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THE VIBRATION DIAGNOSTICS OF THE MOBILE MACHINES TOOTH GEARS

Розглянуто загальний стан вібродіагностики зубчастих передач мобільної техніки, проаналізовано та класифіковано методи діагностування зубчастих передач мобільних машин в експлуатації. Виділено особливості функціонування зубчастих передач, з-за яких використання для їх діагностики стандартних віброакустичних засобів обмежена. Описана розроблена бортова автоматизована система вібродіагностики редукторів мотор-коліс великовантажних самоскидів БелАЗ. Сформульовані перспективні напрямки розвитку вібродіагностики стосовно трансмісійним вузлів мобільних машин.

Ключові слова: мобільна техніка, діагностика, трансмісія, зубчаста передача, апаратно-програмні засоби, класифікація методів, напрями розвитку, мотор-колесо, технічний стан.

Рассмотрено общее состояние вибродиагностики зубчатых передач мобильной техники, проанализированы и классифицированы методы диагностирования зубчатых передач мобильных машин в эксплуатации. Выделены особенности функционирования зубчатых передач, из-за которых использование для их диагностики стандартных виброакустических средств ограничено. Описана разработанная бортовая автоматизированная система вибродиагностики редукторов мотор-колес большегрузных самосвалов БелАЗ. Сформулированы перспективные направления развития вибродиагностики применительно к трансмиссионным узлам мобильных машин.

Ключевые слова: мобильная техника, диагностика, трансмиссия, зубчатая передача, аппаратно-программные средства, классификация методов, направления развития, мотор-колесо, техническое состояние.

The state of vibration diagnostics of the mobile machines tooth gears, peculiarities of hardware and software of manufacturers' products, approaches and methods for diagnostics of mobile machines transmission systems are considered. The systems and methods of mobile machines gear diagnostics in operation are analyzed and classified in detail. Special features of the tooth gears functioning, which restrict use of standard vibroacoustic tools for their diagnostics, are separated. On-board automated system aimed for the vibrodiagnostics of motor-in-wheel reducers for dump trucks BelAZ is described. The perspective directions of vibrodiagnostics development in relation to the transmission units of mobile machines are formulated.

Keywords: machines, vibrodiagnostics, transmission, tooth gear, hardware and software, methods classification, directions for the development, motor-in-wheel, technical condition.

Introduction. The development of sensory base and computing equipment allows to create more and more perfect vibrodiagnostic systems to ensure effective monitoring of current technical condition of complex systems and a fairly reasonable prediction of service life from their most responsible elements. Today in the CIS market in addition to the traditionally well-known manufacturers of vibro- and noise-measuring techniques (Schenck, Larson&Davis, Bruel&Kjaer, SKF, National Instruments, etc. [1–5]) actively offer their products manufacturers of Russia and Ukraine, specializing in the development and sale of equipment and devices for balancing, control and vibroacoustic diagnostics.

Leading Western European and American manufacturers of hardware and software for vibroacoustic diagnostics go towards the creation of *modular systems* ("bricks"), of which the measuring channels are formed and assigned the task of retrieval and storage of information. *Processing and analysis* of measurement information is carried out on a PC using specialized or generic software packages. Such systems have wider possibilities of processing and analysis vibroacoustics signals compared to traditional stationary and portable vibration analysers and sound level meters with a variety of standard features.

In CIS countries the leading position in the field of methods and means of vibration diagnostics is a company "Diameh", "Vast", "Inkotes", etc. [6–13]. Of their vibration analysers are *stand-alone microprocessor-based portable devices*, allowing to measure, process, store and visualize the measured vibroacoustic information.

Most of the tools of vibration diagnostics, both Western and CIS production, have a fairly narrow specialization (balancing of rotors and diagnostics of bearing units of different technological of equipment) and is intended for *manufacturing diagnostics*. For research purposes their use for solving new tasks of analysis and control experiment is hampered by the presence of rigid algorithms, implemented by hardware in a dedicated computer, precluding the possibility of changing the software configuration of the computer means.

