Development, research and design of a diagnostic system for measuring the course of temperatures, vibrations and noise

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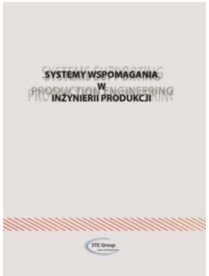

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Abstract: The development of scientific and technical progress in measuring and microprocessor technology, advances in artificial intelligence methods give impetus to the development of technical diagnostics of mechatronic systems. In mechatronic systems, electrical drives are based on asynchronous motors, DC motors, synchronous and stepper motors, and mechanical drives are based on gearboxes. Failure of motors and gearboxes leads to equipment shutdown, continuous production and financial losses of the company. Therefore, tools are needed to monitor the current status of devices.

Keywords: diagnostic system, DC motors, actuators, robot

INTRODUCTION

Drive monitoring can be defined as the process of measuring and analyzing the operating characteristics and diagnostic parameters of the drive so that the results of the analysis can be used to determine the current technical condition of the drive and predict its repair and prevent accidents.

An unexpected breakdown or failure of the equipment can lead to a serious accident and financial loss for the business. Currently, the use of intelligent drive protection and diagnostics systems is quite relevant, which allow the diagnosis of geared motors, taking into account their performance and construction.

In order to clarify the research objectives, an information and patent search (hereinafter referred to as IPR) was carried out.

IPR should be carried out in order to identify ready-made analogues, methods, tools, theoretical and practical parts in a given field, on a given topic, etc. On the basis of the IPR, a clear conclusion on this issue was created.

The IPR on the topic "Development of a diagnostic system for engines in heavy industry" was intended to determine:

1. Companies dealing with this problem
2. Similar analog diagnostic equipment for engines in heavy industry
3. Patents for diagnostics of electric motors and gearboxes

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4. Existing diagnostic methods and tools.

MATERIAL AND METHODS

Overview of existing methods and tools for diagnosing electric motors and gearboxes

In the development of a diagnostic system for geared motors in heavy industry, an information and patent search was first conducted to identify and determine the need for this development. When conducting an information and patent search, several similar analog devices (see Table 1) with similar characteristics were found, but no such device was found for which the diagnostics of such parameters as vibration, current and temperature were simultaneously carried out.

Table 1 Analog equipment diagnostics of electric motors and gearboxes

AMTest-2 - device for diagnosing the state of AC and DC electrical machines 	Portable vibration diagnostic devices.Vibration analyzer ONYX (Diamech) 	MDR - partial discharge monitoring system for the isolation of stators of generators and electric motors 	IDO-05 electrical machine winding fault indicator 
Universal multi-channel portable vibration signal analyzer PULSE (Brühl and Kjær) 	Portable tester for express diagnostics of the technical condition of bearings. Measuring device-vibration analyzer BALTECH VP-3450 (shock pulse method) 	Vibration meter Vibrotest-MG4 	IDP-05 electrical machine bearing failure indicator 

During the development of the diagnostic system for monitoring electric motors, a review of existing methods and tools for diagnosing electric motors and gearboxes was carried out. The main points of this review were:

1. Carrying out analysis of faults of electric motors and gearboxes
2. Carrying out an analysis of diagnostic methods for electric motors and gearboxes
3. Determination of the main technical means for diagnosing electric motors and gearboxes

Analysis of faults in electric motors and gearboxes

Electric motors are produced in different types. This post is about 1 type of electric motors:

- Asynchronous motors with short rotor

Based on this, we can highlight the main, frequently occurring errors of these engines:

1. Malfunctions of the electromagnetic nature of asynchronous electric motors

- gap eccentricity (2 types)
- rotor winding failure
- stator winding failure

2. Malfunctions in the power supply

- asymmetry of the supply voltage
- non-linear voltage distortion
- phase imbalance
- faults in the excitation voltage source
- malfunctions of the starting short-circuit winding
- overcurrent

3. Transmission errors

- errors in the shaft and gearing
- misalignment of the shaft (gear wheel),
- failure of individual teeth of one of the gears involved in the engagement
- gear failure, gear lubrication failure

4. Bearing errors

4.1 Malfunctions of rolling bearings

- general bearing wear
- shocks in the bearing
- insufficient lubrication
- deformation of the outer ring
- distortion of the inner ring
- sliding in the seat
- uneven radial interference
- wear of the outer ring
- shells on the outer ring
- wear of the inner ring
- shells on the inner ring
- chips on rolling bodies
- wear of the separator

Defects of an electromagnetic nature

When insulating electrical machines, the main cause of damage is thermomechanical effects. Under their influence, as well as vibrations at elevated temperatures, mechanical damage to the insulation occurs in the form of delamination or cracking. This causes the appearance of partial discharges inside the dielectric in gas inclusions – the stage of the appearance of a defect. It is the failure that ultimately causes the insulation to break down. In the final stage, when the limit state is reached, a transition to the thermal form of breakthrough formation is possible. Such disturbances are therefore indicators of the number and degree of defect development. Depending on the location of the defect, carbonization of the insulation may occur, leading to an increase in the leakage current. Leakage current, can be measured with direct current by the value of the insulation resistance R. Discharges (or leakage current) along the current flow path can vary depending on the type of insulation damage and the location of the channel:

- phase – earth – in the event of a fault through such a channel, as a rule, there is no significant damage to the winding, the fault is determined by all test methods;
- phase – phase – failure is accompanied by serious damage, the fault is detected using all test methods;
- electrical discharge (or breakdown between elementary conductors) – breakdown through this channel leads to significant damage, the fault can only be detected with operating voltage.

Diagnostics of the insulation condition of rotating machines is relatively well established. In this case, the values of the test voltage do not exceed (1.0...1.5)U, where U is the operating voltage, for both direct current and alternating current. For larger repairs, tests using voltage from an external source are used. Diagnostic features are:
the insulation resistance of the winding when the DC voltage rises to U;

- absorption coefficient (I15/I60sec) and polarization index (I1min/I10min);
- the dependence of the dielectric loss tangent on the frequency when measured at low voltage and the dependence of the dielectric loss on the applied voltage when this voltage rises to 1.1 U;
- Discharge characteristics, especially discharge dynamics when analyzing the entire flow of impulses at operating voltage over a long period of time (6...10 months).2.3 Malfunctions in the power supply.

