Volumetric dynamometer units for laboratory and field testing of tillage equipment

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Abstract. The search for energy efficient tillage technologies and the creation of more advanced machines while reducing the cost of the final product are one of the priority goals. One step in the development of tillage implements is to develop a theoretical basis. In this case, mathematical or simulation modeling is used, but part of the work carried out in the laboratory and in the field is an integral part of the research structure. Of great importance in testing forestry equipment are dynamometer methods, which consist in measuring the forces transmitted from the engine to the machine or acting on the working bodies and parts of the machines. This is especially true for forest implements that interact not only directly with soils, but also with roots, branches, stumps and other components of forest soils. The article is presented in the form of an analysis of the structures of dynamometric installations used to conduct research on tillage equipment. Also given are the designs of installations used for research of combined machines with active working bodies, such as a forest fire engine. Particular attention is paid to structures for volumetric dynamometry (2D and 3D).

1. Introduction
At all times, mankind did not stop searching for more efficient technologies and more advanced machines for tillage. In this case, mainly experimental methods of trial and error were used. Today, researchers have to devote more and more time to studying already conducted research in electronic databases of accumulated knowledge. Own work is done using mathematical or modeling techniques, but some of the work done in the laboratory and in the field is an integral part of the research plan.

The most important test method for agricultural and forestry equipment is dynamometry, the main purpose of which is to read the forces acting in the system. The use of dynamometers is possible both for production conditions during testing of units planned for production, and for conducting scientific research. The process of developing new units and tools also includes the choice of a vehicle. The expenditure of material resources will lead the company to losses, so dynamometry is again required so that fuel consumption can be calculated and a car inspection schedule can be drawn up. Machines for extinguishing forest fires perform work in the immediate vicinity of a fire during the elimination of forest fires, therefore, increased fuel consumption or an incorrectly determined operating resource endangers the life and health of specialists who find themselves in the emergency zone.

2. Materials and methods
Dynamometer testing in working conditions provides an opportunity to evaluate:
allow the most accurate selection of the class of traction means for efficient operation;
allow you to check the strength characteristics of the tools allow you to determine the resource and wear resistance of the unit;
to determine the technology of operation;
allow to assess the quality of the manufactured samples, as well as the repair carried out;
determine the overall performance of the units.

The result of the creation of new units for forestry and agriculture is highly efficient equipment with the lowest energy consumption, increased efficiency in various operating conditions, and the greatest service life. The data obtained from dynamometers allow progress in solving many problems of both general mechanical engineering and in the correct operation of units.

Currently existing research in this area can be divided into several large blocks (figure 1):

- research of traction resistance (longitudinal component of the vector of traction resistance \( R_x \)) [4, 13, 15, 17, 18];
- volumetric dynamometry (study of two - \( R_x, R_z \) or three components of the vector of traction resistance \( R_x, R_y, R_z \)) [1, 2, 12, 14, 16, 3, 5–11].

![Installations for measuring traction resistance](image1)

![Plants for volumetric dynamometry](image2)

**Figure 1.** Dynamometric equipment.

Let us consider in more detail some designs of strain gauges used for volumetric dynamometry of tillage implements.

![Schematic diagram of the tezometric installation](image3)

**Figure 2.** Schematic diagram of the tezometric installation of the University of Saskatchewan.
In the strain gauges used at the University of Saskatchewan [7], the sensors are installed in the following scheme: two S-shaped sensors are installed in the direction of the ground travel and allow measurements along the tool of traction resistance, and three sensors are mounted vertically to measure the force reading and one measures the lateral shear force tools. Figure 2 schematically shows the arrangement of the sensors. The working body installed on the unit is rigidly fixed to the unit frame. The scheme uses 6 sensors at once, installed on the hitch of the unit. This setup has been used in research conducted at the University of Saskatchewan since 1978.

In the scientific work [5], a similar design is described, which allows using 6 sensors to measure in three directions of the action of forces on the unit under study.

The scientific work of Iranian scientists [3] describes a three-point dynamometer that allows you to take and process readings of the total acting force. The dynamometer is shown in figure 3.

The sensors used in dynamometry are also often used when determining the forces on only a few axes (figure 4) [16]. The problem with this approach is its low precision. Another disadvantage of this method is that it ignores the bending moment on the vertical load cell. But such a placement scheme increases the complexity of the research, as well as affects the accuracy, prompting more experiments.
Also, when conducting research, special sensors equipped with an elongated octagonal ring (EOR) are used, which are also used in some studies to measure the force acting on tillage implements [12] (figure 5).

![Figure 5. Dynamometer EOR type.](image)

In studies [9], a triaxial dynamometer (EMOR) was used, with the help of which readings of both the moment and the acting force were taken. Using this method allows to obtain a rigidly fixed structure that researchers can install as close as possible to the investigated working body, as shown in figure 6.

![Figure 6. Three-axis dynamometer EMOR type.](image)

Studies [11] show the design of a three-axis dynamometer designed, manufactured to measure and locate all forces and moments on tillage tools up to a maximum force of 10 kN and a maximum torque of 10 kN m (figure 7).
The structure consists of four frames attached to each other with strain gauges. Tillage implements were attached to the inner frame. The system calibration has shown reliable and accurate dynamometer performance in tracking forces and moments. In addition, the developed installation worked stably in the field. Preliminary measurements were compared with ASABE D497.7 and found to be within the acceptable range. The design of the triaxial dynamometer allows you to study the relationship between the forces and moments that arise on various working bodies in the process of soil cultivation. Based on these data, it is possible to optimize their design depending on the type of soil and the available tractor power.