Methodical and instrumental means of *vibration diagnostics and forecasting of a residual life* according to the change of vibration parameters are most actively developing in relation to the bearings, but *for gears and driving mechanisms* of mobile machines concrete techniques and examples of practical use of the vibration diagnostics in the published descriptions are virtually absent.

The aim of the work was to analyse the current state and tendencies of development of diagnostics and vibration diagnostics of gearing and driving mechanisms of mobile machines.

The vibration drive systems. The analysis of publications [14–25], devoted to the operational assessment of the technical condition of drive mechanisms based on gears, as well as the methods and means of forecasting of a residual life of the transmission system, shows that from existing methods the most perspective are *methods of non-disassembly control of dynamic characteristics* of drive mechanisms through continuous or periodic monitoring of vibration parameters. So, in work [14] considered the possibility of using vibroacoustic analyzer A17 for *monitoring the availability of gears*. On example of refinement of experimental gears discusses the possibility of using vibroacoustic methods for diagnostics of damage of gear wheels in conditions of development fatigue testing. The control and rejection of gears it is proposed to doing by the levels of *spectral components* of rotational and tooth mesh frequencies.

Corporation UTC Aerospais Systems (USA) advertises designed on-board system of vibration diagnostics of transmission helicopter HUMS (Health & Usage Monitoring Systems) [26, 27]. Monitoring of the level of vibration allows to obtain information about the status of main units and assemblies and the possibility of early detection of the defect, the necessary engineering and technical staff for decision making about replacement parts. The key element of the HUMS is software that analyzes the *information coming from ace-*

lerometers, mounted on the engine and transmission, and accumulating by flight recorder. The helicopter has about twenty sensors that give a large amount of data. System interrogates the sensors several times during the flight, through certain time intervals, and stores them in the flight recorder memory. Processing and analysis of these data is carried out on earth, but information about the functioning units of the helicopter is displayed on a display pilot. The system was tested on a batch of 20 helicopters, participating in hostilities. Installation of the system saved up to USD 45 million on costs related to maintenance and flight operation. On the international market of the helicopter equipment system HUMS enhances their competitiveness.

A similar development of the company Farnell (Russia) – on-board diagnostic system enable to perform monitoring and diagnostics of helicopter gearboxes *by vibration parameters* [28]. The system provides simultaneous organization and processing of data from the vibration sensors in real time, the mathematical signal processing and storing of testing results. System monitoring and diagnostics Farnell installed on several MI-8 helicopters of the Russian company "Aviashelf".

Russian helicopter holding "Vertolety Rossii", a subsidiary of the United industrial Corporation "Oboronprom" and is one of the leading world developers and manufacturers of helicopters, presented at the forum "Engineering Technologies–2012" the project of perspective system *health monitoring and accounting of operating time of aggregates and systems* of helicopter A-HUMS [29]. A similar development for helicopter AH-64A – system Vibration Management Enhancement Program (VMEP) is presented in fig. 1 [30].

