Development of a braking energy recovery device for an agricultural robot

N N Barbashov and A A Barkova*
Bauman Moscow State Technical University, Theory of machines and Mechanisms Department, 2nd Baumanskaya st., 5/1, Moscow, 105005, Russian Federation
*E-mail: anastasiia_barkova@mail.ru

Abstract. Designing and creating new agricultural machines, their introduction into agricultural production and effective use requires taking into account and objectively evaluating many factors determined by the requirements of industry and the specifics of agricultural production. The scientific and technical process in the field of automation and mechanization of agricultural production is aimed at reducing specific energy costs, increasing the productivity and manageability of equipment, as well as compliance with environmental standards. To solve these tasks, mobile robots are actively used that can independently perform various operations related to sowing, tillage, plant care and harvesting. A promising method for improving the efficiency of agricultural machinery is the use of braking energy recovery, its accumulation and use during further acceleration. For this purpose, a device was developed and designed to reduce the energy consumption of agricultural robots without reducing the dynamic qualities and performance of the equipment.

Robotic systems are being actively implemented in all spheres of human activity. In many industries, the use of robots can free people from monotonous, heavy and exhausting work. Similar tasks are set for agricultural robots. Back in the 1950s, automatic controlled tractors were designed to copy the movements of a car with a tractor driver. But the tractors gradually strayed from their route due to the difference in external factors acting on them, so the development had to be abandoned.

Currently, mobile agricultural robots can effectively solve several tasks: loosening the soil, planting plants, weeding, watering, spraying, harvesting, and much more. In many cases, they effectively replace human labor, allowing you to accurately make the necessary decisions in accordance with the established algorithm, and work regardless of weather conditions. Robots also allow you to replace human labor in cases where you must perform monotonous, physically heavy or harmful to human health work. Due to the wide range of functions performed by the robot, the modular principle is most often used in the development of an agricultural robot. In other words, a mobile platform is used as a movement device, and various manipulators are installed on it that can move in different planes and perform the required operations. These manipulators change depending on the specific task assigned to the robot and can use almost any necessary garden tools.

As a rule, such robots operate in an unsteady mode, consisting of frequent alternation of acceleration and braking. This is due to the specifics of the work of agricultural machinery when the robot often has to stop to perform the necessary operations with plants or change the trajectory of movement during harvesting.
The efficiency of energy consumption in an unsteady driving cycle is estimated using the total cycle efficiency, which is the ratio of the useful work per cycle to the work expended by the engine during acceleration.

An important task to be solved when designing agricultural robots is to reduce fuel consumption and reduce carbon dioxide emissions into the atmosphere [1]. A common method for improving the efficiency of cars in unsteady modes is the recovery of braking energy [2] and the calculation of optimal parameter values for operation in unsteady modes. The difficulties of such calculations are related to the lack of mathematical models in the educational and scientific literature in the form of describing the optimality criteria for cars with braking energy recovery.

Energy recovery refers to the conversion and storage of energy by a storage device during braking and its use during acceleration and for other useful purposes. The use of braking energy recovery allows you to increase the cyclic efficiency almost without reducing the dynamic qualities of the agricultural robot.

Therefore, the work of accumulating $A_{\text{rec}}$ energy, which is usually lost during braking, should be considered useful. Since the cyclic efficiency $\eta$ of a robot with braking energy recovery increases by a fraction of the kinetic energy of the robot realized during the recovery of $d_{\text{rec}}$:

$$\eta_{\text{cycle with rec}} = \frac{A_{\text{dr}} - A_{\text{loss}} + (A_{\text{rec}})_{\text{cycle}}}{(A_{\text{dr}})_{\text{cycle}}} = 1 - d_{\text{loss}} + d_{\text{rec}} = \eta_{\text{cycle without rec}} + d_{\text{rec}}$$

where,

- $d_{\text{loss}} = d_{\text{friction}} + d_{\text{in}}$ - part of friction losses and kinetic losses;
- $d_{\text{rec}} = \frac{(A_{\text{accum}})_{\text{cycle}}}{(A_{\text{dr}})_{\text{cycle}}}$ - part of engine operation, accumulated over the cycle;
- $A_{\text{accum}}$ - the amount of accumulated and then recovered energy.

The designs of robots with several types of engines, the so-called "hybrid," that is equipped with ICE, electric motors and energy storage devices, are devoid of problems associated with increasing energy consumption in unspecified operating modes. Peak requirements for developed power can be covered by accumulated energy, and ICE may not follow transient modes in other units and operate in an economical steady state.

Intentional creation of a potential energy reserve in the absence of a payload or during braking allows additional loading of the engine in the absence of a payload. Reducing peak loads makes it possible to use an engine of lower rated power and reduce the total energy consumption. This phenomenon is since many engines have a higher efficiency at a ratio of the power used to the nominal close to one.

Therefore, when designing agricultural machinery, particular attention should be paid to the choice of rated engine power, the economy of which can be disproportionately reduced when the power consumed in operation is reduced. For example, the installation of ICE with excessive compared to the optimal power will lead to an overflow of fuel in operation even in steady-state modes of operation. Thus, the objective of achieving economy is to optimally select the engine power, as well as optimally select the transmission mechanism between the engine and the robot working member.

The reduction of acceleration time is a significant reserve for the growth of performance of mobile robots. For many tasks solved by agricultural machinery, the acceleration time is commensurate with the steady state operation time. The robot moves from one plant to another, stops, performs the required operations and continues moving. In such a case, the duration of the acceleration period, which depends on the rated engine power, can be used as a performance estimate. In general, the duration of the acceleration period of any machine is associated with the rated power of the installed engine and the completeness of its use. However, an increase in excess engine power during acceleration due to the use of an engine of significantly higher rated power than is necessary for the steady state operation of an agricultural robot solely in order to reduce acceleration time is not advisable. This leads to a decrease in economy and an increase in the cost of the robot engine, as well as an increase in the size and weight of the entire structure. It is possible to achieve a reduction in acceleration time by choosing the optimal gear ratio of the gearbox, matching engine characteristics and resistance. The gear ratio will be optimal.
according to the speed criterion if it ensures a minimum acceleration time due to a more complete use of the rated engine power.