The study [10] describes a force measurement system consisting of six strain gauges. It is designed to measure traction resistance, lateral and vertical forces of agricultural tractors (figure 8).

The traction measurement system consisted of six compression-tension strain gauges (UU-T2, DACELL, Cheongju, Korea). In addition, a GPS sensor (VBOX 3i, VBOX AUTOMOTIVE) was attached to the tractor's center of gravity to measure the driving speed required for benchmarking using actual measured traction and traction based on ASABE standards.

The purpose of the study [8] was to confirm the magnitude of the error between the integral force sensor connected to the three-point hitch of the tractor and two separate sensors connected directly to the implements to control the soil reaction forces (figure 9).
Figure 9. Installation for volumetric strain gauge with an integral three-point sensor.

The integral transducer was tested in laboratory conditions on calibrated equipment to record changes in force at different distances between arms and different loads. The results obtained showed that the integral sensor is sensitive to the position of the load, equivalent to the depth of tillage, with an error value of 2 to 10%. Field assessments at various depths were performed using the subsoiler, with errors of 13.07 and 41.72%, depending on the location of the subsoiler. When applying a 10% calibration correction obtained in the laboratory, the error was 3.1% for bit lengths from 0.70 to 0.90 m.

Studies [1] describe the design and calibration of an adjustable three-point torque coupler (figure 10).

Figure 10. Three-point torque hitch.

The device is a U-frame used as a hitch between the machine and the tractor. Due to the fact that this approach excludes installation for only one unit, it becomes possible to use it for various types of units under study. Field tests of the dynamometer and data acquisition system have shown that they can be effectively used to measure horizontal and vertical components of forces.

In a study [2, 6], horizontal and vertical forces were measured using a three-axis dynamometer (figure 11).
The dynamometer is capable of measuring three orthogonal forces acting on the implement and three moments acting around orthogonal axes with a maximum force of 35 kN and a maximum torque of 35 kNm. The data acquisition system consisted of strain gauges mounted on two elongated octagonal rings (EOR), a data logger, and a laptop. The strain gauge signals were digitized in a DT-800 data logger (Data Taker Co., Australia), then transferred to a laptop. The data logger was set to record dynamometer signals at 5 Hz. Since the ripper was a symmetrical tool, shear force measurements were not carried out.

The work [14] presents the development process of a new two-frame dynamometer for measuring all forces and moments between the tractor and the implement connected through a three-point hitch (figure 12).

The design solution is aimed at optimizing the overall and strength parameters of the dynamometer and the possibility of its easy adaptation for a wide range of tractors and attachments. A mathematical model was developed to determine the forces and moments on different coupling devices, taking into account the mechanical characteristics of the dynamometer and the slope of the terrain on which the tractor is operating. A prototype dynamometer was created and initial field tests were carried out to verify the design and functionality of the dynamometer.

In studies [19], a strain gauge installation for volumetric strain gauging was used, consisting of two frames connected by three parallel rods and three tie rods, the ends of which are fixed by means of ball joints, six S-shaped strain gauges installed on each rod (figure 13). Installation weight 12 kg.

The use of ball joints avoids the transmission of torques by the rods and only compressive and tensile
forces parallel to the direction of the rods act on the sensors.

![Diagram of load cells](image1.png)

**Figure 13.** Installation for volumetric strain gauge with six S-shaped load cells.

A distinctive feature of the installation is to conduct research without complicated preparatory calibration operations in comparison with triaxial dynamometers [9] and strain gauges [3]. But it is worth noting that when receiving the results of the research carried out, additional processing of the results will be carried out.

Figure 14 shows a schematic of a volumetric strain gauge setup with three S-shaped load cells. Consisting of four triangular frames, with limited degrees of freedom. Each joint has one degree of freedom along the coordinate axis. A hitch is installed between the vehicle and the implement. The axes of movement of the frames are made on shafts fixed on one frame, and to the second they are fixed on linear bearings, excluding circular movements or displacements relative to the three main axes of reading.

![Diagram of load cells](image2.png)

**Figure 14.** Installation for volumetric strain gauge with three S-shaped load cells.
This design was used to study combined and modular soil-throwing units [20, 21] containing several blocks of working bodies: a share-moldboard part and a milling-throwing working body, disk working bodies and a milling-throwing working body. The obtained experimental data made it possible to reduce the power consumption of the unit and improve the quality characteristics of its operation. In the study of such tools, there is an urgent need for a complete dynamometry, which includes not only the measurement of traction resistance, but also the pressure of the working fluid, the cutting forces of active working bodies, and the energy consumption of soil throwing.

3. Conclusions
Conducting theoretical scientific research limits obtaining a complete understanding of the system under study and the results obtained are based on generally known facts about the objects of research and the processes taking place in the system. To reinforce the results obtained in the development and study of tillage tools, ground guns. The review of the structures of dynamometric units presented in the article showed that to create modern energy-efficient tillage tools, it is necessary to use volumetric dynamometry. This approach allows us to study in detail the power characteristics of the working bodies and implements, which is especially important for mounted and asymmetric implements, as well as combined machines with active working bodies.

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