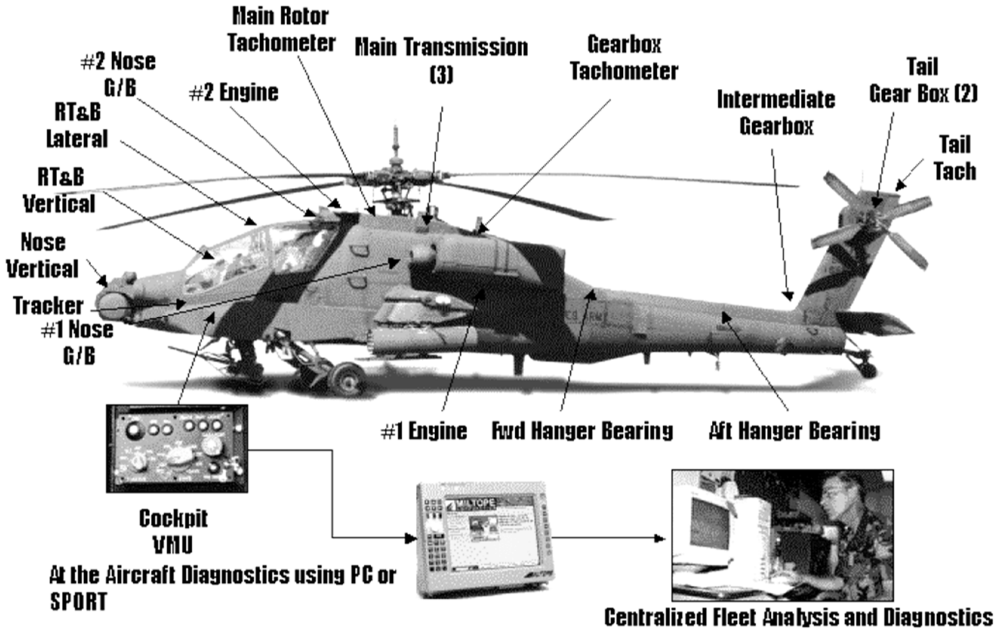

Fig. 1 – Configuration of system VMEP for helicopter AH-64A [30]

The most well-known publications devoted to systems and methods of diagnostics of transmission systems land-based mobile machines is advertising. While the focus is on *diagnosting transmissions of expensive mining equipment* – heavy haulers, excavators, bulldozers, delays which are associated with large economic losses of mining companies. So, in works [16, 23] highlights the questions of application of laboratory methods of physical-chemical and spectral analysis of oils. In operation periodically at maintenance is doing integrated spectrographic analysis of oils worked, for the purpose of determination of the amount of wear products and dirt. Test results revealed violations in the work of units and aggregates of the internal combustion engine, gears of motor-wheels and determine the suitability of oil for further use. Recommendations of fault handling based on these data is issue to repair services, helping to reduce the incidence of breakdowns.

Firm Caterpillar [31] reported of *diagnostic scanner* (Cat ET) of electronic systems that control the motors and electromechanical assemblies of the truck. The diagnosis is carried out on the *amount consumed by the control systems of current*, works in real time and allows promptly to detect and resolve problems and faults.

Firm Komatsu to reduce non-productive costs and increasing the efficiency of transportation has developed a system Komtrax, which uses *a network of satellites* orbiting the earth to transmit information with the truck on the dispatcher's computer [32]. The system allows you to monitor the location and movement of vehicles working on site, to determine the efficiency of drivers, track *fuel consumption, work time in different modes, etc*. Assessment of performance of the most critical components of the machine is the system of control of technical condition of vehicle (VHMS), which can be integrated with Komtrax. The VHMS system sends in real time on the dispatcher's computer *the data about operational modes* of the mechanisms and *problems arising in them*. This allows to quickly contact their customer service and make a decision about maintenance or repair faulty parts of the vehicle, preventing emergency exits.

Liebherr has developed a diagnostic system Litronic Puls [33], which includes real-time monitoring, fault detection and alert, as well as a number of methods of processing data and produce trends of the actual state dump truck. Parameters and methods of diagnosis are not disclosed.

Systems for the diagnosis and monitoring offer next firms: Wenco – system Eventing Systems, Modular Mining

Systems, USA subsidiary of Komatsu, – the MineCare system, Matrikon – system Mobile Equipment Monitor [34, 35], etc.

Named foreign developments are either search and research, or completely closed, as have elements of know-how.

In the Republic of Belarus are also underway to develop systems of control and diagnostics. In particular, at the Minsk automobile plant is actively developing a perspective electronic systems. So, a new on-board system of control and diagnostics is monitors and generates the data on the axle load, fuel used, average speed of truck movement, and digital on a 28-day tachograph allows for any period of time to automate accounting and control of the driver of the vehicle [36].

Belarusian automobile plant jointly with Russian company "Vist-grupp" equips the dump truck BelAZ of loading control system (LCS), operative on base of on-board computer [25]. LCS records in the computer memory speed, weight of cargo, tire pressure, fuel consumption and other maintenance parameters.