Malfunctions in the power supply

The main faults of the power supply network are: asymmetry of the supply voltage, non-linear voltage distortion, phase unbalance, faults of the excitation voltage source, faults of the starting short-circuit winding and current overload.
Vibration frequencies and current components as diagnostic features of faults of asynchronous motors with short-circuited armature and supply voltages are shown in Table 2.

Table 2 Vibration frequencies and current components as diagnostic symptoms of faults of asynchronous motors with short-circuited armature and supply voltage

The name of the fault	Increase in low frequency vibrations	Increase in high frequency vibrations	Current surge	Note
Faults in the stator winding	$2f_1;(R,T)$	$kf_{z_{rt}} \pm 2f_1$	f_1 (3phases)	-
Errors in the rotor winding	$kf_{rt} \pm 2k_1Sf_1$ (R,T)	$kf_{z_{rt}} \pm 2k_1Sf_1Z_{rt}$	$f_1 \pm 2kSf_1$	-
Static gap eccentricity	$2f_1;(R,T)$	$kf_{z_{rt}} \pm 2f_1$	-	-
Static eccentricity with tooth saturation	$2f_1;(R,T)$ $2(k+1)f_1;(R,T)$	$kf_{z_{rt}} \pm 2k_1f_1$ $k_1 \geq 2$	$(2k+1)f_1$ $z_{rt}f_{rt} \pm f_1$	-
Dynamic eccentricity spaces	$f_{rt};(R)$ $2f_{rt};(T)$ $2f_1 \pm f_{rt};(R)$	$kf_{z_{rt}} \pm k_1f_{rt}$ $kf_{z_{st}}$	-	-
Dynamic eccentricity with tooth saturation	$kf_{rt} \pm 2k_1f_1S/p;$ (R,T) $2f_1 \pm k_1f_{rt};(R)$ $2kf_1 \pm k_1f_{rt};(T)$	$kf_{z_{rt}} \pm k_1f_{rt}$ $kf_{z_{st}} \pm k_1f_{rt}$ $k_1 \geq 3$	$kf_{\hat{a}\eth}$	-
Asymmetry of charging voltage	$2f_1;(T)$	-	$f_1(3\hat{o}\grave{a}\c{c}\hat{u})$	All asynchronous motors with the same network
Nonlinear voltage distortion	$6kf_1;(R,T)$	$kf_{z_{rt}} \pm 4k_1f_{rt}$		All asynchronous motors with the same network

where: f1 – supply voltage frequency (Hz); frt – rotor rotation frequency (Hz); fzrt – frequency of rotor teeth (Hz); fzst – frequency of stator teeth (Hz); Zrt – number of rotor teeth; Zst – number of stator teeth; R, T – radial and tangential directions of vibration excitation; LF – low frequency vibrations; HF – high frequency vibrations; S – rotor slip; k, k1 – integers.

TRANSMISSION ERRORS

To find out the indicated errors of the gear wheel, it is necessary to measure the vibrations (in the direction radial to the axis of rotation of the shaft) and the temperature of its bearing units. If it is possible to operate the gearbox in several load modes with a simultaneous change in the rotational speed of the drive, they should be limited to a small number (no more than 2/3) of modes with a high rotational speed and when measuring in each mode, similar to the rotational speed of the driving (driven) shaft. This makes it possible to create trends in the development of defects for each of the selected modes and perform independent diagnostics on each. In gearboxes that have two directions of rotation, it is necessary to measure the vibration (and temperature) of the bearing units for both directions of rotation, and two gearboxes with different directions of rotation should be entered into the database instead of one, thus creating different measurement modes. This makes it possible to separate individual tooth errors, which occur mainly when the gear is turned in one direction, and bearing errors, which occur (often with small changes) when turning in both directions. For the considered gear errors, vibrations can increase in wide frequency bands, which corresponds to:

- rotation speed of one of the shafts (shaft or gear bearing errors),
- frequencies below half the rotation speed of the low-speed shaft (simultaneous errors in the teeth of both gears),
- the second harmonic of the rotation speed of one of the shafts (non-parallelism of the shafts or misalignment of the gears),
- harmonic oscillations with a high multiple of the speed of rotation of one of the shafts (errors in the teeth of the corresponding gear wheel),
- tooth frequency, as well as its second and third harmonics (deteriorated engagement quality, including gear misalignment or bearing wear),
- the frequency range of higher harmonic teeth, as well as high frequencies (errors of engagement, but provided that there is no significant increase in vibration at harmonic rotational speeds).

High-frequency vibrations of gear bearing units can increase due to defects in the bearings themselves and due to defects in the gearing and due to defects in the couplings. In the case of bearing failures (and, as a result, also of its lubrication failures), not only the RMS, but also the peak value of high-frequency and ultrasonic vibrations increases, especially in the case of a single, defective bearing. In the case of gear failures, only the rms value of high-frequency and ultrasonic vibrations of most drive and driven shaft bearings is usually increased, and in the case of clutch failures, most of the drive motor bearings and the mechanical transmission shaft connected to it are increased. When the gears (and consequently the bearings) are overloaded due to errors in the manufacturing and installation of the gear, the temperature of most gear bearings can increase. In the case of gear overload and gear lubrication malfunctions, an increase in the temperature of the transmission lubricant (lubricant temperature in the crankcase) is also possible

BEARING ERRORS

There are two types of bearings: rolling and sliding. This article deals only with rolling bearings.Errors of rolling bearings.

The service life of the main part of the power-mechanical devices of small and medium aggregate power is mainly determined by the service life of the rolling bearings. They are not and are not the most economical method of assessing the condition of bearings is vibration analysis. All errors in the production, assembly and operation of bearings associated vibration signal and have different diagnostic features, their correct assemblies of the complex make it possible to detect and separate the types of errors at the initial stage of development Although the condition is determined. bearings and provide a fairly reliable forecast. The vibration parameters of units with rolling bearings are largely determined by the design devices of the bearing and the specific unit (for example, with the horizontal and vertical position of the rotor, the static load ratio, etc.). In addition, the vibration of rolling bearings affecting three groups of factors: the effect of non-linear bearing stiffness on the vibration of the supports, the effect of errors in the manufacture and assembly of unit bearings, and the effect of operational errors (destruction from material fatigue, damage from reduced wear, damage caused by changes in clearances and bearings).

