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The Process of Operation of a Mobile Straw Spreading Unit with a Rotating Finger Body-Experimental Research

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Abstract: This article presents methods and results of experimental research to determine the power consumed when driving the working bodies of the straw bedding mobile spreader to cover cow stalls (boxes). Analysis of the design and mode parameters of the rotary finger working body influence on the energy consumption of the bedding material spreading process is carried out. Using the experimental data, it was established that the power consumed to drive the rotary finger working body of the mobile straw bedding spreader, at the tractor power take-off (PTO) shaft rotation speed of 540 min^{-1}, the forward unit speed of 2 km/h, and performance of 1.5 kg/s, is equal to 7.633 kW. In this case, due to the installation of a rotary finger working body for spreading straw bedding, the power consumption increased by 9%. This increase will not have a significant impact on the overall energy consumption of the spreading bedding material working process, because this class tractor power reserve allows its use.

Keywords: spreaders; rotary finger working body; experimental research; power consumption; energy consumption

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1. Introduction

At present, for mechanized delivery and spreading of bedding, special machines are used, which can be both universal (forage dispensers, forage mixers) and specialized (bale carriers-shredders "Castor", "Tomahawk", PRIMOR, "GOSPODAR", ISRK-12). However, as practice shows, the well-known bedding spreaders, mainly of foreign manufacture, have quite substantial technological and economic disadvantages. For mechanization of the process of spreading the straw bedding, the Zaporizhzhia Research Center for Livestock Mechanization NAAS of Ukraine developed a spreader designed for making straw bedding at free-stall housing of cattle. The spreader's experimental sample with a rotary finger working body is designed and produced with a set of combination radial and curved fingers on the rotor [1–4].

The practice of domestic farming with free and stall-type livestock housing technology, including our ethological observations on modern wholesale dairy farms in the South of Ukraine, proves that the level of boxes of comfort for dairy cattle is low, and the percentage of boxes occupied by cattle is only 36%–45% (norm 80%–85%). The low level of comfortable boxes on farms is caused, first of all, by a lack of technical means for bedding supplies which meet zootechnical and technological requirements for the mechanization of this process. In practice, the bedding is supplied into the boxes manually without any compliance with these requirements. The existing modern equipment for spreading straw bedding has a significant technological disadvantage that limits its use. The technological disadvantage of modern equipment is the significant energy consumption for the process of grinding and spreading of bedding: roll shredders and spreaders require 40–50 kW to drive the working bodies (1 roll), and mixers require 44–60 kW. In addition, for all technological operations, the offered equipment uses an expensive liquid fuel [5]. Therefore, promising equipment should be energy efficient while reducing the specific energy consumption for the implementation of technological processes in livestock farms [6,7].

Analysis of modern technological equipment for spreading straw bedding (mainly fan type blowers) [4] allows us to draw conclusions that the disadvantages of the existing equipment for the making and forming of straw bedding for box-type housing livestock are high energy consumption of vane technical means and dustiness of the premise [8–10]. One of the ways to solve these problems is the usage of a working body for spreading straw bedding material in the form of a rotor with fingers [11–17]. This issue was studied by such native and foreign scientists: V.D. Rohovyi, A.A. Muzyka, M.A. Tyshchenko, V.V. Sukhorukov, N.V. Braginets, A.O. Pariev and others [1–5,8,9,18–26].

The Zaporizhzhya Research Center for Livestock Mechanization of NAAS of Ukraine, together with the Limited Liability Company "Orikhivsilmash", produced the equipment for the technological process of making straw bedding on the farms of cattle on the basis of forage dispenser type KTU-10 (Figure 1), specifications of which are presented in Table 1. The working body for making the bedding is a rotor with four rows of fingers. The rotary finger working body is installed in the unloading window above the transverse belt conveyor in such way that the unloading mass is thrown from the conveyor by the working body, perpendicular to the direction of equipment movement [1,18].

Figure 1. General view of equipment for the technological process of making straw bedding with rotary finger working bodies (for clarity and complete display of the drive and the working body, the protective barriers were dismantled at the time of photo-fixation).