At the Joint Institute of mechanical engineering of the NAS of Belarus has developed an indirect method of determining the value of peripheral backlash of transmissions trolley buses on the magnitude of jerk (first time derivative of the longitudinal acceleration) of the body of the trolley for the entire overclocking process, allowing you to control the overall technical condition of the machine transmission, comparing the current value of the backlash with the maximum permissible [37]. Feature is using the transition process and its rate (jerk), but not a steady-state process, prevalent in the earlier approaches. In addition, the proposed adaptive system, which is the results of determining the jerk set corrects the characteristic of the traction motor in operation, thereby ensuring reduced dynamic loads of the transmission trolley buses. The method is simple to implement, focuses on periodically (during maintenance) control integral parameters of wear of transmission. However it has certain limitations, because it does not allow to identify specific defective parts and focuses on periodic maintenance procedures.

Summarizing the aforesaid, we can conclude that the most installed both on foreign and domestic cars *systems is still scheduling*. They provide solution of tasks of control and accounting of the cars work on the track or in career, that is tracking in real time during loading, fuel consumption, speed, location, downtime and violations of technological modes of operation. *An effective system of diagnostics of technical condition of gear transmission units of the mobile machines in the reviewed publications are not represented*. There are no specific techniques and practices in the assessment of the technical condition directly gears and forecasting of a residual life by change their vibroacoustic characteristics in the process of testing or operation.

In the design and creation of methodical tools of vibration diagnostics of the automotive engineering gearings should take into account the peculiarities of their functioning, distinct from drivers of other vehicles and equipment.

First, this is a high load, low operating speeds and relatively low degree of manufacturing precision (7...9 degree). These features create conditions for the development of clearly marked local defects and malfunctions, generating a pulse (shock pulse) in the interactions of the kinematic pairs of units and details. In the operation of gear mechanisms, defects and faults create a series of pulses, which are low amplitude, broadband spectrum and therefore in the practice of vibration diagnostics are often made for the noise. It is known that such defects evolve avalanche and can lead to emergency exits or machines fail, so their diagnosis requires information on problems in early stages of development.

The parameters of the shock pulse arising from tooth changeover teeth of gear wheels, determine the magnitude of internal dynamic load in the gear, which correlates with vibroactivity gear. In turn, the parameters of the shock pulse are determined by the geometrical errors of gear wheels, the inertia-stiffness characteristics, load-speed operating modes, operational malfunctions. Thus, the parameters of shock pulses reflect the relationship between technical condition, dynamic loading and vibroactivity gear mechanisms, and are determined by the degree of development and localization of the defect, therefore, can serve as reliable diagnostic signs.

Control in real time of the vibration signal on the casing of the gearbox, combined with the control of loading of tooth by tensometric methods, allows in principle to estimate the strength of the shock interaction in each pair interlocking teeth, with the subsequent estimation of the actual contact stresses in the engagement and access to the evaluation of actual residual life of gearing.

Another feature of the gears of the transmission systems of mobile machines is that they work in a *constantly changing speeds and loads*. A great influence on the vibration characteristics of the transmission assemblies, in addition to internal factors, by external dynamic effects caused by the terrain and road surface, the degree of loading of the vehicle, qualified driver, etc. In such circumstances, the nature of the vibrations (amplitude and frequency) varies continuously and the use of commercially available instrumentation for vibration monitoring of technical condition of the transmission elements through spectral analysis in the process of machine's operation is very difficult [38–40].

These features functioning of the mobile machines gears lead to the fact that using for their diagnostics standard vibroacoustic means of control is largely limited, because the vast majority of developed diagnostic methods and standard tools are focused on the diagnosis of rotor units of machines operating in *quasi-stationary conditions*, i.e. in conditions when working load and speed change slightly, and the dynamics of the mechanism are due mainly to geometric inaccuracies of manufacture and assembly of parts and their changes during exploitation.

