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EQUIPMENT AND TOOLS TO INVESTIGATE THE SPATIAL FORCE LOAD OF COMPLEX MECHANICAL SYSTEMS

ОБЛАДНАННЯ ТА ПРИЛАДИ ДЛЯ ДОСЛІДЖЕННЯ ПРОСТОРОВОГО СИЛОВОГО НАВАНТАЖЕННЯ СКЛАДНИХ МЕХАНІЧНИХ СИСТЕМ



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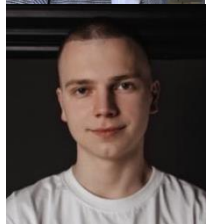
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**Abstract.** The article examines the justification for designing and creating the equipment to determine the characteristics of spatial force loading on physical models of continuous earthmoving machinery actuators in real time when digging the soil. It also discusses measuring and registering tools for recording the parameters of force load when developing the soil.

Research objective: The creation of equipment and registering tools for determining the characteristics of spatial force load of complex mechanical systems.

Research object: Operating equipment of trenching and excavation continuous earthmoving machinery.

Research method: Experimental.

As a result of the conducted research, measuring equipment has been developed in the form of a strain gauge suspension for model structures of the studied operating equipment for trenching and excavation machinery. The equipment enables real-time measurement of the magnitudes and coordinates of applying spatial components of external forces and their moments to the studied mechanical system. Based on strain gauge measurements, determining the magnitudes of external forces and their moments is provided mathematically and by adding or subtracting electrical signals received from strain gauges of corresponding pairs of strain links.

A measuring and registering complex with a set of analog and discrete sensors has been developed to register actual loads applied to the studied operating equipment of earthmoving machinery. This complex enables measuring and registering the actual loads in the system with an accuracy of  $\pm 5\%$  of the real value.

The complex enables to read and record the received information on a micro SD memory card, to convert the received signals into digital code, and store the received information (measurement results) on a digital medium for its further processing and analysis.

**Key words:** force, moment, mechanical system, strain measurement, earthmoving machinery, measuring complex, sensor, memory card, digital code, amplifier, strain gauge module

#### **Problem statement and its topicality**

Creation and ensuring the effective operation of complex mechanical systems with spatially variable in magnitude and time loading is a rather complicated mechanical task. It should be noted that the creation of these systems does not depend on their technological purpose. An essential condition for the creation of these systems is complete information about the extent, nature of the change in magnitude and time of external loads acting on the system created.

The information about external loads in the system is necessary not only for creating the mechanical system itself, but also for ensuring its operation, in other words, for creating a control system for the specified system.

External loads acting in the system are determined by calculation or experimentally. The calculation method does not always enable to determine the external loads, especially when the directions of the external forces components and the points of their application are uncertain.

As for obtaining the necessary information, testing the created systems on models, both mathematical and physical, has been promising recently [1, 2]. More complete and objective information about the loading of complex systems under the conditions of their real operation can be obtained due to experimental studies of physical models of complex mechanical systems. The example is continuous earthmoving machinery on their physical models.

The main requirement for performing such experimental studies is to ensure continuous measurements of the spatial components of external forces and the moments of action of these forces registering their magnitude, patterns of change in time due to changes in the design parameters of the system and its operating modes.

Regarding continuous earthmoving machinery, especially when its operating equipment is simultaneously moved along all three coordinate axes under the action of external loads, it should be noted that to perform the aforementioned studies the necessary equipment was not available and had to be created.