Based on previous studies, it was found that for the qualitative spreading of bedding the rotor should have a diameter from 450 mm to 500 mm, with four rows sharpened at an angle of 15° to 30° of round fingers, which are radial to the axis of rotation. Thickness of the fingers should be no more than 14 mm, and the distance between them in a row from 50 mm to 70 mm [18].

The equipment developed for the technological process of making straw bedding with a rotary finger working body is energy-saving and allows to reduction of energy costs. It also improves the quality of the technological process of spreading the bedding material from rolls. It also complies with the zootechnical and technological requirements.

The goal of our research is to determine the influence of design and mode parameters of the rotary finger working body on the energy consumption of the process of spreading the bedding material from rolls.

Table 1. Specifications of the equipment with a rotary finger working body for the technological process of making straw bedding.

Mobile Hopper Bedding Spreader	
Capacity of the bunker, m^3	10
Transport speed, km/h	30
Working speed, km/h	0.4–3.5
Performance, kg/s	up to 2.0
Overall dimensions, mm	6670 × 2300 × 2500
Track, mm	1800
Distance of bedding spreading, mm	500–2500
Linear density of straw spreading on bedding, kg/m	0.5–1.5
Width of bedding spreading band (max), mm	3200
Compounds with tractors 9 and 14 kN	T40, MTZ, UMZ
Power to drive the working bodies without additional equipment (rotor with fingers), kW	7
Rotary Finger Working Body	
Finger bending angle, deg.	30–45
Finger length, mm	165–180
Speed of rotation, min^{-1}	116–324

2. Materials and Methods

Experimental research program for energetic estimation of straw bedding spreader with rotary finger working body driven by tractor PTO is provided to perform the following tasks [27]:

- to determine the power consumed to drive the rotary finger working body of the straw bedding mobile spreader;
- to determine the specific energy costs of the bedding material spreading process.
- Indicators of energy estimation were determined by the results of measurements obtained during the tests. At least four measurements of each parameter should be made on each operating mode of the agricultural machine or unit, lasting no less than 20 s [28]. When determining the energy estimation indicators of mounted, semi-mounted or trailed agricultural machines with working bodies driven from the tractor power take-off shaft, the following parameters are measured:
- time (duration) of measurement, using a stopwatch;
- track length, which passed by the mobile spreader of straw bedding during the measurement time and width of the spreading band, with the help of tape measure (Figure 2) [1,27];
- torque on tractor power take-off shaft, by passing current collector of mercury amalgamated device (Figure 3) [27,29];
- rotation speed of spreader working body shaft and tractor power take-off shaft, using a tachometer (Figure 4a) [27];
- data registration, with a PC (Notebook: Futjitsu-Siemens, Intel Core 2 Duo T-5500 1.66 GHz) and Oscill software (Version 1.26) (Figure 4b) [27].

(**a**) (**b**)

Figure 2. Determination of track length, passed by the mobile straw bedding spreader (**a**) and the spreading width (**b**).

Figure 3. Determination of torque on the selection shaft tractor power.

(**a**) (**b**)

Figure 4. Determination of the rotation speed of the spreader working body shaft and the PTO shaft (**a**) and registering devices: PC and Oscill software (**b**) (for clarity and complete display of the drive and the working body, the protective barriers were dismantled at the time of photo-fixation).

During machines testing, mercury amalgamated current collectors are widely used for installation on shafts of various diameters. A mercury amalgamated current collector has stationary and rotating copper contact rings, placed in a case with a radial clearance of 0.1 mm. Their contact surfaces are amalgamated; mercury between them is contained due to capillary properties. The contact rings are assembled in a block with organic glass rings. The movable part of the case of current collectors is installed on the shaft with strain gauges. The stationary part is connected with the movable part through bearings. The conductors from the rotating rings are connected to the strain gauges, and the conductors from the fixed rings are connected to the device. Experience of using current collectors with mercury baths showed that they provide reliable and stable electrical connection of resistors with measuring devices [29]. This is why we used such a device for our own experimental studies. To ensure the data reliability of the mercury amalgamated current collector we have made a calibration of the device in the laboratory (Figure 5) [3].

Figure 5. Calibration of mercury amalgamated current collector.