The last two groups of factors include all kinds of rings, rolling bodies and cages, violation and weakening of stiffness in the bearing surfaces and clearances exceeding nominal values, misalignment of bearings, insufficiency, stoppage or change in the quality of lubrication, the occurrence of which can be interconnected. For example, fatigue locking of rolling bearings manifests itself by peeling off the material of the raceways and rolling elements and can occur as a result of too high a load. The failure of the cage occurs due to the failure of the bearing assembly, the application of large axial loads, the breaking of the raceways, fatigue failure, etc. Slippage of the inner ring of the bearing relative to the rolling elements leads to wear of the rolling surfaces. Lack of lubrication and low quality lubrication lead to floating of the rolling elements, coating of material on the surface of the tracks and wear of the cage.

The main frequencies of vibration components due to rolling bearing failures are shown in Table 3. The effect of nonlinear bearing stiffness on bearing vibrations.

Table 3 Frequencies of the main vibration components for faults in rolling bearings with a rotating inner ring and a stationary outer ring

Frequency	Type of manufacturing defect	Type of fault	Defect type wear
Fr	Misalignment between shaft and inner ring		Uneven wear of the inner ring
2Fr	Ovality of the inner ring	Misalignment of the inner ring	Uneven wear of the inner ring
kFr	Inner ring facet		Wear (including uneven wear), craters, cracks in the inner ring
The vibrations caused by the errors listed in the previous three rows of the table appear at the frequency of the rotor and its harmonics and are very difficult to separate from other causes of vibration at these frequencies.			
Fcg a/alebo kFcg	The size of the rolling elements		Uneven wear of rolling elements, fatigue peeling
k1F0±k2Fcg	Appears in static axial load bearings when the outer ring is misaligned and...*		
k(Fr-Fcg)	Appears in angular contact and thrust bearings when the inner ring is misaligned and...*		
*	Dimensions of rolling elements		Uneven wear of rolling elements
kFr01 a/alebo k1Fr01± k2Fcg	Violation of the shape of the rolling elements		Failures (uneven wear, chips) of rolling elements
k1Fr01± k2Fr	Occurs in bearings with static axial load when the inner ring is misaligned		

	and there are defects on the rolling elements (distortion of shape, uneven wear, chips)		
F0		Forced shaft alignment	
2F0		Misalignment of the outer ring	
kF0 a/alebo k1F0± k2Fcg	Uniformity of rolling elements		Faults (overflows, cracks, wear) of the outer ring
k1F0± k2Fr	Occurs in static axial load bearings when the inner ring is misaligned and the outer ring has defects (underflow, cracks)		
Frequency	Type of manufacturing defect	Type of assembly defect	Defect type wear
Fi		Violation of shaft alignment	
2fi		Perkos inner ring	
kFi a/alebo kFi± k2Fr			Faults (overflows, cracks, wear) of the outer ring
k1Fi± k2(Fr-Fcg)	Appears in bearings with static axial load when the inner ring is misaligned and there are defects (underflow, cracks) in the inner ring		
Ffr01	Violation of the shape of the rolling elements		Violation of the shape of the rolling elements
Ffi	Violation of the shape of the inner track		Violation of the shape of the inner track
Ff0	Violation of the shape of the outer track		Violation of the shape of the outer track
Frro1	Resonance frequency of rolling bodies		

The bearing frequencies listed in the table are determined by the following formulas:

- speed of rotation of the separator;

$$Fcg = 0.5Fr(1-(dr01/dcg)\cos\alpha); \qquad (1)$$

usually $Fcg \approx 0.4Fr$

- frequency of rolling bodies rolling along the outer ring;

$$F0 = 0.5Fr * Zr01(1-(dr01/dcg)\cos\alpha); \qquad (2)$$

usually $F0 \approx 0.4Zr01 * Fr$

$$Fi = 0.5Fr * Zr01(1+(dr01/dcg)\cos\alpha); \qquad (3)$$

usually $Fi \approx 0.6Zr01 * Fr$

$Fr01$ – frequency of rotation of rolling bodies;

$$Fr01 = \frac{d_{cg}}{2d_{r01}} Fr\left[1-\left(\frac{d_{r01}}{d_{cg}}\cos\alpha\right)^2\right]; \qquad (4)$$

$Ffr01$ – frequency of excitation in case of shape error of the rolling elements:

$$Ffr01 = 2Fr\left(\frac{{d_{cg}}^2 - {d_{r01}}^2}{{d_{\hat{e}01}}^2}\right); \qquad (5)$$

Ffi – excitation frequency when changing the shape of the internal track:

$$Ffi = 0.5Fr * Zr01\left(\frac{d_{cg} + d_{r01}}{d_{cg}}\right); \qquad (6)$$

$Ff0$ – excitation frequency when changing the shape of the outer track:

$$Ff0 = 0.5Fr * Zr01\left(\frac{d_{cg} - d_{r01}}{d_{cg}}\right); \qquad (7)$$

Frro1 – resonant frequency of rolling bodies:

$$Ff0 = \frac{0.848E}{d_{r01}2\rho}; \qquad (8)$$

where:
Fr – frequency of rotation of the inner ring (rotor) of the bearing;
Zro1 – number of rolling elements in the bearing;
dr01 – diameter of the rolling elements in the bearing;
dcg – diameter of the cage (pitch circle, circles passing through the centers of the rolling bodies) of the rolling bearing;
α is the contact angle between the bodies and the raceways in the bearing; k, k1, k2 Є N;
E – modulus of elasticity; ρ is the specific density of the beads

EFFECT OF MANUFACTURING AND ASSEMBLY ERRORS ON VIBRATIONS

Errors in the production of rolling bearings are deviations of the geometric dimensions and shape of bearing parts from the design (non-observance of manufacturing tolerances of rings, cages and rolling bodies, ovality and faceting of tracks and rolling bodies, uniformity of rolling bodies) and violation of the roughness of the rolling surface.
Errors in the assembly of the bearing assembly are the appearance of a radial overlap in the bearing, misalignment of the inner and outer rings of the bearing, forced centering of the shafts when connecting the components of the unit, and misalignment of the couplings.
The characteristic frequencies of manufacturing and assembly errors are shown in Table 2.
If there is no radial clearance in the bearing due to misalignment or rotor errors, vibrations will appear containing combinations of frequency components caused by all the errors present in the bearing, and the vibration level caused by errors in the outer ring will increase. Radial bearings with an axial load are characterized by the absence of radial play and high sensitivity to the quality of assembly of the bearing assembly. Small deformations of the rings, which always appear during bearing assembly, redistribute the load of the rolling elements mainly to two opposite points of the ring. Radial interference caused by axial loading can lead to the occurrence of combined defect frequencies.

