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DEVELOPMENT OF BUILT-IN MEANS TO MONITOR TECHNICAL CONDITION OF LOCOMOTIVE MECHANICAL UNITS

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СТВОРЕННЯ ВБУДОВАНИХ СИСТЕМ КОНТРОЛЮ ТЕХНІЧНОГО СТАНУ МЕХАНІЧНИХ ВУЗЛІВ ЛОКОМОТИВІВ

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СОЗДАНИЕ ВСТРОЕННЫХ СИСТЕМ КОНТРОЛЯ ТЕХНИЧЕСКОГО СОСТОЯНИЯ МЕХАНИЧЕСКИХ УЗЛОВ ЛОКОМОТИВОВ

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Taking into consideration the necessity of applying monitoring means to diagnose the actual technical condition of driving axle bearings to reduce the number of their failures, some new devices have been developed which take account of a sudden nature of failures of some bearings elements. These devises have been designed to detect and analyse certain bearing vibration characteristics during the motion of the locomotive. The built-in device for monitoring the vibration of the driving axle bearings is attached to the surface of the tractive motor bearing assembly by means of a pin. The pin is screwed in a pre-drilled hole and the part is attached to it. Attaching by means of pins is one of the ways that don't distort the operation characteristics, the resonance frequency and the dynamic range of vibroaccelerometers. To increase the trustworthiness of the results obtained, the monitoring signals are analyzed only in the mode of the locomotive stationary speed. ***Objective:*** *develop built-in means to monitor vibration characteristics of driving axle bearings to increase the efficiency of planned preventive system of locomotive maintenance and repairs.*

Keywords: *bearing, diagnosis, failure, locomotive, operation, vibration*

Беручи до уваги необхідність запровадження діагностичних засобів для визначення технічного стану моторно-якірних підшипників тягових електричних двигунів (ТЕД) та для зниження кількості відмов, були розроблені нові пристрої, що враховують випадкову природу виникнення пошкоджень деяких елементів підшипників кочення. Дані пристрої розроблялися саме для реєстрації та аналізу вібраційних характеристик підшипників під час руху локомотива. Для підвищення достовірності отриманих результатів слід аналізувати сигнали в режимі стаціонарної швидкості локомотива. ***Мета:*** *розробити вбудовані засоби для реєстрації вібраційних характеристик підшипників ТЕД для підвищення ефективності системи потокового ремонту та технічного обслуговування*

Ключові слова: *підшипник, діагностика, відмова, локомотив, обслуговування, вібрація*

Учитывая необходимость внедрения диагностических средств для определения технического состояния моторно-якорных подшипников тяговых электрических двигателей (ТЭД) и для снижения количества отказов, были разработаны новые устройства, которые учитывают случайный характер возникновения повреждений некоторых элементов подшипников качения. Данные устройства разрабатывались именно для анализа вибрационных характеристик подшипников во время движения локомотива. Для повышения достоверности полученных результатов следует анализировать сигналы в режиме *стационарной скорости локомотива.* ***Цель:*** *разработать встроенные устройства для регистрации вибрационных характеристик подшипников ТЭД для повышения эффективности система поточного ремонта и технического обслуживания*

Ключевые слова: *подшипник, диагностика, отказ, локомотив, обслуживание, вибрация.*

Introduction. Under conditions of the operation of locomotives, the requirements to their reliability, higher level of service and maintainability have been significantly increased. In this connection, experts of many countries are working to change the approaches to maintain locomotives, to increase the efficiency of the maintenance, the use of materials and labor, as well as to minimize the downtime of the locomotives and failures of their units, because the costs of maintenance and repair of the locomotives during their operation period is 8-10 times higher than their original cost and the process itself is very labor consuming [1, 2].

Failure prevention of locomotives in the maintenance and repair system is most effective when the cause of an equipment eventual failure is identified at the early stages. This can be ensured by the use of technical diagnosis as a part of the system of locomotive maintenance and repair [3]. The trustworthiness of identifying those items of equipment that are close to their limit capacity influences the effectiveness of the technology of maintaining and repairing locomotives under the planned preventive system, which is the main system to keep locomotives in serviceable condition in Ukraine. This system is characterized by abnormally frequent repairs of traction drive units of locomotives, the disassemble-assemble work being excessively labor consuming.