#### **The analysis of published research results**

Experimental determination of external loads on the system under study (or its physical model), as well as registering the coordinates of these loads application in time by the magnitude and nature of the action

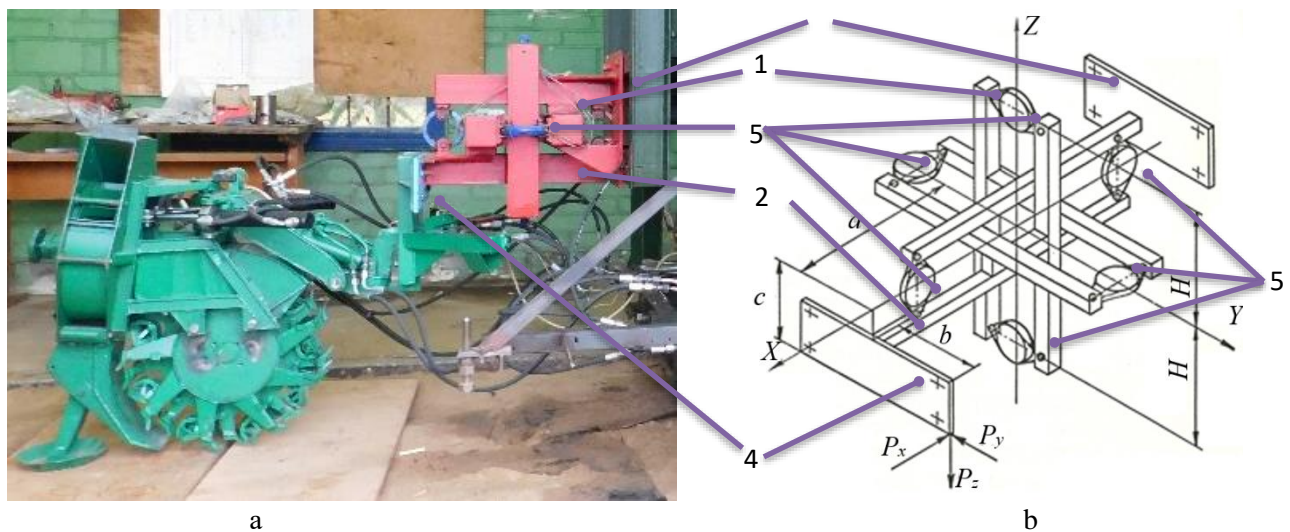
(static or dynamic loads) and the patterns of change is a rather complicated task. Currently, equipment designs [3-7] and apparatus are known to be used to perform this task. It should be specified that the equipment and measuring tools known to the authors cannot be used to solve the problem of experimentally determining external loads acting on the operating and running equipment of continuous earthmoving machinery (trench and ditch machines) for various reasons. As a rule, the existing equipment [8, 9] enables to determine the action of external forces in one plane which does not clarify the load of the object studied. Measuring equipment for registering the loads on each of the coordinates of the X, Y, Z axes separately does not enable to estimate the spatial load of the system as a whole at a fixed point of time with sufficient accuracy. The existing equipment for determining the spatial force load of machine metal structures, their operating and working equipment, and drives is quite bulky and massive. It is therefore difficult for practical use.

Besides, it should be noted the complexity of registering the external loads on complex mechanical systems, when these loads act simultaneously at many points of the system under study and require the actions both in magnitude and in nature to be registered simultaneously. Certain designs of measuring tools [10-13] do not enable to simultaneously register the action of external forces at many points of the system (there may be several dozen of them), which significantly reduces the informativeness of the performed studies. In order to improve this situation, a special cycle of work was carried out. It was aimed at determining the parameters of the spatial force load of complex mechanical systems and registering these parameters.

**Task setting** implies the creation of equipment for determining the characteristics of spatial force loading of actuator models for continuous earthmoving machinery (trench and ditch) when digging the soil in real time. Measuring and registering equipment for force load parameters is also to be created.