Analysis of diagnostic methods for electric motors and transmissions

Currently, there are many methods for diagnosing electric motors. It all depends on what criteria should be used to diagnose the engine. In this topic, electric

motor diagnostics were performed according to current, temperature and vibration criteria. In this context, diagnostic methods were analyzed:
- method of vibration diagnostics;
- wattmetric method;
- temperature method

Vibration diagnosis method

There are also many methods based on vibration diagnostics. But one of the most common methods is the method based on spectral diagnostics or diagnostics based on the spectra of vibration signals (Abramov, Bozek, 2015). This method of diagnosing defects in rotating equipment is usually considered the main and most effective by practical diagnosticians. There are several important reasons to agree with this view. First, the characteristic features of most defects in rotating equipment can be easily distinguished in the spectra of vibration signals. Second, for more than half of the diagnosed defects, the set of characteristic harmonics in the spectrum is unique. In the case of other defects, the sets of characteristic harmonics may overlap each other in terms of harmonic composition and ratio, but if the diagnostician has sufficient practical experience, these defects can be reliably separated.

The third group, which is assigned the "unit" level, contains errors for the diagnosis of which it is necessary to carry out vibration measurements on several or even all mechanisms of the controlled unit. This group also includes errors in the foundation of the unit, which is usually located under all mechanisms. In this case, the foundation itself can be considered a separate element of the controlled unit, its integral part.

This division of defects into three levels fully reflects a real practical algorithm for a specialist to perform the necessary diagnostic work.

Method of eddy currents

Eddy current methods are based on the analysis of the interaction of the external electromagnetic field with the electromagnetic field of the eddy currents induced by the excitation coil in the electrically conductive test object. The density of eddy currents in the object depends on the geometric and electromagnetic parameters of the object, as well as on the relative position of the measuring eddy transducer (EMT) and the object. Induction coils (one or more) are usually used as a transducer. A sinusoidal (or pulsed) current acting in the ETP coils creates an electromagnetic field that induces eddy currents in an electrically conductive object. The electromagnetic field of the eddy currents acts on the converter coils, induces an EMF in them or changes their total electrical resistance. By recording the voltage on the coil terminals or their resistance, information is obtained about the properties of the object and the position of the transducer relative to it (Abramov, Nikitin, and others, 2014a).

One of the properties of eddy current methods is that the transducer signals humidity, pressure and contamination of the gaseous environment, radioactive radiation and contamination of the surface of the tested object with nonconductive substances has practically no effect. This determines both the advantages and difficulties of implementing eddy current methods.

Temperature method

The temperature method consists of determining the temperature of both the engine itself and its individual parts. There are various methods to determine engine temperature. The main ones are the direct method of motor control by heating, the method of average losses and the method of equivalent values (Abramov, Nikitin, and others, 2014). In engineering calculations, the method of average losses and the method of equivalent values are most often used. The essence of the average loss method is to find the average motor losses according to the load schedule of the production mechanism and compare them with the nominal losses. The main quantities of the method of equivalent quantities are: current, power, torque.

DESIGN OF A METHODOLOGY FOR EQUIPMENT DIAGNOSTICS AND ANALYSIS OF THE RESULTS OF GEAR MOTOR PARAMETER MEASUREMENTS

The measurements were carried out in a real company. The subject of diagnostics was 10 geared motors (Figure 1). They are robot drives and are located on the axes of the kinematic pairs of the main and auxiliary robot arms.

Fig. 1 Z68-K4-LA/90L4 gear motor The Z68-K4-LA/90L4 gear motor from Siemens (MOTOX) is designed to rotate the individual arms of the robot

For positioning control, high-precision sensors were installed on the robotic workplace to detect the state of the exact position of the programmed arms. With the introduction of high-precision sensors, PLC and data management system, its accuracy has been improved. The kinematic diagram is in Figure 2.

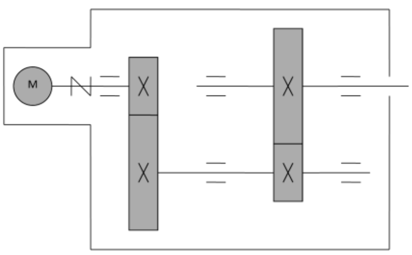
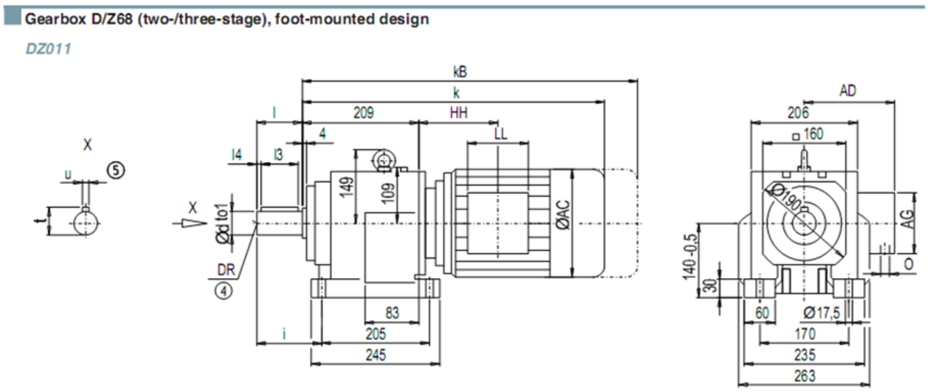


Fig. 2 General kinematic diagram of a geared motor

The structural dimensions of the gear motor Z68-K4-LA/90L4 are shown in Figure 3.



d	to1	l	l4	l3	t	u	i	DR
40	k6	80	5	70	43.0	12	115	M16x36

	Z68		D68						Z68	D68		Weight	
Motor	k	kB	k	kB	AC	AD	AG	LL	HH	HH	O	Z68	D68
LA71	456.0	511.0	474.5	529.5	139.0	146	90	90	103.0	121.5	M20x1.5/M25x2.5	43	45
LA71Z	475.0	530.0	493.5	548.5	139.0	146	90	90	103.0	121.5	M20x1.5/M25x2.5	43	45
LA80	493.0	556.5	511.5	575.0	156.5	155	90	90	102.5	121.0	M20x1.5/M25x2.5	48	50
LA90S	524.0	595.0	542.5	613.5	174.0	163	90	90	102.5	121.0	M20x1.5/M25x2.5	52	55
LA90L	524.0	595.0	542.5	613.5	174.0	163	90	90	102.5	121.0	M20x1.5/M25x2.5	52	55