In case of braking energy recovery, kinetic energy transfer between the robot mobile platform transmission and the flywheel accumulator is possible in two ways:

- Use of an electric generator to transform mechanical work into electrical energy and its subsequent accumulation into an accumulating unit;
- Direct transmission of mechanical braking energy to flywheel by changing transmission ratio by variator or planetary differential [3-5].

The first circuit is often implemented in electric vehicles or lifting and transportation machines with traction motors but requires the installation of a powerful electric battery. The second mechanical power transmission scheme is shorter and is accompanied by less energy loss but requires the design of the mechanical energy storage unit. This method of energy recovery is based on the idea of maintaining a constant supply of kinetic energy of a machine with a storage device.

For the efficient application of energy recovery in the mobile platform of an agricultural robot at BMSTU the following device was developed and patented, which is shown in figure 1. Its application allows reducing engine power without reducing dynamic parameters due to efficient use of braking energy recovery principles. The simulation showed that this device reduces energy consumption and guarantees the reliable and safe operation of the drive of the mobile platform of the robot.

![Diagram of the recuperation of braking energy device.](image)

When the agricultural robot starts moving, the control device lowers the speed of the control reversible electric machine which operates in motor mode. If it is necessary to save electrical energy used to control the robot or move its manipulators it can be switched the reversible electric machine to generator mode. At the end of acceleration to the nominal speed of movement, the speed of the control reversible electric machine and the solar gear is less than $(\omega_1)_{\text{max}}$. In this case the speed of the central wheel reaches the maximum value $(\omega_3)_{\text{max}}$. At the same time the speed of the driver and flywheel take zero values. The speed plan shown by continuous lines moves to the left and corresponds to a mechanism with a degree of mobility equal to one. The speed of the V3 transmission increases and the flywheel gives up its energy and its speed decreases compared to the maximum values. This description is shown in figure 2.
When the car is moving steadily, there is an equality of driving forces and resistance forces. Therefore, the engine power is transmitted through the transmission to the driving wheels of the mobile robot. During acceleration, the power balance is disturbed and additional energy is transferred from the flywheel through the Central gear wheel and transmission to the driving wheels.

When the car is braking, the balance of driving and drag forces is broken in the opposite direction, which causes a change in the direction of energy movement from the driving wheels through the planetary differential to the flywheel. Stopping the movement of the car is caused by a decrease in engine power and, if necessary, the use of the car's braking system.

The use of such a device as a drive for a mobile cart of an agricultural robot will reduce fuel costs by up to 25%, as well as improve handling and maneuverability by reducing the acceleration time [6,7]. The action of a flywheel energy accumulator differs significantly from the operation of a conventional internal combustion engine flywheel, which is connected to the transmission by a constant gear ratio during acceleration, increasing the moment of inertia of which reduces fluctuations[8,9] in the steady-state driving mode and delays the acceleration process. The literature has not published data on the decrease in the dynamic qualities of agricultural robots when using a flywheel battery of braking energy.

Thus, the article found that:

- When the agricultural robot is operating in an unsteady mode with frequent alternation of acceleration and deceleration, an increase in moving masses leads to an increase in the loss of accumulated kinetic energy and the engine operation spent on it, and, thereby, to a decrease in overall efficiency.
- To reduce the installed rated power of the engine and reduce energy consumption, storage devices can be used to compensate for peak loads. In some cases, it is possible to reduce the rated engine power and power consumption in a more efficient way by using unloading devices to reduce peak loads.
- The developed device allows to recover braking energy in a wide range of speeds and loads, reduce energy losses and increase the efficiency of the agricultural robot.

References

[1] Zukova Y M, Nikulina S N, Yakovleva O V and Cherikanova E A 2020 Analysis of the main trends in the development of the waste management system in Russia: problems and prospects Ecology and industry in Russia 24 66-71
[2] Kuznetsov A, Kharitonov S and Ryzhov V 2018 Experimental and calculation study of diesel generator performance in transient conditions Journal of engineering for gas turbines and power 140 121009
[3] Ovsyannikova E E and Guskov A M 2020 Stabilization of a rigid rotor in conical magnetic bearings Problems of mechanical engineering and machine reliability 49 11-20
[4] Polyakov S A, Kuksenova L I and Alekseeva M S 2019 Methodological foundations for choosing the materials for gears according to wear resistance criteria Journal of Machinery Manufacture and Reliability 48 328-35
[5] Temis M Yu and Lazarev A P 2018 Influence of centrifugal forces on oil flow in journal bearing of planetary gear *Journal of fluids engineering, transactions of the American society of mechanical engineers* **140** 021109

[6] Polyakov S A and Kuksenova L I 2017 Methods for estimating the adaptive properties of mechanical systems as means of improving their performance indicators *Problems of mechanical engineering and machine reliability* **46** 20-4

[7] Boztas G and Aydogmus O 2019 Design of a High-Speed PMSM for flywheel systems *4th Int. Conf. on Power Electronics and their Applications* (Elazig: IEEE) p 1-5

[8] Voronov S A and Veidun M A 2017 Mathematical modeling of the cylindrical grinding process *Journal of machinery manufacture and reliability* **4** 394-403

[9] Sadykhov G S and Babaev I A 2016 Computations of the least number of objects necessary for the cyclical reliability testing *Journal of Machinery Manufacture and Reliability* **3** 239-46