The planned preventive system to maintain and repair locomotives is becoming more flexible and better suited to the requirements of keeping them in working condition. The term of locomotive repairing vary depending on the operating conditions in some post-Soviet countries.

There are two approaches to maintain and repair locomotives. In the first case, the frequency of diagnostic procedures is arbitrarily connected to the frequency of maintenance and repair procedures. In the second case, the frequency of the diagnosis is established for each unit, based on its reliability and the advisability of diagnostic procedures [4].

When diagnosis is arranged according to the second type variant, it will allow to warn several months in advance about an eventual failure of a locomotive unit, to ensure timely procurement of the necessary spare parts and to select an opportunity window for the maintenance and repair of the specific locomotive in the train running schedule, the early diagnosis preventing complete destruction and serious faults of the locomotives. In this case the maximum advantage can be obtained at the stage of initial use of diagnostic means for critical units or unreliable locomotives available in Ukrainian railways.

In Western Europe, a decisive factor in improving efficiency of locomotives is an adaptation of locomotive units to diagnosis which should be considered during their designing and manufacturing [5]. Locomotives of older generations which are still operated on Ukrainian railways are not adapted for full monitoring their equipment in terms of measuring the parameters of their working processes, however there is a possibility to implement diagnostic means to monitor the equipment working under steady-state conditions by secondary processes — i.e. vibration and thermal radiation [6].

There are many effective methods within various approaches [7, 8] of diagnosing mechanical units (bearings and gears) by their vibration. Thus, the choice of parameters of a vibroacoustic signal as a source of information on technical condition of locomotive units is an evident and the least costly way of diagnosing outdated locomotives not only under stationary conditions in depots, but also during their movement. The changes of vibroacoustic signal are correlated with the changes in the technical condition of the units, caused by their degradation, that is the change of dimensions of their components, the change of the traction motor insulation parameters, and of the parameters of the motor commutator-brush adjustment setting.

As a result of using diagnostic means, the amount of unscheduled maintenance of locomotives and the number of unexpected failures in running are reduced. Serviceability monitoring of locomotives enables early warning of eventual failures, diagnosing types of faults, and predicting the real remaining service life of important locomotive units.

The aim of the paper is development of procedures which are expected to improve the efficiency of built-in diagnostic systems which are meant to identify with high trustworthiness faults of the rolling bearings and gears of driving axles.

Peculiarities of maintaining and repairing locomotives using diagnostic means. At the stage of locomotive diagnostic system formation it is important to solve the task of selecting the optimal set of diagnostic means, taking into consideration their technical and economic parameters [4].

At the early stage of monitoring it is suggested [2] to select 10 components that are exposed to the most frequent or significant faults as the first priority for inspection. Then specialists determine the thresholds of locomotive technical condition by the "red/yellow/green" scale.

Specialists of Alstom company use many technologies for predicting faults of locomotive units and their components, applying a two-level approach. In the first short-term approach it is monitoring of components to reduce the number of failures in operation by identifying unforeseen cases of failure and unplanned replacements. In the middle and long-term service the company intends to reduce the amount of maintenance work and shorten the periods between overhauls of locomotives. This company has a technical passport for each locomotive, which enables it to track the life cycle of all main components and describe the trends of technical condition of the entire park of locomotives. This enables to develop a program of fragment overhauls according to which the main subsystems (units) and critical components are replaced or subjected to overhaul on a cyclic basis during their routine maintenance that is preferable and more efficient than their disassembling every six months.

In "Pendolino" trains with force inclinated body cars in curved sections of the track the inspection of the component wear is usually carried out on the basis of the worst-case scenario that does not always reflect the real technical condition. Traditionally, specialists do it by hand, which decreases the trustworthiness of the results and limits the amount of data to be processed. It should be noted that most of the components have a high cost and it is not expedient to replace or modernize them on the basis of limited information [2].

