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METHODOLOGY OF EXPERIMENTAL AND ANALYTICAL RESEARCH OF TECHNICAL SYSTEMS

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Abstract. *An analysis of modern measuring systems for assessing static and dynamic loads was carried out. A multifunctional measuring system has been developed for the study of operational load modes and assessment of the stress-strain state of technical systems. Real-time experiments of the operating load of mobile machines and the stress-strain state of the overhead crane beams were conducted.*
Key words: *design, load, research, measurement, technique, multifunctional measuring system.*

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1. INTRODUCTION

Metal structures of buildings, modern machines structures, their equipment, mechanisms and aggregates are being continuously developed and improved to increase power, speed, payload capacity, productivity and other parameters, which, with the simultaneous desire to reduce metal consumption, causes increased dynamic loads and the growing role of oscillatory processes in the structural elements and machines.

Harmful vibrations, impacts and their complex influence can violate the programmed laws of motion of machines, mechanisms and their structural elements. They can also cause resonance phenomena and lead to failures and complete system breakdown. An increase in the level of dynamic loads in structural elements, nodes and connections, and the related increase in stress, lead to a decrease in the load-bearing capacity of the elements, the initiation of cracks, and the occurrence of fatigue failures [1].

The failure of any unit or supporting structure causes the entire machine to be at a standstill, which leads to significant losses. Solving this problem by increasing safety margins leads to an increase in the initial cost of the machine, and the obtained mass-inertial parameters turn out to be unreasonably overrated [2].

Since mobile technical objects, primarily their mechanical parts, are characterized by a significant variation in operating conditions and load conditions, the creation of new equipment, modernization and improvement of existing equipment without the probable dynamic load characteristics in real operating conditions does not correspond to modern level, and even more to the promising level of machines.

In this regard, the objective of the work is to create a methodology for assessing the static and dynamic parameters of mobile equipment based on experimental research.

2. TEST METHODS ANALYSIS

The development of the theory of mobile machines at the current stage is carried out in next directions: ensuring the functional (operational) properties of the mobile machine;

assessment of its operating conditions and consideration of loading modes, static calculation, assessment of the mobile machine durability [1, 2].

To solve these problems, such approaches and methods are used as analytical studies, finite element analysis, virtual tests of machines and individual units, virtual experiments (HIL-technologies), full-scale machine tests [3, 4, 17].

The general design cycle of a technical or information system can be presented in the form of a V-model (Fig. 1).