3. Results and Discussion

Experimental studies of power estimation of the equipment with a rotor finger working body driven from a tractor PTO have defined the power consumed to drive a rotor-finger working body of a straw bedding mobile spreader, and have defined specific power costs of bedding material spreading process [3]. For equipment with working bodies driven from tractor PTO, power (kW) is calculated by the formula [27]:

$$N_{PTO} = 1.047 \times 10^{-3} \times M_{PTO} \times n_{PTO} \quad (1)$$

where: M_{PTO} is the torque on the shank of power take-off shaft of the tractor, Nm; n_{PTO} rotational speed of the power take-off shaft of the tractor, min^{-1}.

Specific energy costs (kJ/kg) of straw bedding spreader with a rotary finger working body are calculated by the formula [27]:

$$E = \frac{N_M}{W_O} 3.6 \quad (2)$$

where: N_M is the power consumed by a straw bedding spreader with a rotary finger worked body, kW; W_O is the performance of the straw bedding spreader with a rotary finger working body, kg/s.

The torque reached its maximum value at 25.2 Nm in approximately 1 s after launching. Starting with 8 s of the experiment, the medium torque value was 22.5 Nm (Figure 6). The rotation speed of the rotary finger working body with a drive transmission ratio of 0.6 was 324 min^{-1}. So, power consumed to drive the rotary finger working body of mobile straw bedding spreader is equal:

$$N_{PTO} = 1.047 \times 10^{-3} \times 22.5 \times 324 = 7.633\text{kW} \quad (3)$$

The results of experimental studies to determine the energy parameters of the mobile straw bedding spreader with a rotary finger working body are shown in Table 2.

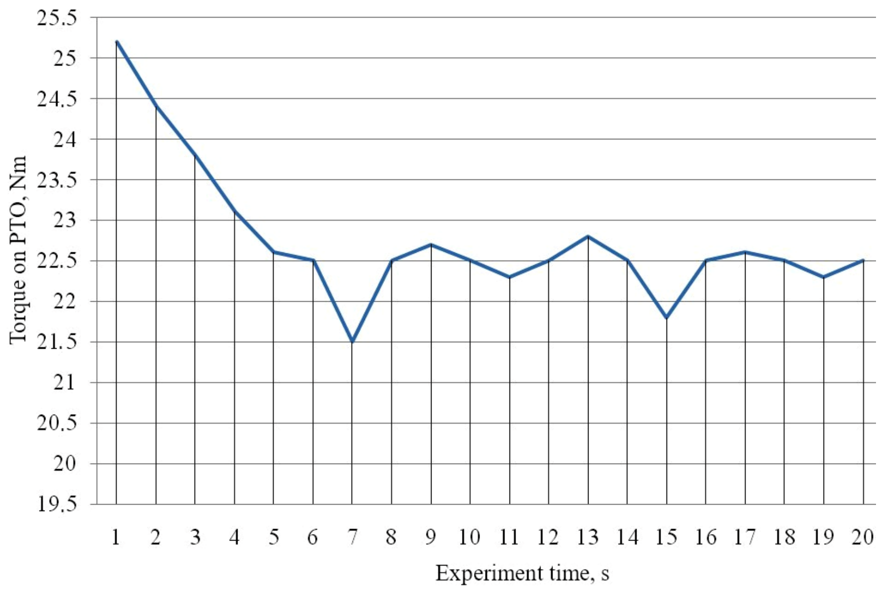

Figure 6. Dynamics of torque change at tractor PTO at shank rotation speed of 540 min^{-1}.

Table 2. Operation modes and experimental research results.

Parameter	Value
Mode of operation:	
- forward speed of the unit movement, km/h	2
- bedding spreading distance, mm	2100
- bedding spread width (max), mm	3000
- performance, kg/s	1.5
Power required to drive the working bodies with additional equipment (rotor with fingers), kW	7.633
Specific energy consumption, kJ/kg	1.2–3.8

Experimental data analysis has shown (Figure 6) that the most intense moment is the start of the mobile straw bedding spreader working body in case when the shank of the PTO reducer of the UMZ-8040.2 tractor is set to the rotation speed of 540 min^{-1}.