**Presentation of the materials**

The spatial force load characteristics for the model of the studied earthmoving machinery actuator when digging the soil in real time can be measured with a universal strain gauge suspension created at the Department of Road Machinery of NTU, [14] Fig. 1.



a – design of the strain gauge suspension; b – scheme of strain link installation in the strain suspension  
1,2 – metal structures; 3,4 – mounting plate; 5 – strain links

**Figure 1** – Universal strain gauge suspension

The strain gauge suspension consists of two spatial all-welded metal structures interconnected by special strain links using embedded hinges. Using the Cartesian coordinate system, it enables to register three forces and three moments of these forces acting on the studied structure of the operating equipment when developing the soil in real time. These parameters include: traction force  $T$ , vertical component of the soil digging force by the rotor  $P_v$ , lateral force  $P_l$ , which can act on the actuator under study, coordinates of the application points

of the specified forces to the soil-developing actuator relative to the center of the strain gauge suspension [14]. In addition, relative to the stern of the base chassis (the center of the strain gauge suspension), normal  $P_N$  and tangential  $P_\tau$  forces acting on the rotor cleaning bearing plate, moment  $M_b$  acting on the stern of the base chassis in deepening-excavating process of the actuator can be registered.

To assess the action of unknown external forces, denoted as  $P_x, P_y, P_z$ , the application center of which is shifted relative to the center of the strain gauge suspension  $O$  to unknown distances ( $a, b, c$ , respectively), an equation system of forces and moments of forces relative to the specified coordinate system has been developed, which describe the system equilibrium.

Each strain link operates only in compression or tension, the reactions in the strain links are denoted as  $R_1, R_2, R_3, R_4, R_5, R_6$ . Therefore, the equation system characterizing the spatial load of the strain gauge suspension (the stern of the basic chassis of the "full-scale" machinery) takes the form:

$$\begin{cases} \sum_{i=1}^n F_{ix} = 0; \sum_{i=1}^n F_{iy} = 0; \sum_{i=1}^n F_{iz} = 0; \\ \sum_{i=1}^n M_{ix} = 0; \sum_{i=1}^n M_{iy} = 0; \sum_{i=1}^n M_{iz} = 0; \end{cases} \begin{cases} R_3 + R_4 - R_x = 0; \\ R_5 + R_6 - R_y = 0; \\ R_1 + R_2 - R_z = 0; \\ (R_5 - R_6) \cdot H - P_y \cdot c - P_z \cdot b = 0; \\ (R_2 - R_1) \cdot H - P_z \cdot c - P_x \cdot a = 0; \\ (R_3 - R_4) \cdot H - P_x \cdot b - P_y \cdot a = 0. \end{cases} \quad (1)$$

Based on the measured absolute values of the reactions  $R_1$ - $R_6$  in the corresponding strain links, a system of six linear equations with six unknowns  $P_x, P_y, P_z, a, b, c$  is solved. As a result, the moments of the forces  $M_x, M_y, M_z$  relative to the entire specified coordinate system and the forces  $P_x, P_y, P_z$  themselves are determined.

All six strain links operate in pairs:  $(R_1, R_2), (R_3, R_4), (R_5, R_6)$ . To determine the forces, algebraic addition is performed. And to determine the moments of forces, subtraction of the absolute values of the force reactions in the corresponding pairs of strain links is carried out, i.e.:

$$\begin{cases} P_x = R_3 + R_4; \\ P_y = R_5 + R_6; \\ P_z = R_1 + R_2; \end{cases} \begin{cases} M_x = (R_5 - R_6) \cdot H; \\ M_y = (R_2 - R_1) \cdot H; \\ M_z = (R_3 - R_4) \cdot H. \end{cases} \quad (2)$$

This equation system can be solved not only by the traditional algebraic method, but also by adding or subtracting electrical signals coming from the strain gauges of the corresponding pairs of strain links.