In the United States one of the main directions of improving the system of locomotive repair is a complex system of diagnosis and computing. Automated monitoring systems for repair and maintenance of locomotives were created, as well as general purpose technical diagnostic means which enable to differentiate the terms of repairs. Under conditions of tough competition in the United States railways one tries to maximize the efficiency of using locomotives, and to minimize the costs [4].

Modern locomotives are equipped with powerful information on-board systems. US diesel locomotives have the world's largest historical experience in creating built-in and on-board diagnostic systems, primarily for diesel engine diagnosis. Diesel locomotives have two on-board computers: for motion control and for locomotive technical condition diagnosis. There is positive experience of interaction of the locomotive on-board monitoring and diagnosis system with the control centre by Wi-Fi technology. The diesel locomotive sends to the control centre the diagnostic information including location, speed, diesel engine condition, the fuel left and video from a built-in camera (a picture every 5 sec) and control signals are sent to the locomotive. The experience of developing the locomotive built-in and on-board systems in the United States is considered to be unique.

European high-speed electric trains have additional third on-board computer to control digital radio communication. The Russian AC electric locomotive "Yermak" has in each of its sections two microprocessor control systems and an on-board computer [9].

On some Russian diesel locomotives there are built-in diagnostic subsystems of main diesel units designed to facilitate the work of the locomotive crew on the way, to reduce the time of searching and eliminating faults which appear during operation. The system controls 140 discrete signals, 113 analog ones (among them 17 parameters of pressure, 34 parameters of temperature), and 8 frequency signals of major locomotive systems. The system does not have a clear differentiation of control and diagnostic functions. Most of the signals are used both for control and diagnostic functions. The technical condition of the diesel locomotive systems is diagnosed automatically, without any interference of the engine driver. The system itself defines the operation modes of certain units and initiates any diagnostic algorithms if necessary. In case of emergency, an alarm message is displayed on the monitor screen. During the diesel locomotive operation, continuous measurement of the mentioned parameters is carried out with 1 sec periodicity and the measurement results are accumulated in special format files. The recorded data can be viewed with the help of a special software [10]. The on-board diagnostic system provides storage and transfer of all operational diagnostic information available aboard the locomotive to the diagnostic database installed in the depot and to the server of Russian railways. Data transmission over the Internet uses a secure VPN-connection. When the locomotive is in motion, the main diagnostic parameters are continuously recorded by the on-board equipment, as well as the quantity of fuel in the tank, the motion speed, and the geographic coordinate [1].

The capacity of the modern industrial computers allow to improve the functionality of the systems. Locomotives being equipped with appropriate sensors, diagnostic information about the condition of tracks, legs, switches, man-made structures, etc. can be generated [9].

Over the last 40 years in Europe, the United States, and the USSR a technology was developed to diagnose mechanical units by secondary process, i. e. vibration under stationary conditions in the depot. A technology was developed to diagnose mechanical parts of wheel-motor blocks (driving axles) such as mounting bearings, commutator bearings and gearboxes. Special jacks were developed and manufactured for lifting driving axles under the electric locomotive. The motor rotating speed stabilization was accomplished using the diagnostic means according to a special program. The signals from vibration accelerometers through analog-to-digital converter (ADC) were transmitted to the diagnostic means for further analysis and diagnosis [9]. When locomotive units are diagnosed on the basis of secondary processes, the technical condition of the units is monitored by several methods. For example, diesel locomotives axle boxes are monitored by stationary systems of thermal control "PONAB" or "DISK", in some cases they are monitored by on-board systems of thermal control, the means of vibrodiagnosis and on the basis of the results of grease spectral analysis. Thus, it is possible to state that diesel locomotive units can be diagnosed concurrently in several ways using various diagnostic means.

The developers of diagnostic means to solve the problem of predicting failures set the intervals of diagnostic procedures of the units being monitored not according to their current technical condition and the dynamics of developing faults, but according to a rather rigid scheme. It is recommended to diagnose driving axles by vibrodiagnostic complex «Prognosis-1" during each 3^{d} level maintenance or every other 3^{d} level maintenance. This organization of diagnosis technology process is applied to most units being diagnosed and is characterized with a long duration of repair [4].