The research results of the influence of rotary-finger working device design and mode parameters on the energy consumption of the bedding material spreading process in graphical presentation are given in Figures 7–9, and consist of a pairwise dependence of the energy consumption on the rotation speed of the rotary drum ω, the radius of the center of mass δ, and an angle that complements to 90° the angle of the finger installation relative to the radius α_o (Figure 7) [3].

The analysis of Figure 7 points to the fact that at low rotation speed of the rotary finger drum, increasing the radius of the center of masses, will not significantly increase the energy consumption, while with the growth of the drum rotation, frequency of more than 100 rad/s energy consumption of the process also significantly increases. This is due to the increase of the inertial component. The increase of energy consumption at high speeds with increasing radius of the center of mass is due to the increase of the effort required to overcome the growing torque. We also made a graphical interpretation of energy consumption dependence on angles complementing up to 90° the angle of finger installation relative to radius αo, and the rotation speed of the rotary finger working body ω with a constant radius of center of mass δ (Figure 8).

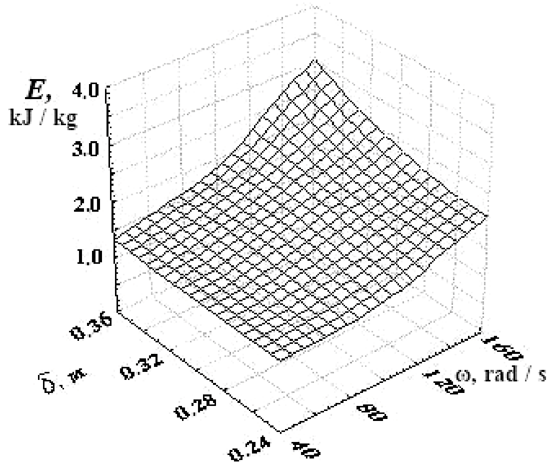

Figure 7. Dependence of energy consumption E on the radius of the center of mass δ, and the rotation speed of the rotary finger working body ω at α_o = const.

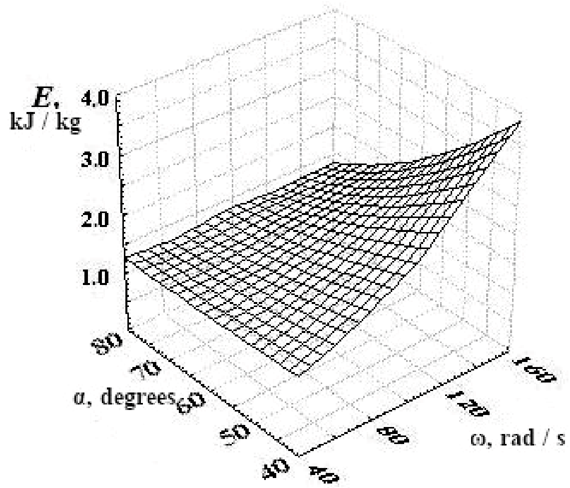

Figure 8. Dependence of energy consumption E on the angle, complementing up to 90° the angle of finger installation relative to radius α_o and rotation frequency of the rotary finger working body ω at δ = const.

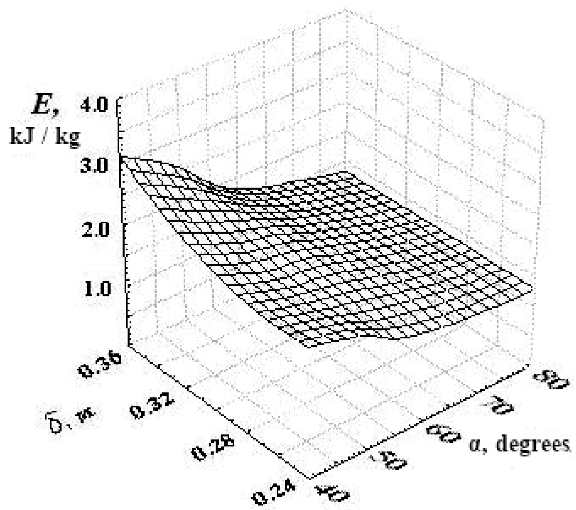

Figure 9. Dependence of energy consumption E on the radius of the center of mass δ and the angle, complementing up to 90° the angle of the fingers installation relative to the radius α_o, at ω = const.