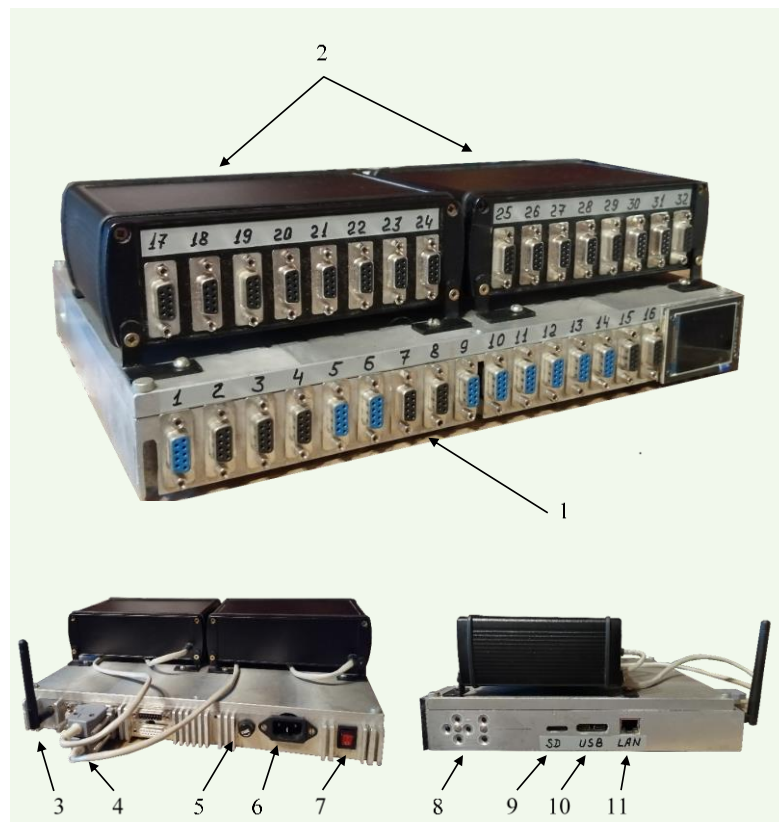
During experimental studies in the force load of the operating equipment of continuous earthmoving machinery when developing the soil, a specially created measuring and registering complex (Fig. 2) with a set of analog and discrete sensors was used to register real loads. The tools of the complex are capable of reading signals from the strain gauges (for example, a universal strain gauge suspension), as well as from pressure sensors, displacement (linear and angular), speed sensors, and registering the position of final switches in real time. The complex enables to record the received information on a micro SD memory card, convert the received signals into digital code, and store the received information (measurement results) on a digital medium for its further processing and analysis.

The complex (Fig. 2) includes:

- sixteen-channel unit for amplifying and recording of signals from measurement sensors (UAR16);
- two eight-channel amplification units (AU8).

The UAR16 unit of the complex includes two eight-channel strain gauge modules, a control unit and a

power supply unit. It amplifies signals from the strain gauges of the strain gauge suspension, which are connected to the unit using "bridge" or "half-bridge" schemes, and signals from analog sensors.



1 – 16-channel amplification, recording and control unit (UAR16), 2 – 8-channel amplification unit (AU8).

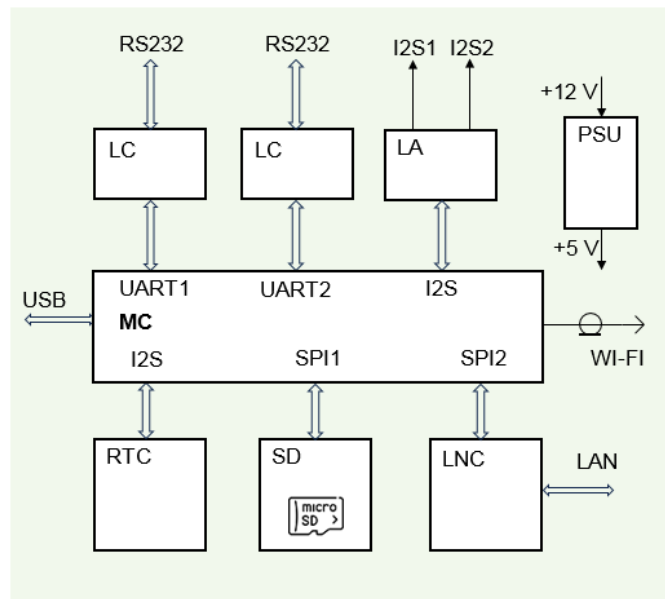
**Figure 2** – General view of the complex

The strain gauge module of the complex (UAR16) is designed to provide power to strain gauges with precision DC voltage with an ultra-low oscillation level, to amplify and convert signals from strain gauges into digital code, and to correct "zero" when the strain gauge "bridge" or "half-bridge" is imbalances.