There are currently no effective methods to diagnose locomotive units by secondary processes with the help of built-in diagnostic systems, and some investigations to assess the technical condition of the locomotive driving axle bearings in motion have shown that it is extremely difficult to identify the faults of axle box bearings and the commutator bearings, and the results often have low trustworthiness [6]. The main reason of this is the shock loads on the bearings from the wheels which have numerous non-round facets, as well as the wheel axle misalignment with the geometric axis of the wheel, yet another reason being the complexity of comparing the results of the measurements under conditions of the widely varying frequencies of wheel rotation.

The vibroacoustic prediction of the technical condition of locomotives without disassembling both before the maintenance and running repairs, and after repairs, is of a very great importance for intensive use of locomotives. Despite the practical importance of vibrodiagnostics, this problem has not been solved yet for many physical aspects because of the lack of a unified theory and also due to the fact that the results of some investigations [3] are contradictive.

Built-in systems to monitor locomotive driving axle technical condition on the basis of secondary processes. Fig. 1 shows the analysis of failures and unplanned repairs of diesel locomotive systems and units made in [4] and other works. It is shown that over 30 years diesel engine and electrical equipment failures have the highest level of occurrence which determines their low reliability.

The operation of driving axle bearings as well as that of commutator bearings is not reliable. This unit accounts for about 15 % of the failures among other driving axle failures. The analysis of bearing faults shows that the majority of these faults (80 %) are the faults of the outer ring and the cage (fig. 2), over 50 % of the faults of the commutator bearing occuring in the first twelve-sixteen months of their operation after the repair, which is the result of poor repairs and the lack of quality diagnostic means [3].

There are other data [13], according to which up to thirty percent of driving axles on the Trans-Baikal Railway in Russian Federation after disassembling had a great residual resource and needed no repair. As a result of this, the run between two 3d level repairs was increased from 400 to 420 thousand kilometers, which caused a reduction of non-productive costs for repairs and maintenance.

Currently, a state program of renewing the locomotive park of the Ukrainian railways is being implemented, which envisages the purchase of 509 locomotives during the 2012 — 2016. Contracts have already been concluded for delivering 460 electric locomotives [11]. However, the locomotives being operated are currently out of date and are repaired under the planned preventive system which implies inspecting and recovering the technical condition of the locomotives. The planned preventive system had been created on the basis of long-term experience of maintaining locomotives of various series, analysis of operation results and the intuition of repair workers. Presently, locomotives are repaired according to a schedule and at the intervals specified in operating instructions.