Existing methods of diagnostics of a condition of gears and bearings are mainly based on the analysis of the Fourier spectrum, but this approach is not effective enough, because the spectrum, representing the average for the period of the frequency response, hide faults and defects. Applied instrumental methods of analysis pulse component difficult to implementation and expensive, as they require the use of special expensive equipment. At the same time, they allow us to estimate only the general energy parameters of the pulsed component in a random vibration process that in the operational diagnostics of gear mechanisms are clearly insufficient.

Thus, today the actual problems of development of methods and algorithms of allocation *of pulse component* and determine their parameters under variable load-speed modes of transmission in random process of vibrations, recorded in real time; methods for obtaining corrected vibration spectrum, purified from disturbances and spurious spectral components due to the processes of accessing and processing digital measurement information; practical methods of determining the actual loading of the gear on the amplitude of the shock vibrating impulses generated by the engagement, and thus exit on *the actual residual life* of elements of the transmission units of machines.

On basis of the analysis of known publications is developed the classification of modern systems of diagnostics of the automotive engineering gearings in operation (fig. 2).

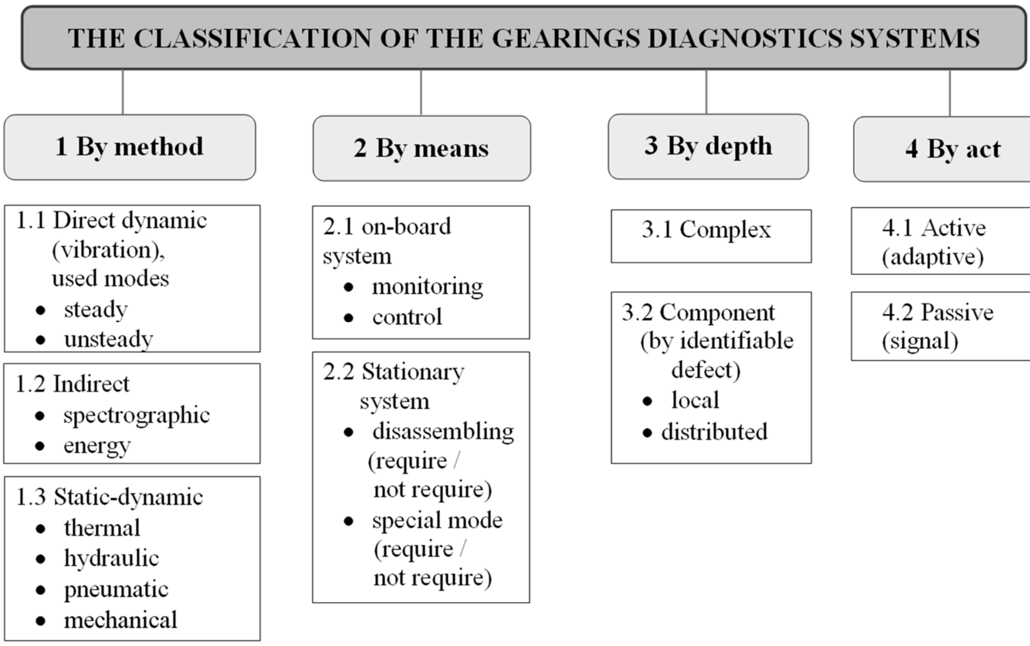

Fig. 2 – The classification of the gearings diagnostics systems in operation

The basis of classification is four main characteristics: 1 – methods of diagnostics; 2 – means of diagnostics; 3 – depth diagnostics; 4 – the act of diagnostics results.

Signs 1 and 2 detailed in more detail.

Methods of diagnostics are separated by 1.1 – direct dynamic (vibration), which can be realized under steady operating conditions of the object, or unsteady modes (transients); 1.2 – indirect methods; 1.3 – static-dynamic.