The block diagram of the strain gauge module is shown in Figure 3.

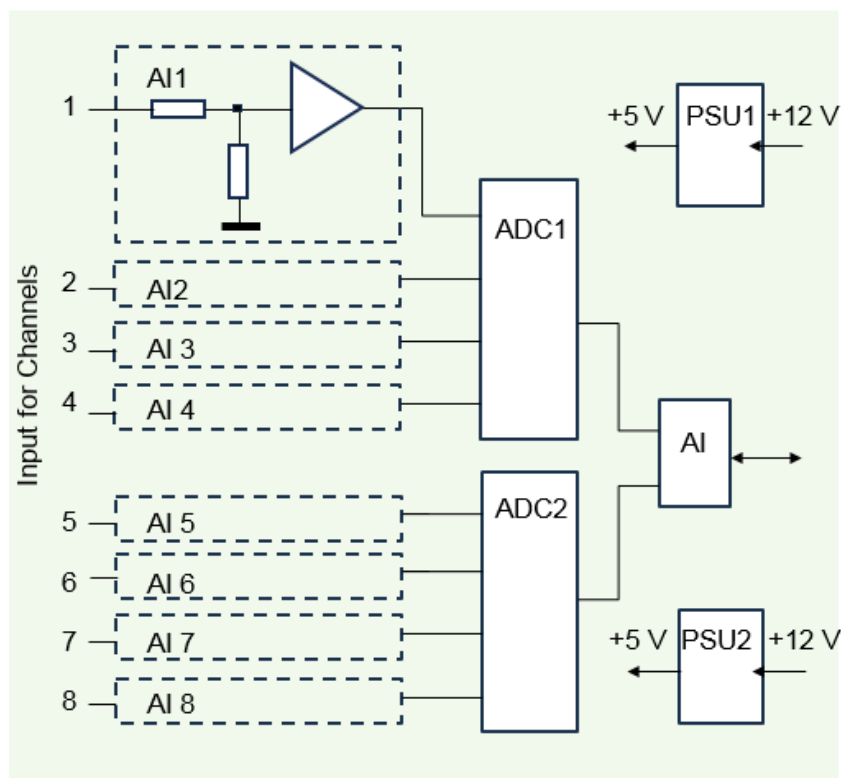
The module is controlled by an 8-bit microcontroller with built-in program memory. It includes a "bridge" of preamplifiers with a differential input and a built-in circuit for additional balancing of the strain gauge bridge ("zero" correction circuit). The zero correction circuit includes a digital-to-analog converter (DAC), which is controlled by a microcontroller. The signal at the DAC output is summed with the signal from the strain gauges, which register specific information from the point of signal measurement from the strain gauges. This ensures that the output signal of the amplifier is shifted to a constant value. At the same time, inputs 1 and 2 of the strain gauge module are designed to process signals from sensors that have an output signal of a higher voltage than the signal from the strain gauges. They do not have preamplifiers and are directly connected to the multiplexer. The multiplexer sequentially connects the signal of the corresponding input to the programmable amplifier and ensures the conversion of the analog signal from the sensor into a digital one using a precision analog-to-digital converter.