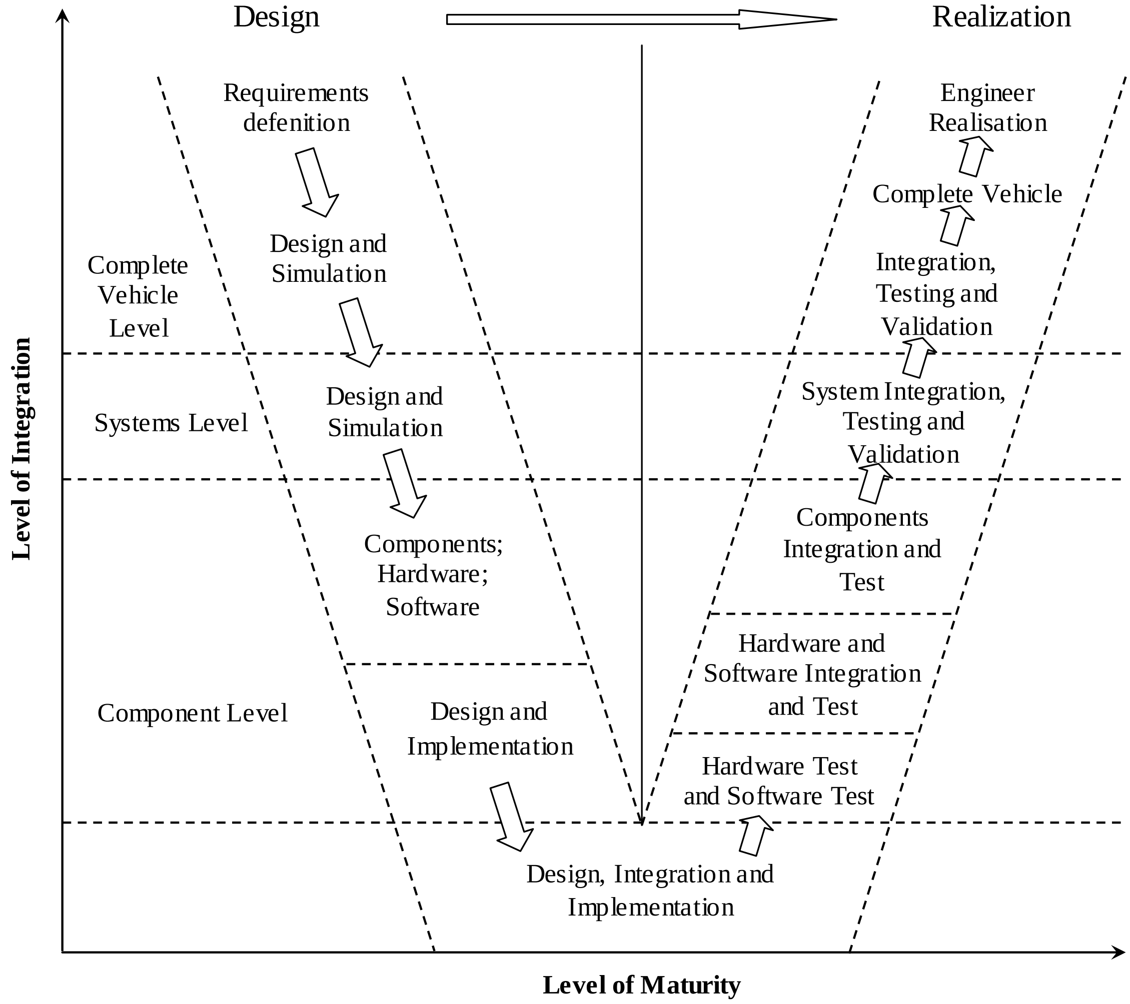


Figure 1. Model Based Design

The left part describes the conceptual requirements, where the functional and technical characteristics of the vehicle, its systems and components are defined. The right side indicates the verification and testing process. At the same time, in the process of developing a vehicle, the car concept is first broken down into systems and components, and then re-integrated into a whole vehicle.

Modern manufacturers of mobile equipment perform a set of virtual tests (for example, engines) in order to evaluate the created structures for compliance with the requirements of many norms and rules. Considering that 90% of innovations in the automotive industry are carried out at the expense of electronics, mechanical systems are closely related to electronics. In this regard, parallel development of the technical part and software is required [5].

Model-oriented design, based on the concept of «in the loop testing», has several options that depend on the object of testing. If the test object is a model, then this approach is called «model in the loop» (MIL), if the software is «software in the loop» (SIL), if the device prototype is «processor in the loop» (PIL) , and if the unit is ready – «hardware in the loop» (HIL). MSC ADAMS, MPP LS-DYNA, etc. software are used for virtual tests.

The HIL hardware and software testing technology has moved to a new level of creation of technical objects and systems in recent decades [6]. The main feature of this transition is that some components of the virtual model began to be replaced by real units. Thus, in the HIL system created by the authors [6], the internal combustion engine is real, and the car model is virtual. Bench equipment for HIL testing of this type is produced by Froude and Horiba. The reproduction of the studied operating conditions of a real engine and its systems during the virtual movement of a car, which reflects the dynamics of the car and the dynamics of its wheels in laboratory conditions, significantly reduces the time for design work under the conditions of verified virtual models and loading modes; they must be verified by full-scale tests of machines determined by the experimental plan.

A similar situation applies, for example, to ensuring the reliability of a vehicle or body. Frame or body structures meet the requirements of strength and durability due to correctly selected shapes and sections, various combinations of materials and hybrid technologies for their connection. For this, the high quality of forecasting and the effectiveness of modelling methods are important. Achieving both factors is possible only with constant comparison of simulation and test results. Thus, according to the V-model, small connecting nodes and elements are physically tested for strength and fatigue, and then the most effective types of them are implemented in a frame structure or body, and then in a virtual and full-scale experiment of the vehicle as a whole.

It is worth noting that the assessment of the resource and viability of the design object [7] accompanies the entire design cycle, starting from its structural and schematic representation during conceptual design and ending with the final design positions (Fig. 1).

The need for full-scale tests of mobile equipment is also related to the synergistic effects inherent in every complex system [8, 9].