Direct dynamic (vibroacoustic) methods of functional diagnostics are used in the process of object's work. The indirect methods are: spectrographic method (measurement of wear products in oil); energy methods based on the analysis of current indicators of power flow (the change in efficiency, power, capacity) and integral indicators (energy consumption, fuel consumption over a certain period of time or operating time of the machine). The standard static-dynamic methods include: thermal – by the change of unit's temperature; hydraulic and pneumatic – by pressure changes, pulsations, flow; mechanical methods, including cinematomeria, backlashmeria (the coupling gaps) and the control of deviations of geometrical parameters details.

In used tools of diagnostics the methods can be divided into 2.1 – on-board and 2.2 – stationary. On-board tools perform continuous monitoring or periodic control of the technical condition of the mechanism in operation with using of dynamic or static-dynamic methods of diagnostics. Stationary tools are used to diagnose a repair or during maintenance machines. They are divided into tools that require removal of components (for example, special running-in stands for diagnostics of the transmission units), or not requiring the removal of components, and may or may not require special modes of diagnostics (for example, by lifting or mounting on roller of drive wheels of the machine).

Signs 3 and 4 present enlargement. In depth diagnostics methods are divided into 3.1 – methods allow to carry out a integrated assessment of the transmission, and 3.2 – methods allow to diagnose individual components (units) of the transmission, which, in turn, are divided into methods for diagnosing a single local defect and fault details, and distributed, allowing to assess the damage integral parts in general.

On realizable corrective actions selected 4.1 – active diagnostics (adaptive diagnostics) with a reverse impact on the fault (for example, the monitoring system of a condition of working surfaces of teeth of gears, which in case of pitting adds to the lubrication system of the gear suspension with particles of molybdenum disulfide, forming the microlayer, leveling microcracks and gaps, leveling the surface) and 4.2 – passive diagnostics (signal diagnostics) which is limited to the message about problems in the drive by means of light or sound signals or automatic shutdown.

The analysis of existing methods and tools of diagnostics of a gear transmission of mobile machines suggests that the most promising direction in this area is the development of methods and means of functional vibration diagnostics and vibration monitoring which will allow to effect on-board, continuous and non-disassembly assessment of the technical condition of each element of the transmission under variable load-speed operating mode (in use), automatic (without human intervention) the diagnosis and assessment of residual life of elements.

Development of on-board automated system aimed for the vibrodiagnostics of transmission units of the mobile machines. Known systems and methods of vibrodiagnostics are at least one of the following defects: 1) the diagnostics of equipment working only with quasi-stationary and unstressed conditions (change the speed of the shaft and the load at the time of diagnostics should not exceed ± 5%); b) the lack of algorithms of separation of the informative component of the signal from the vibration caused by external influences on the diagnostic object; c) low degree of automation of diagnostics, necessitating the availability of highly qualified in the field of vibrodiagnostics personnel; d) the impossibility of functioning in real time; e) the presence of hard algorithms, precluding the possibility of changing the software configuration of the computer means; f) diagnosting bearing units only.

In addition, it should be noted the high cost of foreign analogues: the installation of the system HUMS is estimated from 6 to 50 thousand USD [30]; the total cost of the monitoring system based on a CSI 6500 with mounting on open-mine excavator is 200-250 thousand USD [24], etc.

At the Joint Institute of mechanical engineering NAS of Belarus created on-board automated system aimed for the vibrodiagnostics of motor-in-wheel reducers for dump trucks BelAZ (fig. 3). The assignment of the system – prevention of emergency failure of the motor-in-wheel reducers in the operation of the truck.