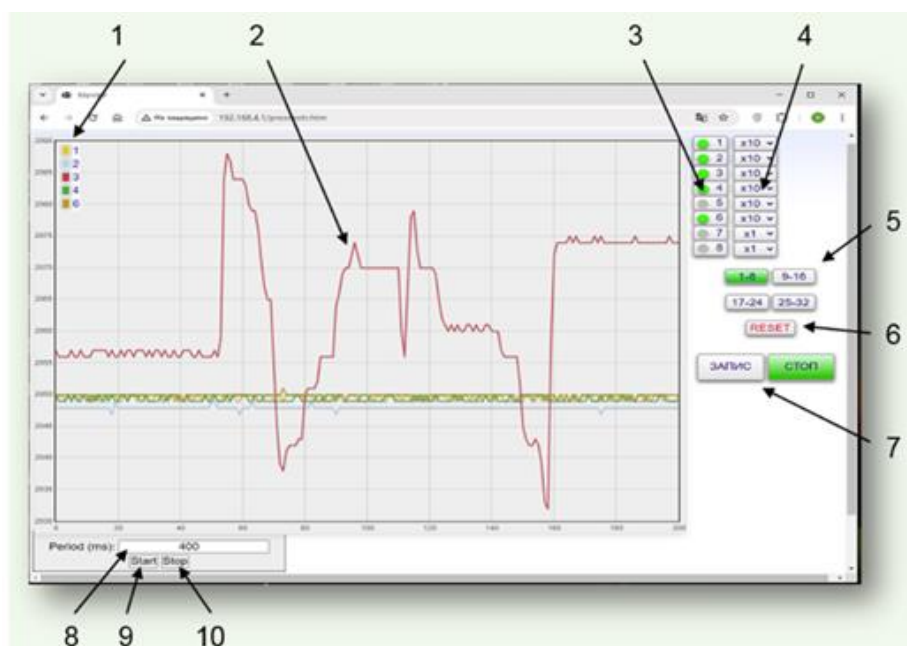
PSU – power supply unit, RTC – real-time clock, LNC – local network controller, LA – linear amplifier, MC – microcontroller, LC – level converter.

**Figure 4** – Block diagram of the UAR16 control unit



ADC1 – analog-to-digital converter for channels 1-4, ADC2 – analog-to-digital converter for channels 5-8, PSU1 – power supply unit for channels 1-4, PSU2 – power supply unit for channels 5-8, IA1-IA8 – input amplifiers for channels 1-8, IA – I2S interface amplifier.

**Figure 5** – AU8 Block Diagram



- 1 – color identification of oscillograms, 2 – oscillogram of channel No. 3, 3 – oscillogram visibility turn-on, 4 – setting the channel amplification coefficient, 5 – switching channel tabs, 6 – system restart, 7 – on/off recording of channels to a file, 8 – setting data update period, 9 – screen refresh turn-on, 10 – screen refresh turn-off.

**Figure 6** – Oscilloscope screen

The oscilloscope screen has several fields with information and control over the process of reading and recording the information coming from the sensors.

This enables to identify the oscillogram of a separate channel through which a signal from a specific sensor is supplied by color, to change the visibility of the channel on the oscilloscope screen, to provide changes in the signal amplification of the corresponding channel (sensor) 1; 10; 100, to change the duration of the update period on the oscilloscope screen when performing this update.

### Conclusions.

1. Measuring equipment has been created in the form of a strain gauge suspension for models of the studied structures of the operating equipment for trenching and excavation machinery. Using the Cartesian coordinate system, it provides real-time measurement of the magnitude and coordinates of applying three components of external forces and the moments of these forces action on the studied structure of the operating equipment when developing the soil.

2. Determining external forces and moments of force action based on strain gauge measurements using a strain gauge suspension is possible not only mathematically, but also by adding or subtracting electrical signals coming from the strain gauges of the corresponding pairs of strain links.

3. To register the real loads acting on the studied structure of the operating equipment of the earthmoving machinery, a measuring and registering complex with a set of analog and discrete sensors has been created. It enables measuring and registering the actual loads in the system with an accuracy of  $\pm 5\%$  of the real value.