Fig. 3 Design dimensions of the gear motor Z68-K4-LA/90L4

Selection of vibration measurement points of monitored drives

The informative point and direction of measurement is the one in which the vibration signal excited by the defect is maximal and vibrations of other origin are minimal. The selection of vibration measurement points is governed by GOST (Abramov, Nikitin, and others, 2014b). The installation locations of vibration sensors depend on the characteristics of the machine and the measured parameters. Measurements are made on protruding parts of machines that are freely accessible. It is necessary to make sure that the measurement results correspond to the actual vibrations of the bearing and are not distorted by the influence of local resonances. Measuring points and directions should be chosen so that the measured vibrations carry sufficient information about the dynamic forces acting in the machine. Measurements must be taken in two orthogonal radial directions on each bearing housing or support. The bearing vibration measurement direction can be chosen arbitrarily, but usually horizontal and vertical directions are preferred for a horizontally mounted machine. It is allowed to carry out measurements not in two, but only in one direction using one sensor, provided that this makes it possible to obtain sufficiently complete information about the vibration of the bearing. However, it should be taken into account that the selected orientation of one sensor may not provide the maximum vibration value for a given bearing. Measurements should be made on bearings, bearing covers or other structural elements that are most responsive to dynamic forces and characterize the overall vibration state of the machine. During the in-service inspection, one or two measurements are usually taken in the radial direction (usually horizontal and/or vertical). Operational inspection is performed only with the machine completely assembled on standard supports at the place of its operation (Kravchik, Shlaf and others, 2022).

Methods of installing sensors on the device

High-quality and reliable mounting of the vibration sensor on the surface of the investigated object is one of the most important conditions for achieving accurate and reliable results when measuring vibrations and recognizing the state of equipment. Unreliable mounting of the sensor leads to a decrease in the area of linearity of the amplitude characteristic of the sensor and consequently to a significant decrease in the measuring range of the accelerometer. Therefore, before the first measurement, the installation locations of the sensors should be determined exactly and, if possible, not changed. It is best to mark the installation location with a bright color. The sensor must be in contact with the entire surface of the magnet with the body of the monitored object. The surface where the sensor is connected must be clean and accessible. It should be free of paint and grease to ensure proper measurement of high frequency vibrations. A dirty surface creates a spring effect that lowers the sensor's resonant frequency and reduces high-frequency pulsed energy signals.

DIAGNOSTIC CONDITIONS

The following questions need to be resolved during diagnosis:

- Selection of design parameters that determine the results of the evaluation of the technical condition of the machine;
- selection of diagnostic signs of faults, on the basis of the analysis of which it is possible to estimate the values of structural parameters, that is to carry out diagnostics;
- Selection of the place of installation of the vibration sensor.

The selection of design parameters is usually carried out based on the study of statistical data on failures and is generally determined for the purpose of diagnosis. As design parameters, we take values characterizing the structure of the rotating machine (dimensions of parts, errors in their production and assembly, supports in kinematic pairs, imbalance of rotating shafts, etc.), operating mode (number of revolutions, energy consumption, etc.), as well as external operating conditions, for example load) (All about electric motors, 2022, Bialy, Bozek, Boloz, 2023). All these parameters must affect the sound production in the machine, otherwise their changes could not be reflected in the acoustic signal and could not be measured acoustically.

Measurement recommendations

Vibration measurements at the same point should only be compared if they were taken under the same machine operating conditions and the same sensor installation method. For periodic measurements, sensors are installed at exactly the same points, which are called control (regular) points. It is best to outline the installation location with a bright color. The surface where the sensor is connected must be clean and accessible. It should be free of paint and grease to ensure proper measurement of high frequency vibrations. A dirty surface creates a spring effect that lowers the resonant frequency of the sensor and reduces high-frequency signals. When fixing the sensor to the pin, the surface at the installation location must be flat and the axis of the sensor must be exactly perpendicular to the installation plane. It is necessary to use a lubricant that is applied in a thin layer between the accelerometer and the surface. It creates a rigid, incompressible layer between the sensor and the surface that transmits high-frequency vibrations. When using a magnet, it is better to use ordinary machine oil applied in a thin layer on the surface, it will also help to improve the transmission of high-frequency vibrations.

Measurement methodology

The subject is the most frequently malfunctioning components, asynchronous motors and robot gearboxes.

Vibration measurements should be performed in a frequency range that covers the frequency spectrum of the machine. The width of the frequency range depends on the type of machine (for example, the frequency range needed to assess the integrity of rolling bearings should include higher frequencies than for plain bearing machines). Recommendations for the selection of the frequency range for specific types of machines should be given in the relevant standards (Bozek, Krenicky and others, 2022, Gupalov, Lagutkin, Stanislav, Bozek, Pivarciova, 2023, DIAX, 2017, GOST).

Measured quantity

- deflection of vibrations in micrometers (μm);
- vibration speed in millimeters per second or decibels (mm/s/dB);
- vibration acceleration in meters per second per second (m/s^2).

Values of vibration parameters

The value of the vibration parameter for a specific position and direction of measurement is understood as the result of measurements made using equipment that meets the requirements.

When monitoring the broadband vibration of rotor-type machines, the root mean square value of the vibration velocity is generally used as an estimated parameter because it is related to the vibration energy. However, in some cases it is more appropriate to use other parameters: those related to vibration deflection or vibration acceleration, or peak values instead of square root. In these cases, other criteria must be used, which are not always connected by simple relationships with the criteria for root mean square values of the vibration speed.

Measuring points

Measurements are made on protruding parts of machines that are freely accessible. The measurement results correspond to the actual vibrations of the bearing and are not distorted by the influence of local resonances. Measuring points and directions should be chosen so that the measured vibrations carry sufficient information about the dynamic forces acting in the machine. Measurements shall be made in two orthogonal radial and one axial direction on each bearing cap or support.

The measuring points on the geared motor were determined so that the distance from the source of vibrations - the bearings (or gears, also transmitted through the bearings) to the measuring sensor was minimal and access to these points was free. On the kinematic diagram (Figure 4), the numbers indicate the sources of vibration of the geared motor:

-1,2 – engine vibration sources;

-1'-7' – sources of gearbox vibrations.