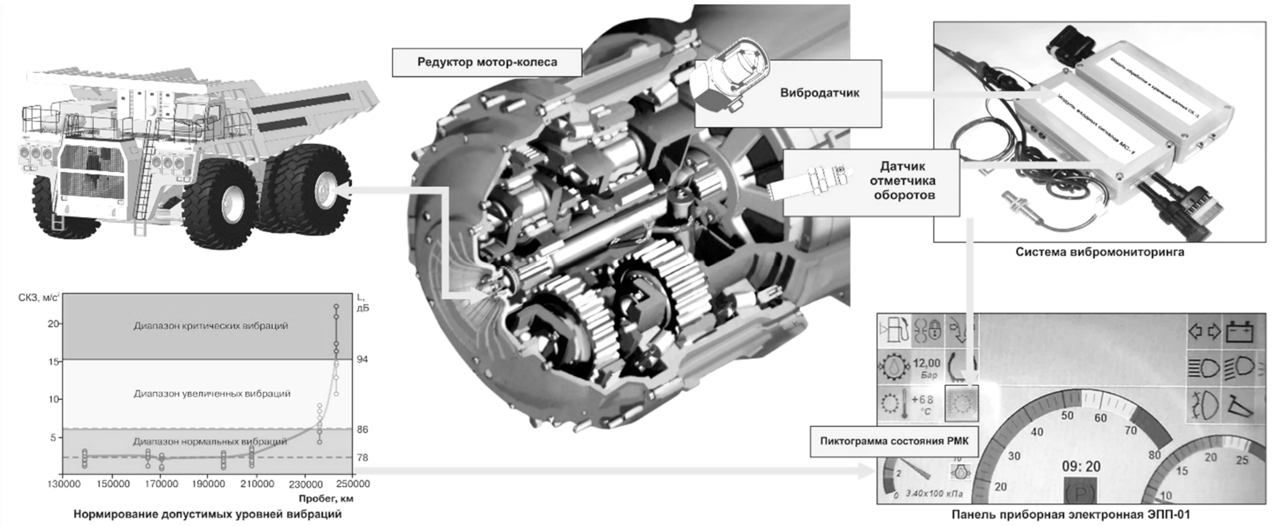

Fig. 3 – On-board system of the vibrodiagnostics of motor-in-wheel reducers for dump trucks BelAZ

The methodology of diagnostics and structure of the diagnostic system based on the use of the most perspective approaches for diagnosing (as proposed in fig. 2 classification) in relation to a specific object. System in depth diagnostics allows to estimate faults of the individual components of the transmission units, their local and distributed faults and defects; in corrective actions system applies to passive (signal) diagnostics; according to the method of diagnosis is to direct dynamic (vibration) based on the analysis of vibration processes; according to diagnostics tools is to on-board diagnostics with periodic vibration monitoring.

The two main components are basic in the system of vibrodiagnostics of motor-in-wheel reducers: *hardware and software* – algorithms capture, processing and analysis of measurement data with subsequent delivery of diagnostic solutions about the technical condition of diagnosis object, and *the object of diagnostics with the indicators of the technical condition* (good, acceptable, unacceptable). On this basis is built the corresponding system of conditions recognition (faults) linking the measured oscillation parameters with specific defects of motor-in-wheel reducers.

The problems of vibrodiagnostics, associated with the irregularity of the gears rotation, solved by using the developed algorithms for processing the vibration signal and the signal of marker of shaft rotation angle, recorded simultaneously in real time. As a result, the temporary realization of vibration signal is converted into implementation on rotation angle of the shaft with the diagnosed gear. The analysis of this implementation with using the method of synchronous accumulation and sequence analysis, adapted to solve the specific tasks, allows the results of one measurement to estimate the parameters of vibration at each shaft of reducer.

Implemented in the on-board system the algorithm of processing of the vibrations parameters in the diagnostics of motor-in-wheel reducers for dump trucks allows to carry out the real-time diagnostics of the state of all gears of motor-in-wheel reducers in the process of machine operation. The system automatically performs periodical scanning of the vibrations sensors of the left and right motor-in-wheel reducer of the dump truck, calculates current values of diagnostic parameters of vibration, compares them with preset threshold values, determines which level of the technical condition they belong, signaling to the driver the icon of the appropriate color on the dashboard (see fig. 3).

The application of this system provides: rapid and non-disassembly control of current condition of all gears of motor-in-wheel reducer; automatic alarm system warning the driver; obtaining information on the vibrational characteristics of elements of motor-in-wheel reducer for analysis services of maintenance; facilitating of fault tracing and decision about the repair; time-saving maintenance; fast payback (the cost of the system does not exceed 1 thousand USD).