The principle of synergy (dependence of elements) is fundamental and provides a basis for explaining the differences in the behaviour of the system in comparison with the behavior of individual elements. Typical manifestations of the effects of the interaction of the elements that make up the technical system are:

- oscillatory processes of the mechanical system, when minor oscillations can lead to disproportionate disturbances - resonance phenomena;
- the dependence of the stress-strain state and resource of the elements on the general level of load caused by the operating conditions of a specific mechanical system. This property is global and inherent in all mechanical systems; it differs in the degree of detection from a strong quasi-deterministic connection to a weak probabilistic one.

In our opinion, another manifestation of synergy is the connection between the damageability of the element and the bearing capacity of the mechanical system as a whole. The specifics of this phenomenon require additional research.

The listed effects are typical for mechanical systems and are significantly related to the operating conditions of technical systems. They lead to the deviation of the behaviour of the mechanical system from the expected one, which is predicted on the basis of the characteristics of the elements. A typical design cycle of a mobile machine can be depicted in the form of a diagram (Fig. 2).

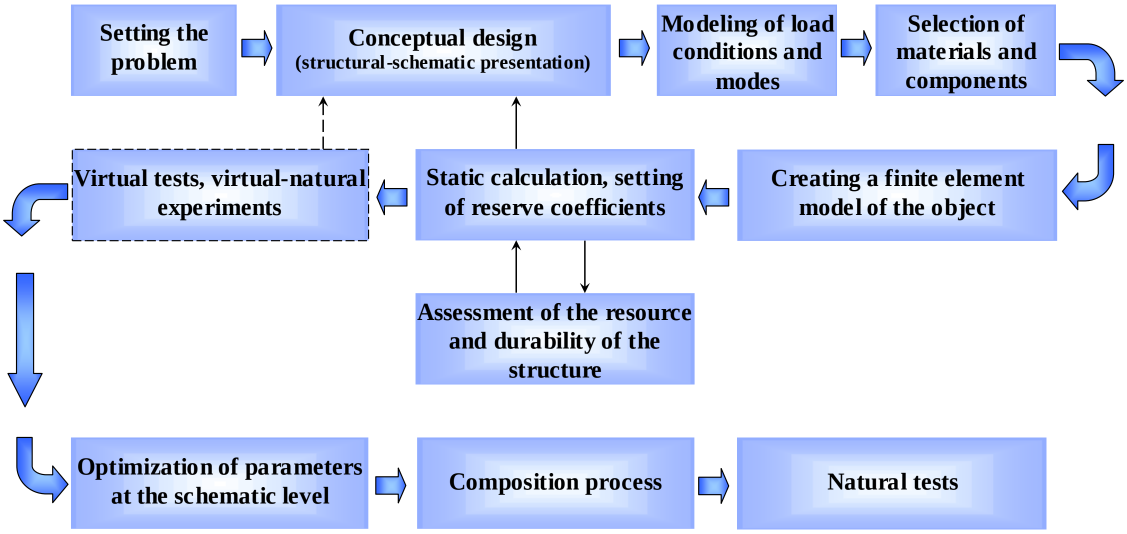


Figure 2. Typical mobile machine design cycle

The initial stage is concept design, which allows assessing the possibilities, ways and means for its implementation. At this stage, the structural and schematic presentation of the design object is decided. Next, modelling of load conditions and modes, selection of structural elements, materials and components is carried out.

Computer modelling [4] with the use of specialized software (SolidWorks, Lira, ANSYS, etc.) is an important element of the design of mobile machines under the conditions of setting probable loading modes of their operation.

The usefulness of simulation modelling is that it allows you to explore and experiment with the internal interactions within a complex system. In particular, static analysis (Static Analysis) is used to determine movements, stresses, and deformations in the load-bearing structure caused by constant loads that do not cause significant inertial and damping effects. Based on the results obtained during the design of the simulation model, it is possible to determine ways to improve the system being modeled (for example, reducing stresses in the frame nodes). This effect is achieved by modifying the design solutions (Design modification or Re-design) of the frame structure, for example. Therefore, modification of design solutions is a process of achieving a certain set of specifications.

Model-oriented design and virtual testing (shown in dotted line in Fig. 2) are additional elements of the development process that allow reducing the time frame for the development of a technical system.