4. The complex enables to read and record the received information on a micro SD memory card, to convert the received signals into digital code, and store the received information (measurement results) on a digital medium for its further processing and analysis.

## REFERENCES

1. Josef Kuneš (2012) Similarity and Modeling in Science and Engineering. Cambridge International Science Publishing; <https://doi.org/10.1007/978-1-907343-78-0>.
2. Paraska H.B., Prybeha D.V., Maidan P.S. (2017). *Metody ta zasoby eksperymental'nykh doslidzhen* [Methods and means of experimental research] Rivne, Condor Publ., 138 p. [in Ukrainian].
3. Khmara L.A., Holubchenko O.I., Tsvetkov F.V., Hlavatskyi K.T. *Stend dlya doslidzhen' zminnykh robochykh orhaniv hidravlichnoho ekskavatora* [Testbench to study removable actuators of a hydraulic excavator] Patent UA, no. 4910393, 1994. [in Ukrainian].
4. Khmara L.A., Dakhno O.O. *Stend dlya doslidzhennya roboty teleskopichnoho robochoho obladdannya odnokivshevoho ekskavatora zi zminnymy robochymy orhanamy* [Testbench to investigate a telescopic operating equipment of a single-bucket excavator with removable actuators] Patent UA, no. 103649, 2015. [in Ukrainian].
5. Holoborodko G.M., Perperi L.M., Palennyi Yu.G., Mihushchenko R.P. (2016). *Vymiryval'nyy stend dlya eksperymental'noho vyznachennya parametriv vilnykh kolyvan* [Testbench to determine the parameters of free oscillations experimentally] *Systemy obrobky informatsii – Information processing systems*, 3 (140), pp. 48-51. Access mode: [http://nbuv.gov.ua/UJRN/soi\\_2016\\_3\\_14](http://nbuv.gov.ua/UJRN/soi_2016_3_14) [in Ukrainian].
6. Ratajczak Janusz. (1979). Accuracy of Measurements of the Loosening Force in Power Shovels. *Przeglad Mechaniczny*, 38 (21), pp. 19-21.
7. Dabrowski Henry, Kujawski Walery. (1989). Mapping of the operation load and wear estimation of the toothed gears of excavators at the stands for accelerated durability research. *Politechnika Warszawska, Prace Naukowe, Mechanika*, (121), pp. 81-90.
8. Khmara L.A., Dakhno O.O., Kosiak O.V. (2015) *Doslidzhennya protsesu kopannya gruntu teleskopichnym robochym obladdanniam odnokivshevoho hidravlichnoho ekskavatora* [Research into the process of digging the soil with the telescopic operating equipment of a single-bucket hydraulic excavator] *Visnyk of NUVUtp – Bulletin of National University of Water and Environmental Engineering. Technical Sciences. №2 (70)*, pp. 364-381. [in Ukrainian].
9. Haponov O.O. (2021) *Pidvyshchennia efektyvnosti bahatoskrebkovykh lantsyuhovykh transheinykh ekskavatoriv na osnovi krytychnohlybynnoho blokovanoho rizannya gruntu* [Improving the efficiency of multi-scraper chain trench excavators based on critical depth soil blocked cutting]. PhD thesis. Kharkiv: KhNAHU [in Ukrainian].
10. Dergunov O., Demenko A., Zalevska A., Fostenko K. (2017) *Kompyuteryzovanyi stend dlia vyprobuvannia hvyntomotornoi ustanovky lehkykh bezpilotnykh povitrianykh suden* [Computerized testbench to test pilotless aerial vehicles with propeller engines] *Systemy obrobky informatsii – Information processing systems*, 3 (149), pp. 10-13. [in Ukrainian].
11. Purdyk V. P., Pozdniakov M. Y. (2015). *Eksperymentalnyi stend ta metodyka vyznachennia dynamichnykh kharakterystyk hnuchkykh truboprovodiv vysokoho tysku* [Testbench and methodology for determining the dynamic characteristics of flexible high-pressure pipelines] *Visnyk mashynobuduvannia ta transportu – Bulletin of Mechanical Engineering and Transport. №1*, pp. 96-102. [in Ukrainian]
12. Khmara L.A., Dakhno O.O. (2014). *Modeliuvannia protsesu kopannya gruntu teleskopichnym robochym obladdanniam odnokivshevoho hidravlichnoho ekskavatora* [Modeling the process of digging the soil by a telescopic operating equipment of a single-bucket hydraulic excavator] *Hirnychi, budivel'ni, dorozhni ta melioratyvni mashyny – Mining, construction, road and land reclamation machines*. 84, pp. 11-23. [in Ukrainian]
13. Rahulin V.M. (2020) *Pidvyshchennia efektyvnosti vykorystannia robochoho obladdannia avtohreidera stabilizatsiiei navantazhennia mekhanizmu pidvisky tiahovoi ramy* [Improving the efficiency of using motor grader operating equipment by stabilizing the load of the traction frame suspension mechanism]. Candidate's thesis. Kharkiv: KhNAHU [in Ukrainian].
14. Dmytrychenko, M.F., Musiiko V.D., Biliakovych, M.O., Koval, A.B. Voshchak, Yu.V., Kucher, O.P., Horkovenko, O.V. *Universalna tenzopidviska ta sposib dlia vyznachennia sylovykh parametriv prostorovykh navantazhen' robochykh orhaniv zemlerynykh mashyn* [Universal strain gauge suspension and