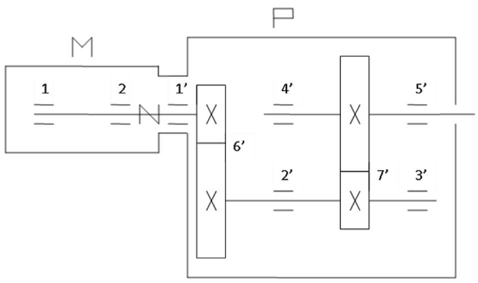


Fig. 4 Kinematic diagram of a motor with a gearbox with the main sources of vibration

The sum of the vibrations of all the internal components of the gear motor, determined by the principle of superposition, is a reflection of the vibrations of the gear motor case. The node closest to the measuring sensor contributes especially to this amount. Therefore, to determine the vibrations on the engine, it is necessary to place the sensor on the engine bearing supports, to determine the vibrations on the gearbox, it is necessary to place the sensor as close as possible to the gearbox bearing supports.

For the developed diagnostic model, we use those values of engine and gearbox vibrations that were maximum during the measurements.

DISCUSSION

Analysis of measurement results for the "vibration acceleration" parameter

The OKTAVA-110A-ECO device was used to measure the vibration acceleration of geared motors.

Several points were selected on the geared motor to which an accelerometer sensor was attached to measure vibration accelerations (Figure 5):

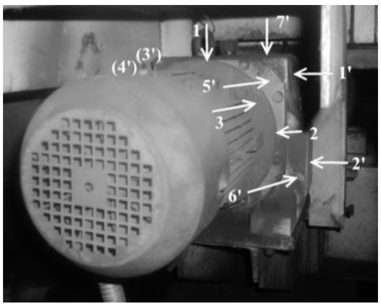


Fig. 5 Image of accelerometer sensor installation locations on Z68-K4-LA/90L4 engine gearbox

- 3 points on the engine;
- 7 points on the gearbox.

The numbers indicate the order of measurements on the engine (1 – vertical, 2 – horizontal, 3 – axis) and the gearbox (1', 2', 3', 4' – horizontal, 7' – vertical, 5', 6' – axis).

The actual vibration acceleration values of the motor in the axial direction were greater than those of the gearbox, and in the vertical and horizontal directions were approximately the same or greater for the gearbox (Table 4 and Figures 6).

Table 4 Values of the overall indicators of the engine and gearbox in three mutually perpendicular directions

Vertical	Motor	Gears...	Horizon	Motor	Gears	Axis	Motor	Gears..
H-1	2403	2365	H-1	2305	2334	H-1	2419	2328
H-2	2357	2345	H-2	2332	2314	H-2	2384	2368
H-3	2413	2414	H-3	2325	2331	H-3	2474	2479
H-4	2416	2473	H-4	2421	2396	H-4	2511	2429
H-5	2350	2371	H-5	2370	2379	H-5	2375	2356
H-6	2370	2455	H-6	2440	2395	H-6	2425	2393
H-7	2514	2491	H-7	2552	2507	H-7	2574	2507
H-8	2637	2692	H-8	2643	2749	H-8	2708	2666
H-9	2514	2672	H-9	2583	2735	H-9	2610	2597
H-10	2481	2581	H-10	2525	2546	H-10	2588	2509

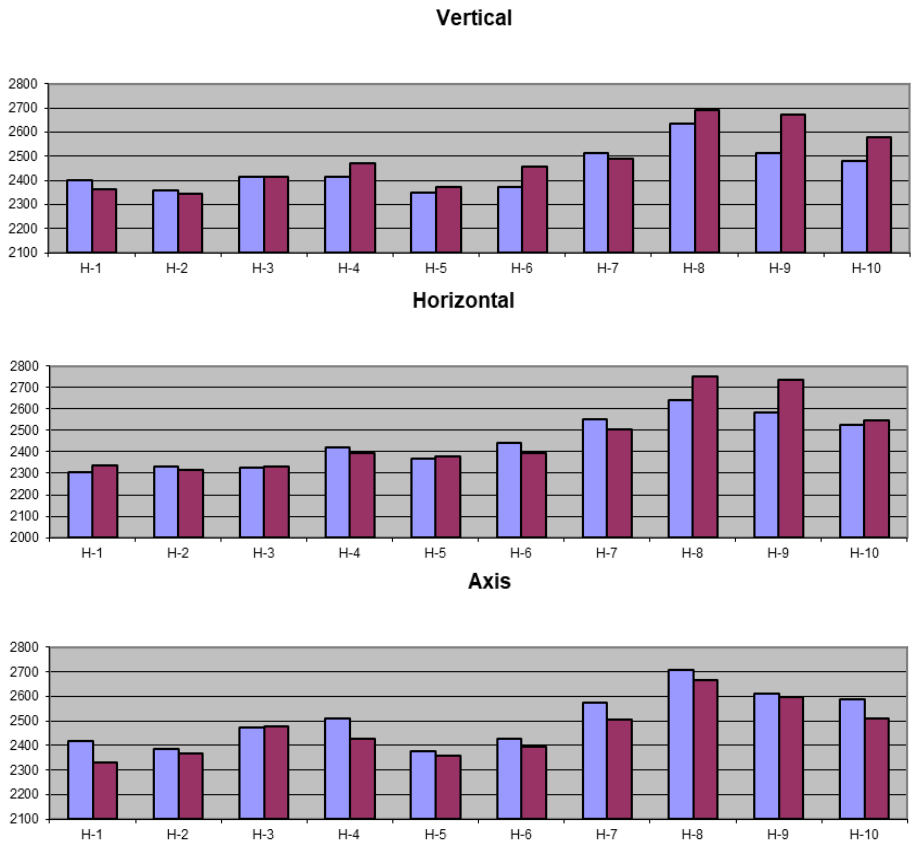


Fig. 6 Vibration acceleration values of the overall indicators of the engine and gearbox for three mutually perpendicular directions

In the analysis of engine vibration acceleration, the speed values of the engine and gearbox and the largest of them were selected. In this way, 3 informative measuring bodies were defined for the entire gear motor.

Point 3 of the motor – informative point of the axial direction of the gear motor [8].

Point 7' of the gearbox is an informative point for the vertical direction of the gear motor

Point 1' of the gearbox is an informative point for the horizontal direction of the gear motor

The vibration refinement values of the geared motor at these points were used in fuzzy logic.

DATA PROCESSING

The data were recorded using the OCTAVA device. The data were transferred to a computer and processed in the Microsoft Office Excel software product.