Therefore, to determine the real load of parts and structures of machines at the stage of design and testing of experimental samples in real operating conditions, field research methods are of great importance, which allow obtaining reliable data for evaluating the reliability of machine operation under stochastic changes in the operating conditions of mobile equipment [10].

In particular, special measuring devices are used for the experimental study of machine motion parameters (displacement, angular velocities and accelerations), forces and VAT in structural elements: angular velocity sensors, accelerometers, tensor resistors, dynamometers, etc.

A modern experiment, as a rule, requires synchronous registration of values, such as movement parameters, forces, time, pressure, temperature, etc. [11]. Therefore, multi-functional information and measurement systems are now widely used, which provide receiving and processing of information from various sensors in real time.

3. MULTIFUNCTIONAL MEASURING SYSTEM

The new generation of measuring systems for assessing static and dynamic loads is distinguished, first of all, by the use of modern computer equipment, in particular portable, and software for synchronous registration of values and processing of information from various types of sensors in real time. High metrological and operational characteristics are defined by sensors and equipment of foreign companies «Hottinger» (Germany), «Crystal instruments» (USA), «ECON» (China) and others. [12].

Stationary and mobile multifunctional measuring systems (MMS) are distinguished. Stationary MMS are used for bench and laboratory tests [11]. They are powered by a 220 V network. On-board systems work in real conditions of machine operation. Therefore, they are subject to strict requirements to ensure performance under extreme environmental influences, such as harmful vibrations during field tests of machines, temperature changes, high humidity, etc. On-board systems should be compact, possess autonomous power from built-in batteries or power from the batteries of a mobile car.

As you can see, MMS are diverse in performance, purpose and cost. Thus, for static tests (estimation of the stress-strain state of structures during research and design work, metrology and automation of technological processes) the modular digital universal system «MGC plus» (HBM company) is used [12]. Up to 100,000 channels can simultaneously and synchronously carry out analog-to-digital conversion, digital filtering and signal scaling, for example during multi-point ground tests of aircraft.

Dynamic signal analyzers of the MI series (ECON company) [13] are designed for testing in both laboratory and field conditions. They work independently of the control computer, have a wide library of software modules for measurement and analysis of vibrations and noise, modal analysis, acoustic analysis, registration of shocks and impulses, machine condition monitoring (MVHM). Signal registration frequency up to 204.8 kHz per channel.

Systems of the Spider-80 series (Crystal Instruments, VCS) [14], which perform dynamic signal analysis (Dynamic Signal Analysis, DSA), remote condition monitoring (RCM), possess similar characteristics and a range of measurements.

The theoretical foundations of the functioning of such information and measurement systems are described in [15, 16].

In accordance with modern trends in the development of experimental studies of mechanical systems in real operating conditions, a multifunctional measuring system (MMS) has been developed. The developed MMS operates in autonomous mode through a microcomputer built into the crate with information registration on a built-in flash drive or in a system with an external computer when communicating through the LPT port (Fig. 3) [10].

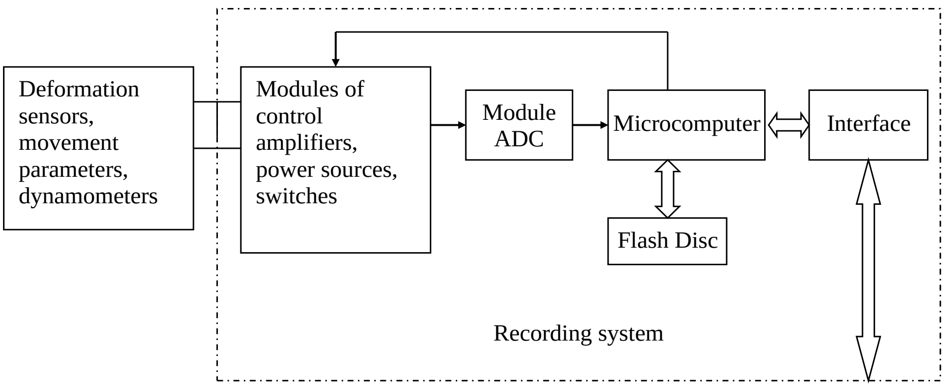


Figure 3. Schematic diagram of a multifunctional measuring system for the study of operational load modes and assessment of the stress-strain state of mobile machine structures

Main characteristics of the measuring system.