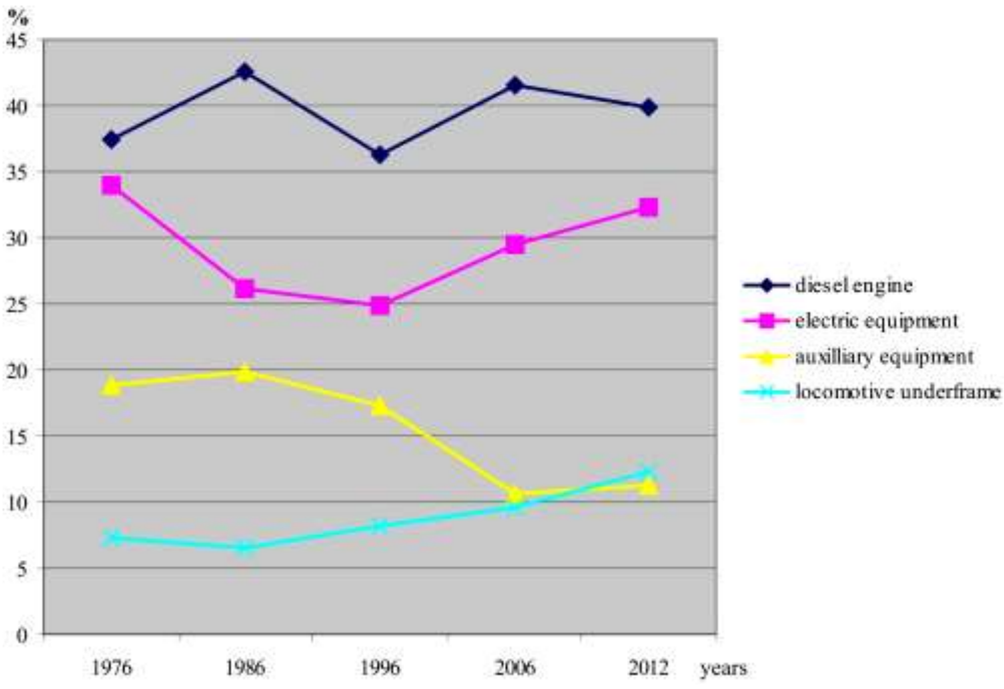

Fig 1. Analysis of faults and unplanned repairs of diesel locomotives

The diagnosis of locomotives by secondary processes in depots requires measurement of the following parameters: vibration, temperature, values of the electric current of the motors and the grease composition, forecast assessments of the insulation resistance nonlinearity depending on the high-voltage testing tension, the absorption coefficient of the driving axle insulation being also necessary [5, 6]. However, the diagnostic methods based on the electric motor current have low sensitivity to bearing faults, at least until the wear and the faults of the bearings cause the clearance fluctuations in the motors which may lead to failures of gearboxes [1]. Noise as a source of information has high capacity and in contrast to the motor temperature, which due to large thermal inertia of components is one-dimensional, noise has a wide spectrum and therefore, its parameters form a vector in the multidimensional signal space [3].

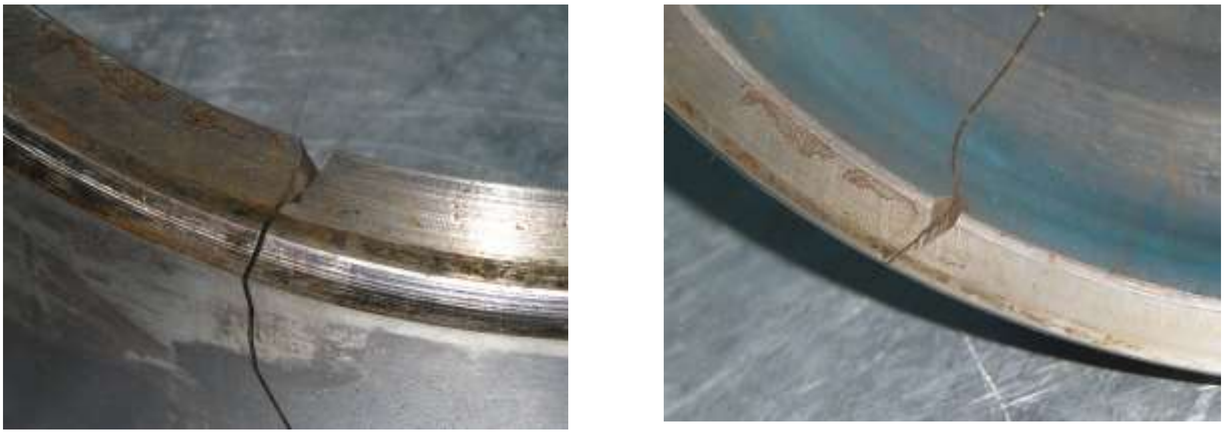

Fig. 2. Cracks of locomotive driving axle commutator bearing races

Typically, locomotive driving axles have a variety of operating modes, however the depot diagnostics is carried out only in an untypical operation mode. When diagnosing locomotives, one cannot expect a natural change of stages of the fault development, as each element of the repaired bearing may be at a different stage of its life with different speed of developing the same fault. The information about the operation modes of driving axles cannot be taken into account either, especially that of the overload modes which occur in the period between the diagnostic measurements [6]. Built-in diagnostic systems are usually based on measuring working processes of the units being monitored, and these systems are rarely supplemented by measuring the temperature of the individual units (fig. 3). Therefore, the actual problem is to work out trustworthy methods and implement hardware means of diagnosing the technical condition of driving axle rolling bearings and axle boxes in their standard operating modes during movement.