The use of vibration monitoring systems for heavy dump trucks of the Poltava mountain-beneficating combine has made it possible:

to prevent accidental damage to the motor-in-wheel reducers;

to improve the technical readiness of the dump truck;

to reduce the time of maintenance of machines at 15...17 %;

to reduce the time of fault tracing of motor-in-wheel reducers in 1,5...2 times;

to increase average time between failures not less than 10...15 %.

In the future this system will be finalized in the expert, additionally providing automatic operation with the database of vibration characteristics of motor-in-wheel reducer, the indication of the residual life of each gear reducer and forecast demand for spare parts.

The perspective directions of vibrodiagnostics development in relation to the transmission units of mobile machines. The need for on-board systems of monitoring and diagnostics is dictated primarily by the need to reduce unplanned downtime of machines, maintenance costs, improving reliability and efficiency of engineering operation. The transition to the service drive machines according to the *actual condition* provides increasing safety, performance of mobile machines, as well as ecological compatibility (by reducing the content of toxic substances in the exhaust gases).

The basic perspective directions of development of the mobile machines gearing vibrodiagnostics can be formulated as follows:

– the development of theoretical propositions, based on the research of dynamic model of elastic impact of solid bodies in relation to problems of vibration diagnostics, and linkages to dynamic processes, due to the shock interaction tooth profiles when tooth changeover, with the parameters of the vibrations;

– the development and testing of computational-experimental methods for estimating the parameters of the technical condition of mechanical drives on their vibroacoustic characteristics, including the identification of the nature, character, level, frequency content, the major resonances, damping and other characteristics of the oscillatory systems, and the study of processes connected with recognition of the dynamic structure of the system depending on change of parameters of the gearing, the study of laws of damage accumulation and their relationships with changes in the parameters of dynamic structures, under variable load-speed modes of operation of gear mechanisms;

– upgrading the methods of the vibrations standardization associated with the classes of the technical conditions of gear mechanisms to create algorithms for automated vibration monitoring of transmission systems and their elements;

– the generation and application of real-time on-board tools for vibration monitoring of technical condition and forecasting of a residual life of the transmission units of automotive engineering in terms of bench, field tests and operation;

– creating a database of experimental data on vibration characteristics of the transmission components of machines to improve the reliability of diagnosis;

– the creation of expert systems of vibration diagnostics based on the use of artificial intelligence in order to exclude the man from the diagnostic system;

– development of a combined on-board control and diagnostic systems realizing the functions of dispatching and diagnostics of technical condition of the basic criteria units and elements of the machine with the creation of its electronic service book on the basis of Internet technologies;

– creating the methodology for servicing vehicles, associated with the transition from planned precautionary maintenance to maintenance based on technical condition, based on the implementation of on-board systems of the vehicles components continuous monitoring.

It is necessary to take account of such important problem questions as the cost of the system of vibration diagnostics, the level of spending on its maintenance, reliable activity in various operating conditions of machines, the accuracy of the diagnosis and a number of other issues specific to the on-board control and diagnostic equipment of mobile machines.

Conclusion. On the basis of analysis of the state of vibrodiagnostics of the mobile machines gears and transmission units shown the tendencies of development of this direction and proposed the classification of modern methods of diagnostics, covering existing and perspective approaches, what allow to initiate the development of relevant directions and practical techniques.

The most perspective and popular approaches are approaches, which are relate with:

– further the individualization and more detailed study of objects, in particular, with the research and evaluation of loading each pair of interlocking teeth, linkages to the loading teeth and the parameters of the vibrations measured on the gearbox housing;

– the creation and practical application working in real-time on-board tools for vibration monitoring of technical condition and prediction of residual life of units in operation.

The availability and equipping of mobile machines such facilities is a key criterion for a transition from the high-cost preventive maintenance of machines to their maintenance according to actual condition, which significantly reduces operational expenses for maintaining machines in working condition, and thus increases the attractiveness and competitiveness of the vehicles produced.

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