1. The structure of the measuring system:
   – universal recording device;
   – a set of special devices:
     1) dynamometers of three-component dynamic characteristics;
     2) sensors of angular velocities;
     3) vibration acceleration sensors;
     4) dynamometric traction of the three-point hitch system;
     5) tensor resistors;
     6) devices for energy assessment of machines, etc.;
   – software.
2. Basic technical characteristics of the registration system:
   – the total number of measuring channels is 8;
   – use of channels – combined;
   – sampling frequency per channel 1-2000 Hz;
   – the time of information registration in automatic mode at the maximum sampling frequency is 52 min.

The recording system (Fig. 4) provides amplification, filtering, and registration of static dynamic signals coming from the sensors. The application program package ensures the functioning of the system and statistical processing of the received data.

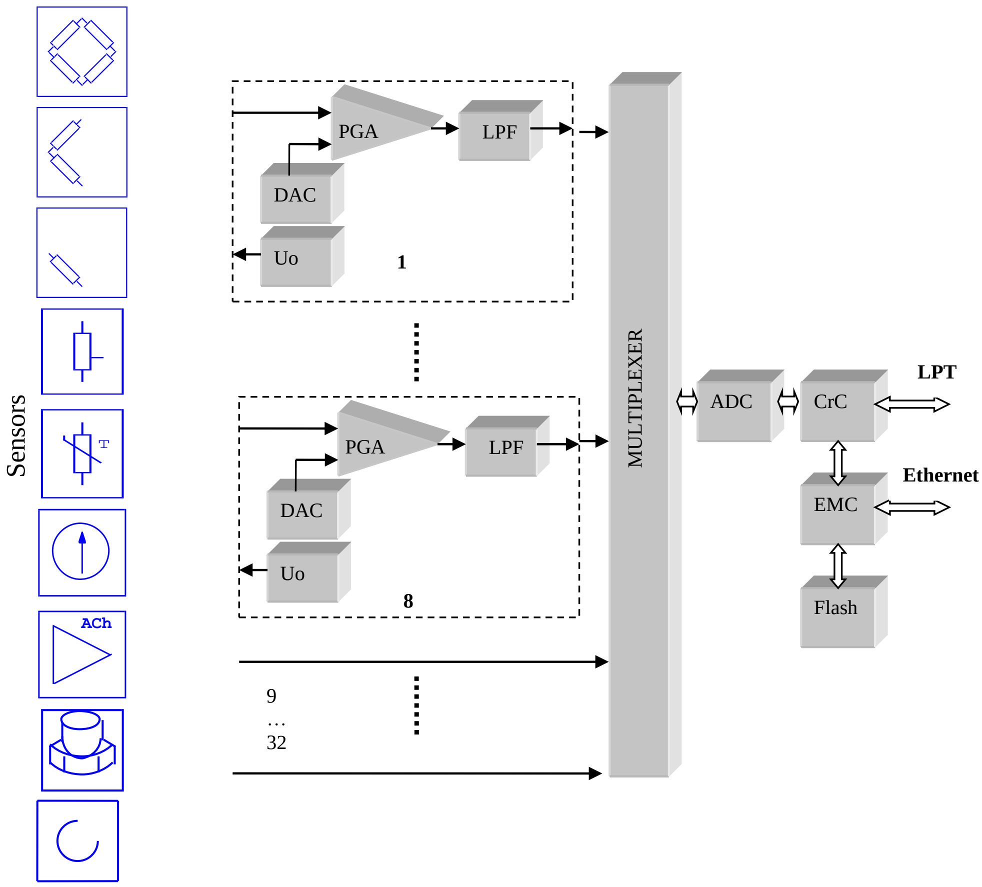


Figure 4. Structural diagram of the recording system

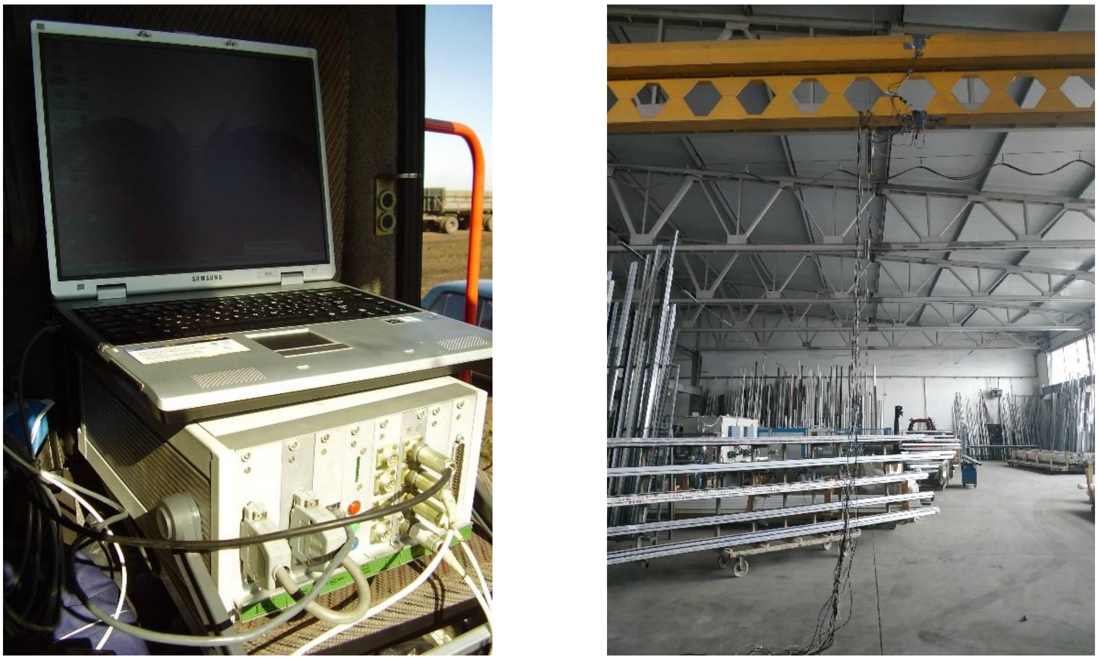
The recording system works as follows. Normalized measuring signals from the sensors are sent to the high-speed analog-to-digital converter ADC through the MULTIPLEXER switch. Further transmission of information is carried out through the CrC crate controller. When working with an external computer, information is exchanged through a parallel LPT port.

When working in offline mode (without an external computer), information is recorded on a Flash disk using the built-in EMC microcomputer. In this case, setting the necessary operating modes and reading information is carried out via Ethernet, providing the possibility of working in a local network.

Analyzing special technical indicators, it should be noted that providing analog filtering has undeniable advantages in conditions of significant interference. When working with an external computer, the developed recording system (like foreign systems [12-14]) has a higher sampling frequency. At the same time, when working in autonomous mode, the sampling frequency is significantly lower and inferior to foreign measuring systems. However, the achieved maximum value of 2 kHz per channel in the offline mode of the system allows complete covering the range of tasks of electrical measurements of mechanical quantities during tests of mobile equipment.

Testing of the measuring system was carried out under its operation with an external portable computer, as well as in offline mode, when information was recorded on a flash drive using a microcomputer built into the system unit. The high reliability of the measurement system in real operating conditions was noted.

Fig. 5a shows the general view of the multifunctional measuring system when conducting research on agricultural machinery in the field of operation, in fig. 5,b shows the study of operational load modes of bridge crane structures with a span of 24 m in production conditions.



a) b)

Figure 5. Field studies of the operational load of mobile equipment and the stress-strain state of durable structures in the field (a) and production conditions (b)

A fragment of the recording (0.25 s) of sensor signals is shown in Fig. 6 (1–3 – displays of electrotensive resistors, 6 – displays of the accelerometer and 8 – displays of the angular velocity sensor).