The modern concept of controlling systems requires a diagnostic computer in the engine-driver's cab. The computer does not participate in the drive control and is used for storing the diagnostic information during, its visualization to the engine-driver during the operation and for the technical staff during maintenance in depots. However, the specific features of its operation require that a separate class of built-in diagnostic systems should be formed on its basis, these diagnostic systems being external to the control system, but internal to the locomotive diagnostic system [9].

The specialists of the chair of the rolling stock operation and repair of the Ukrainian State Academy of Railway Transport developed requirements to the built-in device of bearing unit vibration monitoring for locomotive driving axles [14].

A built-in device of vibration monitoring should consist of two parts (fig. 4):

1). a part of vibration signal measurement and conversion (VSMC);

2). a part showing that the locomotive speed is stationary (LSS).

The VSMC part consists of an integral vibroaccelerometer, a microcontroller, an autonomous power supply module and a wireless network module.

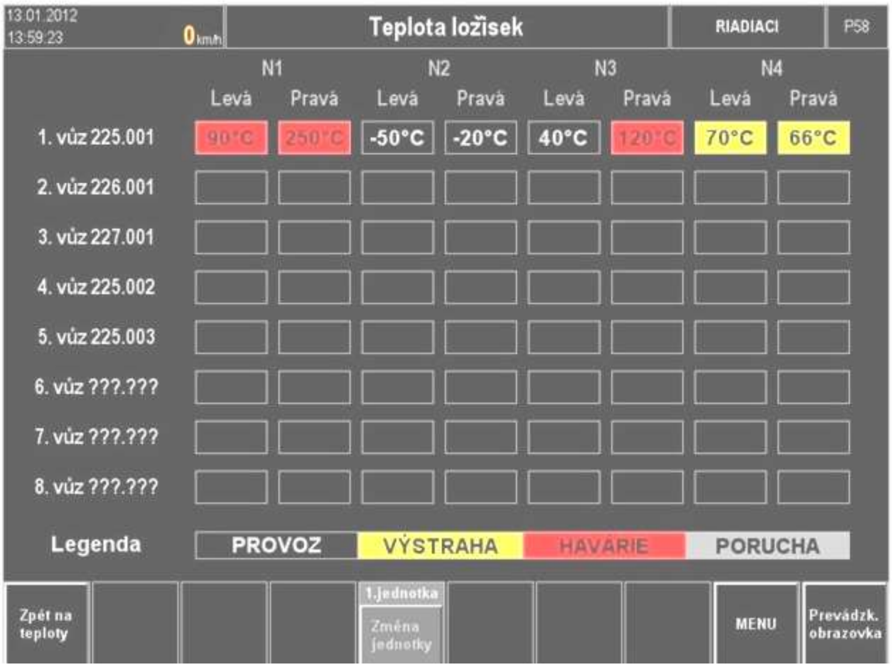

Fig. 3. A service screen which shows the temperature of the axle box bearings of electric train "Skoda EJ 675"