Studying the graph of the dependence of energy consumption on the angle, complementing up to 90° the angle of installation of the finger relative to the radius, and the speed of the rotary finger working body, an identical tendency with increasing drum rotation frequency of more than 80–100 rad/s can be seen. That is, energy consumption begins to increase rapidly, because the increase in angle, complementing up to 90° the angle of installation of the finger relative to the radius to 80°, almost neutralizes the increase in rotation speed. This is due to an increase in the resistance force of the bedding slipping on the finger. Graphical interpretation, which is shown in Figure 9, shows the dependence of energy consumption from the angle, complementing up to 90° the angle of installation of the finger relative to the radius, and the radius of the center of mass at a constant of rotation speed of the rotor finger working body.

Graph of the paired interaction of energy consumption with the radius of the center of mass and angle, complementing up to 90° the angle of installation of the fingers relative to the radius, shows the existing optimal angle of installation of the rotary working body fingers, which is in the range of 60°–65°. This allows us to obtain the specified productivity with a small energy consumption of the process of throwing the bedding, separated from the flow. Further, the increase in the radius of the center of mass also gives an increase in energy consumption of the bedding material throwing process.

4. Summary

Experimental data showed that the power consumed to drive the rotor-finger working body of the mobile straw bedding spreader in the forage spreader unit KTU-10A and tractor UMZ-8040.2, at a rotation speed of tractor PTO of 540 min^{-1}, unit forward speed of 2 km/h, and performance of 1.5 kg/s is equal to 7.633 kW.

According to the basic model specifications of the forage spreader KTU-10A, power consumed to drive the working bodies is equal to 7 kW. In our case, due to the installation of a rotary finger working body for spreading straw bedding, power consumption has increased by 9%. This increase in power consumption will not have a significant impact on the overall energy consumption of the bedding material spreading process, as the nominal operating power of the tractor of this class according to its specifications is 57.4 + 3.7 kW.

The study of changes in energy consumption of the spreading process from the radius of the center of mass of a part of the bedding material and the rotation speed of the rotary finger working device indicate its insignificant increase (up to 2.1 kJ/kg) at drum rotation frequencies up to 100 rad/s, while a significant increase in specific energy consumption (more than 3.0 kJ/kg) will occur with increasing rotation frequency and center of mass radius of more than 100 rad/s and 0.3 m, respectively, due to the increased force required to overcome the growing torque.

The analysis of rotary finger working body rotation speed impacts on energy consumption of the bedding material spreading process indicates its significant increase (more than 2.0 kJ/kg) at the rotation frequency of 80–100 rad/s. That is, the energy consumption begins to rise sharply, because the increase in angle, complementing up to 90° the angle of finger installation relative to the radius of 80°, almost neutralize the increase in rotation frequency, all this is associated with an increase in resistance force of the bedding material slipping on the finger.

Energy consumption of separated bedding material spreading process in the stall (box) was E = 1.2–3.8 kJ/kg, and increased with a decrease in the angle, complementing up to 90° the angle of finger installation relative to the radius α_o from 80° to 40°, which indicates on the existing optimal angle of rotary drum fingers installation, which is within 60°–65°.

The analysis of the existing machines for the application of litter of straw in livestock farms showed that this equipment has significant technological disadvantages:

- unstable and unreliable operation of the working bodies of the fans,
- no application of dosed litter,
- causes increased dust in production plants.

- It is therefore advisable to develop a litter spreader that works without the use of air flow with the possibility of dosing it into boxes. Reducing the size of the trusses will affect the service life of the spreaders with a rotary working body (low specific energy consumption). This solution will enable the implementation in practice of a significantly improved innovative technology, which:
- increases the efficiency of using plant materials as litter,
- reduces labor costs at the spreading stage,
- reduces the morbidity of animals,
- improves their living conditions,
- allows the use of tractors with lower power.

The developed experimental sample of a mobile straw litter spreader with a rotary-finger working body in accordance with previously conducted experimental studies fully meets zootechnical, technological and energy requirements, and can be recommended for implementation on livestock farms.

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