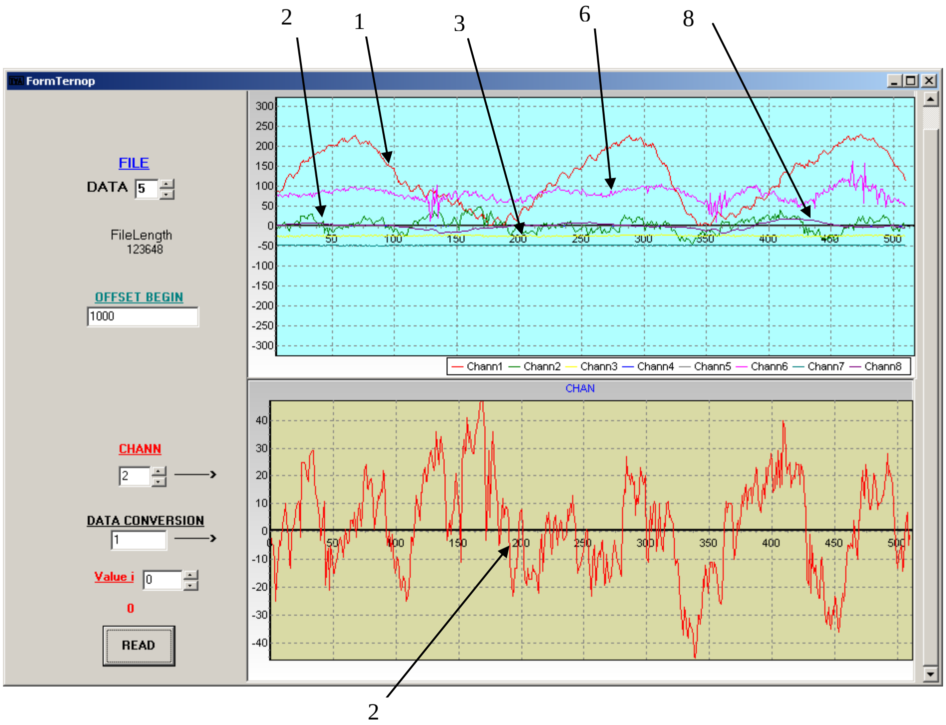


Figure 6. Fragment of sensor signal recording

4. CONCLUSIONS

The developed multifunctional measuring system allows solving the most difficult, in our opinion, problems of experimental research at a new qualitative level: determining the real load dynamics of mobile machines and researching the stress-strain state of structural elements and aggregates.

Such studies are carried out during the production of new or modernization of existing equipment, as well as for recommendations on predicting their durability and residual service life.

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МЕТОДОЛОГІЯ ЕКСПЕРИМЕНТАЛЬНО-АНАЛІТИЧНИХ ДОСЛІДЖЕНЬ ТЕХНІЧНИХ СИСТЕМ

Микола Підгурський[1]; Микола Сташків[1]; Іван Підгурський[1]; Василь Олексюк[1]; Олег Підлужний[1]; Денис Биків[1]; Іван Борис[1]; Руслан Булаєнко[1]; Віктор Сташків[1]; Андрій Мушак[2]

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Резюме. *Проаналізовано особливості розвитку теорії сучасних машин та конструкцій. Розглянуто типові цикли проектування машин та конструкцій, що описуються за допомогою V-моделі. Розглянуто особливості проектування рамних конструкцій у загальному випадку та несучих конструкцій мобільних машин зокрема. Зазначено, що на сучасному етапі проектування конструкцій важливим елементом є комп'ютерне моделювання за умов задавання вірогідних навантажувальних режимів їх роботи. У зв'язку з цим обґрунтовано проведення натурних та напівнатурних експериментальних досліджень. Проаналізовано сучасні вимірювальні системи для оцінювання статичних та динамічних навантажень. Відповідно до сучасних тенденцій розвитку експериментальних досліджень розроблено багатофункціональну вимірювальну систему для дослідження експлуатаційних режимів навантаження та оцінювання напружено-деформованого стану технічних систем із використанням давачів різного типу (тензорезистори, акселерометри, давачі кутових швидкостей). Наведено структуру вимірювальної системи та її основні технічні характеристики. Пакет прикладних програми забезпечує функціонування системи та статистичне опрацювання отриманих даних. Наведено порівняльний аналіз розробленої багатофункціональної системи з аналогічними за функціональними характеристиками приладами інших розробників. Проведено натурні дослідження експлуатаційного навантаження мобільної техніки та напружено-деформованого стану балок мостових опорних кранів у польових та виробничих умовах відповідно. Випробування розробленої вимірювальної системи проведено при її роботі як з зовнішнім портативним комп'ютером, так і в автономному режимі. Відзначено високу надійність роботи вимірювальної системи при проведенні експериментальних досліджень як у лабораторних, так і в реальних умовах експлуатації конструкцій.*

Ключові слова: *конструкція, навантаження, дослідження, вимірювання, методика, багатофункціональна вимірювальна система.*

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