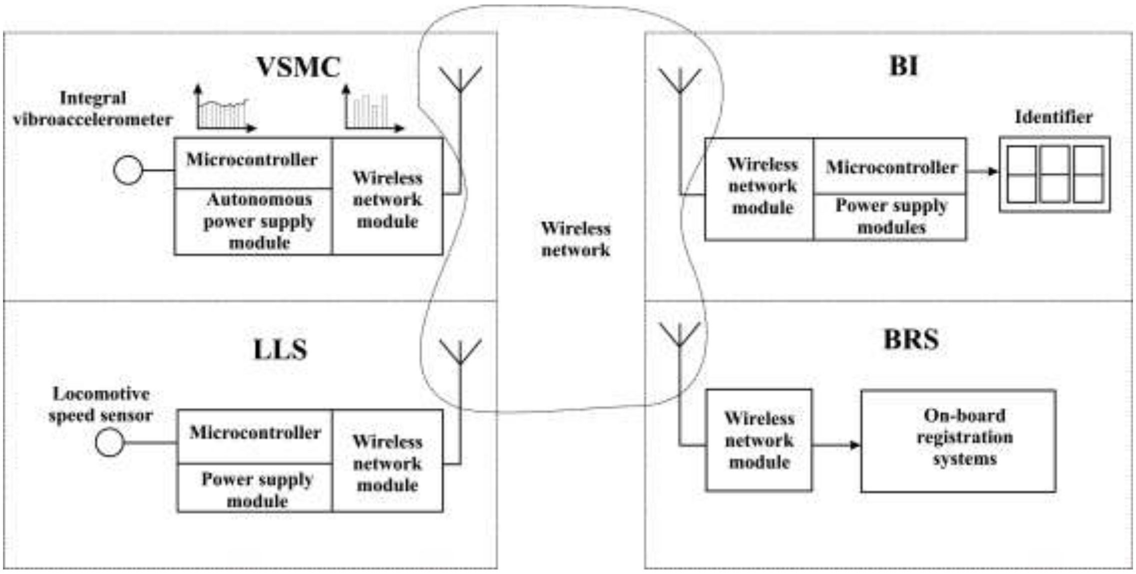

Fig. 4. The structure of the built-in device of vibration monitoring

The integral vibroaccelerometer is a small, thin, ultralow power, 3-axis accelerometer with high resolution (13-bit) and with the range of measurement of at up to ±16 g it performs the function of receiving vibration signals from bearings.

The microcontroller is a computing device that works on a certain algorithm and is used for receiving, converting and transmitting the information about the technical condition of the bearings. The information about the technical condition of the bearings is transmitted outside by the wireless module, which is controlled by a microcontroller.

At the output of the VSMC part we have the range of the values of the bearing technical condition in the form of quantitative estimates. The input to the part is a vibration signal time domain.

The LSS part consists of a locomotive speed sensor, a microcontroller, a power module and a wireless network module.

The microcontroller accepts the signal from the speed sensor and analyses it for being or not being stationary.

The power module provides the LSS part with electric energy from the on-board network of the locomotive.

The device works as follows. After switching on, the VSMC part is in the waiting regime to get a locomotive stationary speed signal. In this regime the electricity consumption from the autonomous power supply source is minimal. The VSMC part receives a stationary speed signal and begins to take and convert the vibration signal and sends the converted signal outside by using the wireless network. The LSS part constantly analyzes the signal from the locomotive speed sensor checking whether it is stationary. After identifying that the speed is stationary, the LSS part informs all other VSMC parts through the wireless module that the speed of the locomotive is stationary. Information about the technical condition of the bearings is sent to the exchange information network where the receivers of this information can be built-in indicator (BI) or presently available on-board registration systems of locomotives (BRS).

The wireless network is physically based on the IEEE standard 802.15.4, data addressing and transmitting are based on MiWI protocol.

The built-in device for monitoring the vibration of the driving axle bearings is attached to the surface of the tractive motor bearing assembly by means of a pin. The pin is screwed in a pre-drilled hole and the part is attached to it. Attaching by means of pins is one of the ways that don't distort the operation characteristics, the resonance frequency and the dynamic range of vibroaccelerometers.

Further investigations detected the following disadvantages of the device: a) it is necessary to install on board a locomotive stationary speed part (LSS part) in the case of failure of which the whole vibration monitoring device will also fail; b) the wireless network module should be powered continuously which reduces the autonomous working time of the LSS part in a standby mode, and c) incomplete detection and poor use of vibroaccelerometer information.

A new device was developed [15], which consists of a built-in vibration monitoring part (BVM) (fig. 5), that signals that the locomotive speed is stationary, measures and converts the vibration signal.

The BVM part consists of an integral vibroaccelerometer, a microcontroller, an autonomous power supply module and a wireless network.

The integral 3-axis accelerometer allows to measure the deceleration and acceleration of the locomotive, and the vibroacceleration of the locomotive bearing assembly.

