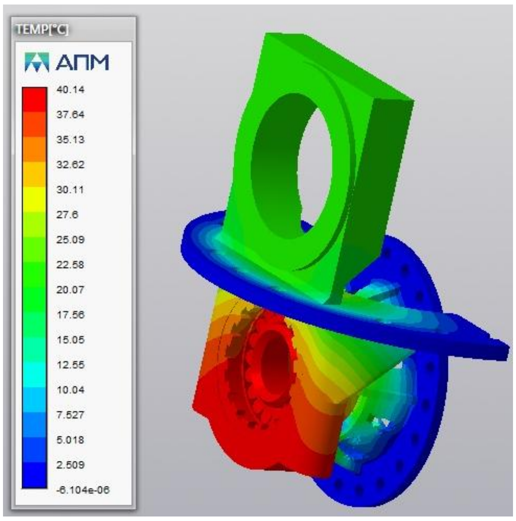

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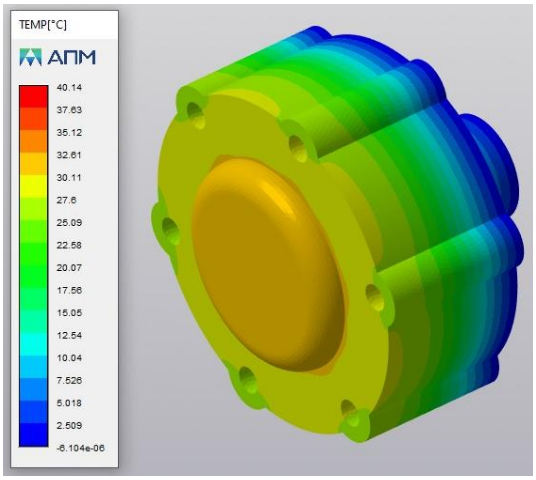

e)

Fig. 8. Temperature distribution maps of bearing assemblies: a) Bearings A and B; b) Bearing C; c) Bearings D and E; d) Bearings G and F; e) Bearing H

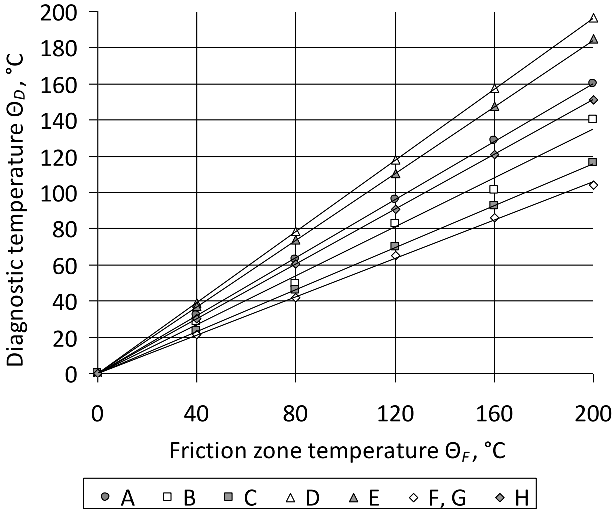

Fig. 9. Graphs for determining the proportionality coefficients of finite element models

A summary of the research results – the digital twin data array is presented in Table 1. An analysis of Table 1 shows that the calculated temperatures in the friction zone do not exceed the lubricant's maximum temperature, except for bearing C. The temperature increase is insignificant; furthermore, the rear axle gearbox mechanisms are lubricated with TAD-17 transmission oil (GOST 23652-79), which facilitates effective heat dissipation. The data from Table 1 can be used to monitor the technical condition of bearings. For example, if the measured temperature on the surface of the rear axle gearbox housing, taking into account the ambient air temperature in the area of bearing A, is compared with the data from its digital twin, a conclusion can be drawn about its technical condition. Thus, if the measured temperature is subtracted from the ambient air temperature and the resulting value exceeds 68.5°C, the bearing is generating excessive heat and is in a faulty condition. If the lubricant temperature (104°C) is exceeded, this clearly indicates a malfunction—bearing wear or insufficient transmission oil—and requires replacement.

Table 1. Digital twin data of bearings

Bearing (Fig. 5)	Temperature at nominal loads, °C		*k*	Maximum temperature of lubricant, °C	
	Θ_F	Θ_D		Θ_F	Θ_D
A	85.6	68.5	0.80	130	104
B	85.6	57.4	0.67		81.7
C	**132.3**	76.7	0.58		75.4
D	65.1	63.8	0.98		127.4
E	65.1	59.9	0.92		119.6
F	49.7	26.3	0.53		68.9
G	38.1	20.2	0.53		198.9
H	21.0	16.0	0.76		98.8

Fig. 10 shows a thermal image of the rear axle in the area of the body surface corresponding to support A.