Data processing algorithm in Excel:

1. One measurement was taken for one minute; it was completely recorded with a vibrometer.
2. The root mean square values obtained over 10 seconds were selected from the data set of one measurement. Filtering was done using such data. The result was a filtered 24x30 table (Table A.2 - Appendix A).
3. Using this table, graphs were created for each frequency band (Figure 7 on the example of a frequency of 50 Hz).

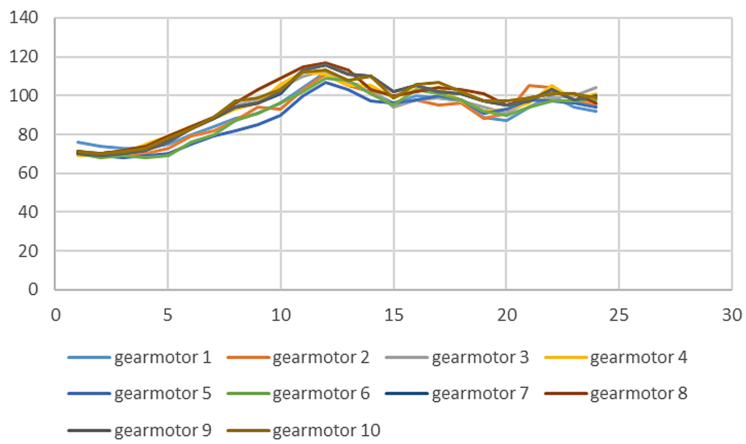


Fig. 7 Average vibration acceleration graphs measured for the vertical direction of ten gearmotors

4. Each of the 24 curves of the graph was processed, that part of the curve remained, which was the response of the vibrometer to the failure of the motor with the gearbox from the occurrence of a load on it (Figure 8 on an example with a frequency of 50 Hz).

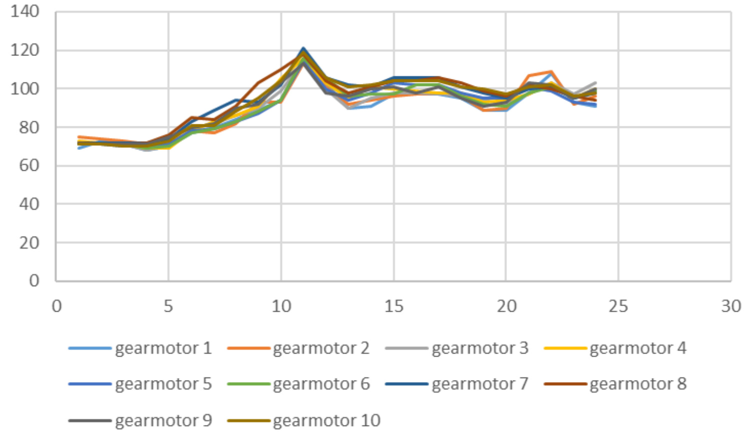


Fig. 8 Average vibration acceleration graphs measured for the horizontal direction of ten gearmotors

5. On one geared motor, 10 measurements were made every day out of 17. After 17 days, the average value of the processed data was calculated for each frequency band from which the graphs were compiled.
6. After calculating the average vibration acceleration values of ten geared motors, graphs were constructed for each frequency. When analyzing the graphs (Figure 9), we introduced the term "overall indicator", which reflects the technical condition of an individual gear motor compared to others.

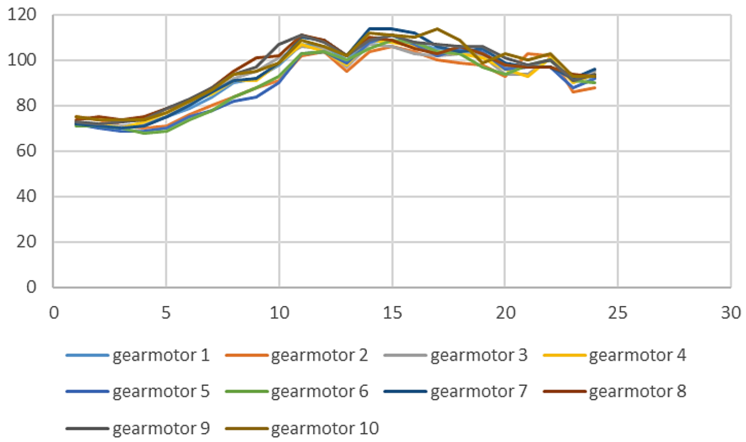


Fig. 9 Average vibration acceleration graphs measured for axial direction of ten gearmotors

7. The overall indicator was determined by the formula:
   - for the vertical plane;
   - for the horizontal plane;
   - for the axial plane;

where:

- average values of vibration acceleration (vertical, horizontal, axial) at each frequency of the 1/3-octave filter;

For each gear motor, the total indicator was calculated (Table A.3) and projected into the fuzzy logic diagnostic model (DIAX, 2017).

At the time of diagnosis, the gear motors had been in operation for 2 years. According to GOST R ISO13373-1-2009 (Kosinár, Kuric, 2011), the state of vibration of such machines corresponds to zone B. Based on the collected statistical data, we determine the boundary of zone B using the formula:

$$b = \frac{b_1 + b_2 + \ldots b_{10}}{10} \tag{10}$$

where:

b1, b2,...b10 are the total indicators of geared motors.

The calculated values of b are shown in Table 1.

According to authors (GOST, Kosinár, Kuric, 2011,Kuric, Zajacko, Císar), it is recommended to set the WARNING level not higher than the limit of zone B by 25%. If the baseline changes, the ALERT level may be adjusted.

In zone C, the machine is operated until further modifications or repairs, in this zone the machine is usually unsuitable for long-term operation.

Since the engine with a gearbox is a complex system consisting of an engine and a gearbox, the initial boundaries of the zones were set not 1.25 times, but 1.2 times larger than the basic one, by 20%. The upper limit of zone C is determined based on statistics. In this work, we do not define the boundary c with a clear identification, because there were no gear motors with faults during operation, so the boundary c was determined symmetrically. In the case of known defective gear motors, the upper limit can also be set. The STOP level is determined only on the basis of statistics, therefore, according to GOST (Kosinár, Kuric, 2011), it was set at the upper limit of zone C. When statistics are collected, the limit can be adjusted.

DEFINITIONS OF TRENDS

When measuring the parameters of gear motors in different time periods, the vibration acceleration values (overall indicators) increase in direct proportion.