The device works as follows. Once enabled, the BVM part is in a starting mode with minimum consumption of electrical energy from the autonomous power supply unit. In programmed periods of time the microcontroller "wakes up" and detects whether a signal from the vibroaccelerometer is available (locomotive motion inspection). If the locomotive is in motion, the microcontroller makes several attempts to identify whether the locomotive speed is stationary by means of analyzing the acceleration signals along the axis of the locomotive motion.If the locomotive speed is found to be stationary, the microcontroller processes the incoming vibration signal and transmits the bearing technical condition information to the information-exchange network, where the receivers of this information can be built-in indicator (BI) or presently available on-board registration systems of locomotives (BRS). If the speed was not found to be stationary after several attempts, the BVM part returns to its starting mode.

Conclusions. The developed device allows to form an integrated serviceability assessment of the units being monitored (at the "serviceable" — "nonserviceable" level) and predict the changes of their technical condition to determine the amount and intervals of maintenance, the trustworthiness of the bearing assembly technical condition information being increased by the motion stationarity identification. In future, this device can be included in the maintenance process of the locomotive, as the primary source of information about the driving axle bearing technical condition.

The development of technical diagnostic means and their wide application in the locomotive maintenance facilities will not completely permit to go from the planned preventative system of repairs to repairs on demand, the latter being applicable only to relatively simple devices, the elements of which can be restored independently of the others. To repair most of the locomotive units, especially mechanical equipment, it is necessary to put the locomotives under repair in depots and carry out labour-consuming dismounting-mounting operations. Performance of such operations while repairing each unit individually would significantly increase the locomotive repair duration and the cost of the repair. Therefore, when putting a locomotive to repair due to the failure of a unit or when its lifetime is over, it is expedient to repair not only the faulty unit, but also other components and units whose lifetime has not expired, but is nearing its limit value. Such a system, being planned preventative, also takes into account the real technical condition of the locomotive units.

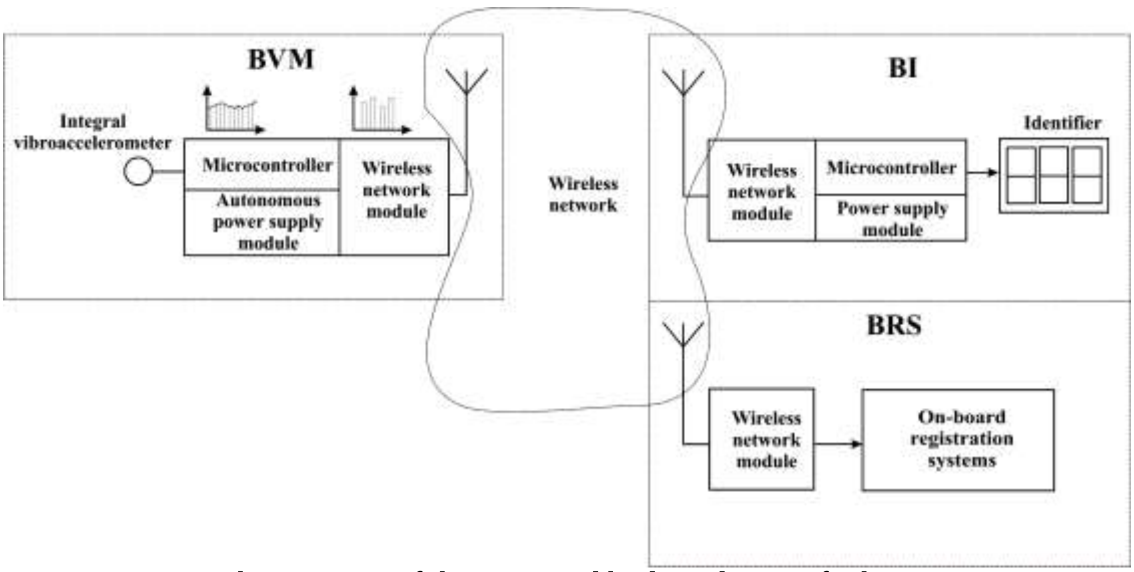

Fig. 5. The structure of the improved built-in device of vibration monitoring

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15. UA100550 Device for on-board vibro-control (monitoring) of bearing unit of wheel-motor block (driving axle) of locomotive.

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