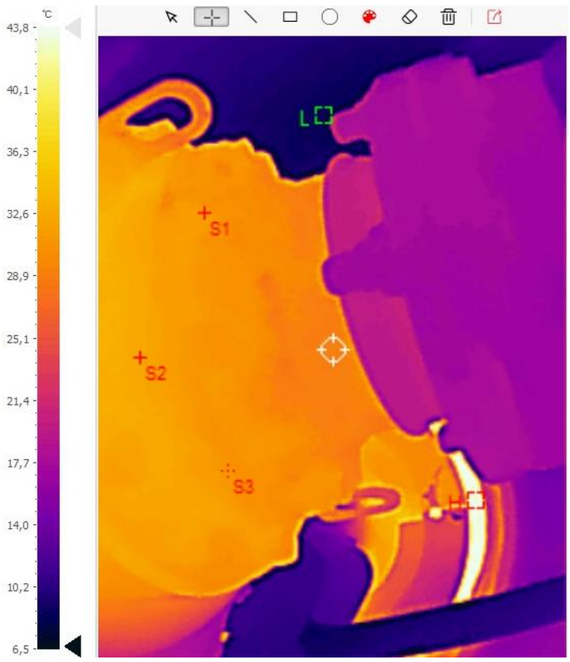

Fig. 10. Thermogram in the support zone A

The measured temperature of 21.2°C in Fig. 8 does not exceed the diagnostic temperature at nominal loads.

Based on the conducted research, practical recommendations can be proposed for the technical diagnostics of bearings. A transmission fault recorder programmed with digital twin data of the bearings can be used to diagnose rear axle bearings. Furthermore, technical diagnostics can be organized using existing measurement tools. This requires periodic manual monitoring of the temperature state of transmission components and assemblies immediately after stopping the transmission, which was previously operating at nominal loads.

Infrared pyrometers or thermal imagers can be used as measuring tools. Temperature measurement can also be organized using irreversible thermal indicator stickers that change color as the temperature rises. However, in this case, the influence of ambient temperature becomes difficult to account for.

To practically implement digital twins in diagnostics, it is necessary to mark the zones for measuring diagnostic temperature. These zones are determined by computer analysis of temperature distribution maps based on the three conditions described above. Figs. 11 and 12 show the rear axle differential with marked zones for measuring bearing temperature.

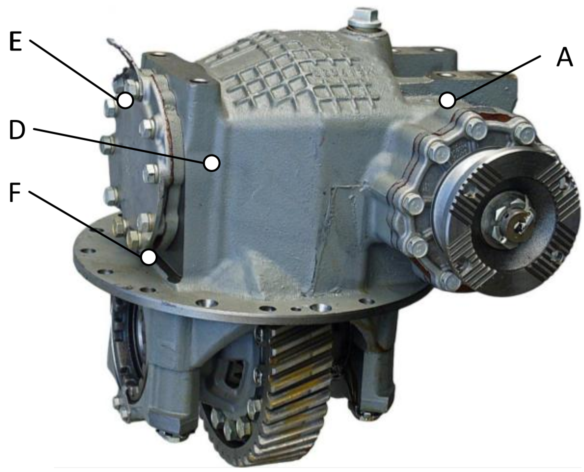

Fig. 11. Rear axle gearbox with markers for bearings A, D, E and F

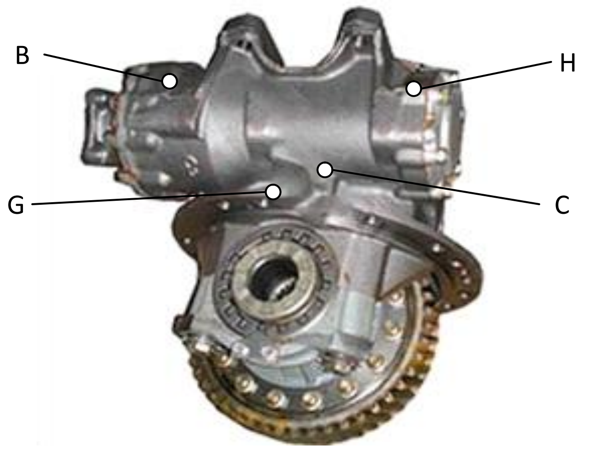

Fig. 12. Rear axle gearbox with markers for B, C, G and H bearings

The areas shown in Figs. 9 and 10 are marked with a dark matte color to improve the accuracy of measurements with infrared pyrometers and thermal imaging cameras, as their operation requires a surface with minimal reflectivity and high emissivity.

Similar studies on the development of heat generation models for rolling bearings and gear transmissions have been conducted by other scientists and yielded comparable results [20-22].

4. CONCLUSION

Based on the conducted research, the following conclusions can be drawn:

1. Timely diagnostics of bearing assemblies are essential for maintaining operational reliability.

2. Developing a model for the relationship between the operating processes of the bearing being diagnosed and its thermal state will enable the application of digital thermal diagnostics technology, and such models will serve as digital twins of the actual bearings being diagnosed.

3. During the development of digital twins of the rear axle gearbox bearings, temperature values in the friction zone and proportionality coefficients of finite element models were obtained based on the nominal load criterion and lubricant properties.

4. Thermal imaging demonstrated the practical applicability of digital thermal diagnostics technology and the developed digital twins.

5. Practical recommendations are proposed for technical diagnostics of bearings using infrared pyrometers, thermal imagers, temperature indicator stickers, and a transmission fault recorder.

Future research will focus on the development, creation and testing of a multi-channel transmission fault recorder, which will allow simultaneous monitoring of multiple transmission components based on certain critical temperature values and temperature rise rates.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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