method for determining the force parameters of spatial loads of earthmoving machinery actuators] Patent UA, no. 111690, 2015. [in Ukrainian].

### ОБЛАДНАННЯ ТА ПРИЛАДИ ДЛЯ ДОСЛІДЖЕННЯ ПРОСТОРОВОГО СИЛОВОГО НАВАНТАЖЕННЯ СКЛАДНИХ МЕХАНІЧНИХ СИСТЕМ

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**Анотація.** У статті розглянуто питання обґрунтування конструкції та створення обладнання для визначення в реальному режимі часу характеристик просторового силового навантаження фізичних моделей робочих органів землерийних машин безперервної дії під час копання ґрунту, вимірювальної та реєструючої апаратури для фіксації параметрів силового навантаження в процесі розробки ґрунтів.

Мета дослідження: створення обладнання та реєструючої апаратури для визначення характеристик просторового силового навантаження складних механічних систем.

Об'єкт дослідження: робоче та ходове обладнання траншейних та котлованих землерийних машин безперервної дії.

Метод дослідження: експериментальний.

В результаті виконаних досліджень створено вимірювальне обладнання у вигляді тензометричної підвіски моделей конструкцій досліджуваного робочого обладнання траншейних і котлованих машин. Обладнання забезпечує в реальному режимі часу вимірювання величин та координат прикладання просторових складових зовнішніх сил та моментів дії цих сил на досліджувану механічну систему. Забезпечується визначення величин зовнішніх сил та моментів цих сил за даними тензометричних вимірювань не тільки математичним шляхом, а і шляхом додавання або віднімання електричних сигналів, що поступають від тензодатчиків відповідних пар тензоланок.

Для фіксації реальних навантажень, що діють на досліджувані конструкції робочого обладнання землерийних машин, створено вимірювально-реєструючий комплекс з комплектом

аналогових та дискретних датчиків, який дозволяє здійснювати вимірювання та реєстрацію діючих навантажень в системі з точністю 5% реальної величини.

Комплект дозволяє зчитувати та записувати отриману інформацію на карту пам'яті типу micro SD, перетворювати отримані сигнали в цифровий код та зберігати отриману інформацію (результати замірів) на цифровому носії для подальшої обробки та аналізу.

**Ключові слова:** момент, , тензометрія, землерийна машина, вимірювальний комплекс, датчик, карта пам'яті цифровий код, підсилювач, тензометричний модуль