The trend was determined using the following formula:

$$D = \frac{\sum_{i=1}^{3} \frac{F_i}{\hat{A}_i} - 1}{3} \tag{11}$$

where:

Fi is the actual value of the vibration acceleration in each of the three directions. The two-base value of the vibration acceleration in each of the three directions. The basic value is determined based on the results of the first measurements, the actual value is the value that was measured last.

RESULTS AND CONCLUSIONS

1. Based on fuzzy logic, a diagnostic system model was developed for Z68-K4-LA/90L4 gear motors for mobile robots.

2. A new integral parameter of diagnostic quantities was proposed – the sum of amplitudes of vibration acceleration in the frequency bands of the 1/3-octave filter (Nikitin, Bozek, Peteka, 2020).
3. When suddenly switching the engine speed (930 rpm) to another (1370 rpm), the vibration acceleration values of the geared motor do not change, but remain the same (100 dB – the highest value is 1.25 kHz). The change in vibration acceleration on a rotating gear motor is affected by the load that appears on it (120 dB – the highest value is 1.25 kHz).
4. At a rotation speed of 930 rpm, the current is 2.57 A, at a rotation speed of 1370 rpm, the current is 1.71 A. These current values are nominal for the given operating mode. Zones of acceptable values are set according to these values (Stetsenko, 2021).
5. A small difference in electric current between phases (0.05 A – maximum) in all electric motors indicates the asymmetry of the supply voltage.
6. The temperature of the gear motors of the roller table is 40˚-42˚C.
7. A trend of changes in the overall vibration acceleration indicator of the gear motor was detected - more than 300 dB for the gear motor, which indicates the beginning of malfunctions of these gear motors.

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REFERENCES

Abramov, I. V., Bozek, P., Nikitin, J. R. Abramov, A. A., Sosnovich, E. V., Stollmann, V. (2015). Diagnostics of electrical drives. In The 18th International Conference on Electrical Drives and Power Electronics . EDPE 2015. The High Tatras, Slovakia, 21 - 23. September 2015. Pp. 364-367. DOI: 10.1109/EDPE.2015.7325321

Abramov, I. V. , Nikitin, Y. R. Abramov, A. I., Sosnovich, E. V. Bozek, P. (2014a). Control and diagnostic model of brushless DC motor. In Journal of Electrical Engineering. Vol. 65, No. 5 online, p. 277-282. ISSN 1335-3632

Abramov, I., V., Nikitin, J. R., Abramov, A. I., Sosnovich, E. V. Bozek, P., Stollmann, V. (2014b). Diagnosis of rolling mill line gear-motors. In IN-TECH 2014 : Proceedings of International Conference on Innovative Technologies, Leiria, Portugal, 10. - 13. 09. 2014. Rijeka : Faculty of Engineering University of Rijeka, s. 155-158

Kravchik, M.M. Shlaf, V.I. Afonin, E.A. Sobolevskaja. M. (2022). Energoizdat. Asynchrónne motory radu 4A / A.E

All about electric motors, generators, transformers and other electrical machines [Electronic resource] (2022). Method of average losses for checking the motor by heating [page]. URL: http://el-dvizhok.ru/metod-srednix-poter-proverki-dvigatelya-po-nagrevu

Bialy, W, Bozek, P., Boloz, Ł. (2023). Diagnostic methods and ways of testing the workability of coal - a review. In Production Engineering Archives. Vol. 29, iss. 4, s. 401-412. ISSN 2353-515

Bozek, P., Krenicky, T., Stepanov, P., Ivanovich N., Jurij R. (2022). - Gupalov, Boris Alekseevich - Lagutkin, Stanislav Vladimirovich. Development of a system for predictive diagnostics of traction asynchronous electric drive for trains. In MM Science Journal. November, s. 6123-6126. ISSN 1803-1269(P)

Bozek, P., Pivarciova, E. (2023). Development of control system of mobile robot with differential drive. In MAPE 2023 : XX International Conference Multidisciplinary Aspects of Production Engineering, 19. - 22. September. Gdansk, Poland. 1. vyd. Zabrze : Department of Production Engineering Silesian University of Technology, 2023, S. 83. ISBN 978-83-968715-0-3.

DIAX. Expertný systém na sledovanie technického stavu točivých strojov. (2017). [Elektronický zdroj] // Monitorovací systém na sledovanie výbojových javov v točivých strojoch: [webová stránka]. URL: diacs.com›ru/article/2.doc (dátum prístupu: 23.08.2013).

GOST R 51689-2023. Elektrické točivé stroje. INDUKČNÉ MOTORY S VÝKONOM OD 0,12 DO 400 kW VRÁTANE.

Kosinár, M., Kuric, I. (2011).Monitoring possibilites of CNC machine tools accurary. Meeting: 1st International Conference on Quality and Innovation in Engineering and Management (QIEM), Location Cluj Napoca, ROMANIA MAR 17-19.

Kuric, I., Zajacko, I., Císar, M. Analytical intelligence tools for multicritelrial diagnostics of CNC machines. ADVANCES IN SCIENCE AND TECHNOLOGY-RESEARCH JOURNAL, Volume 10, Issue 32, Page 59-64. DOI10.12913/22998624/65105

Nikitin, Y. R. Bozek, P. Peteka, J. (2020). Logical-Linguistic Model of Diagnostics of Electric Drives with Sensors Support. In Sensors. Vol. 20, iss. 16, s. 1-19. ISSN 1424-8220

Stetsenko, A. A. (2021). Machine monitoring and diagnostics systems: a collection of articles. scientific tr. Amount: Scientific and technical center "Diagnostics",p. 21-34.

Opracowanie, badanie i zaprojektowanie systemu diagnostycznego do pomiaru przebiegów temperatur, drgań i hałasu

Abstract: Rozwój postępu naukowo-technicznego w dziedzinie techniki pomiarowej i mikroprocesorowej, postęp w metodach sztucznej inteligencji dają impuls do rozwoju diagnostyki technicznej systemów mechatronicznych. W systemach mechatronicznych napędy elektryczne bazują na silnikach asynchronicznych, silnikach prądu stałego, silnikach synchronicznych i krokowych, a napędy mechaniczne bazują na przekładniach. Awaria silników i przekładni prowadzi do zatrzymania urządzeń, ciągłej produkcji i strat finansowych firmy. Dlatego potrzebne są narzędzia do monitorowania bieżącego stanu urządzeń..

Keywords: system diagnostyczny, silniki prądu stałego, siłowniki, robot

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