Improving the Efficiency of the Power Take-Off Drive

G V Redreev, A N Sorokin, A A Luchinovich, V D Chervenchuk, S D Popov

Omsk State Agrarian University named after P.A. Stolypin
644008, Omsk, Institutskaya pl. St., 1

E-mail: weerwg@mail.ru

Abstract. Power tools that are used in various industries have power take-off drives for aggregating various machines and mechanisms. In the agro-industrial complex, one of the most common power tools are tractors manufactured by the Minsk Tractor Plant. The drive of power take-off in these tractors is carried out at the expense of the planetary mechanism. The wheel and the solar gear of the planetary mechanism are connected to the drums, alternately stopping the drums is carried out on and off the drive. The brake tape of the firing drum connected to the sun gear is most susceptible to wear, as the drum is loaded with a torque of at least one third of the torque to the drive of the aggregated machine. Due to the design features of the existing control mechanism, the turn–on time is 1.5–2 times less than recommended for devices of this kind. As a result, there is an intense wear of the friction lining of the inclusion drum tape. Regulation of the control mechanism of adjusting screws is carried out untimely, as a result, the durability of the tapes is very low. To improve the durability and efficiency of the power take-off drive, a drive-on design is proposed by electromagnets. Applying force to the tape by electromagnets at four points, instead of one in the previous design, will improve the braking efficiency of the inclusion drum. It is possible to include electromagnets not at the same time, but with some time offset, with a gradual pressing of the tape, starting with the portion of the tape closest to the axis of its suspension. This improves the fit of the tape to the drum inclusion. In the transition from a mechanical drive to an electrical device, the control operation is eliminated, which reduces maintenance time, significantly increases the life of the brake belt and increases the efficiency of the power take-off drive.

1. Introduction

MTP tractors are widely used in the cultivation of crops as part of units with machines with active working bodies. The technological process is implemented by the energy supplied from the power take-off shaft (PTO) of the tractor (Fig. 1).

A planetary mechanism is used to change the torque. Turning on and off the PTO drive is carried out by two belt brakes. The pulley of one of the brakes is connected to the planetary gear drive; the pulley of the other is connected to the solar gear (Fig. 2).

2. Power take-off drive analysis

The most loaded in PTO is the brake tape of the inclusion drum (see 13 in Fig. 1) connected to a sun gear. Due to the fact that the periodic adjustment of the PTO control mechanism is not made in time, the stop time of the drum switching is large enough, prolonged slippage of the drum in the brake tape leads to increased wear of the friction lining. The durability of the tape is significantly reduced, and in the practice of agricultural enterprises can be 2–3 months with the duration of the season of field work for at least 6 months.

One of the reasons for the increase in wear during slippage of the drum 13 (Fig. 1) is the design features of the inclusion mechanism. When turning the control roller, 9 double-shouldered levers act on the adjusting screws 10 and 11, loosening one of the brake bands and pulling the other. During the activation time of \( t_{\text{ac}} \), the frequency of rotation of the drum carrier \( n_c \) increases from zero to a certain value, the frequency of rotation of the drum of the sun gear \( n_s \) decreases from a certain value to zero. At the same time, the activation time is rather small and does not exceed 1 s, which leads to increased
wear of the friction lining of the activation drum tape. For shoe brakes of hoisting machines having a similar design, the recommended braking time is 1.2–2 s.
2.1 Determination of kinematic and power characteristics of PTO
Consider the calculated PTO scheme and define its individual kinematic and power characteristics (Fig. 3):

![Figure 3 - Calculation PTO scheme](image)

Designations on the scheme:
- \( Ra \) – radius of the dividing circle of the sun gear
- \( Roh \) – radius of the circle axes of the satellites
- \( Rb \) – radius of the dividing circle of the ring gear
- \( Rd \) – radius of the inclusion drum
- \( Rg \) – radius of the pitch circle of the satellite
- \( Ftd \) – circumferential force on the inclusion drum
- \( Ftb \) – circumferential stress on the ring gear
- \( Foh \) – circumferential force on the carrier on the circumference of the satellite axes
- \( Fta \) – circumferential force on the sun gear.

The circumferential force on the \( Ftd \) start drum will be determined:

\[
F_{td} = \frac{T_a}{Ra} N \tag{1}
\]

where \( T_a \) is the torque on the sun gear, Nm

\[
T_a = T_b \left( u_{bh}^a \eta_{ph}^a - 1 \right), \text{Nm} \tag{2}
\]

where \( u_{bh}^a \) is the gear ratio of the planetary gear from the ring gear to the carrier when the sun gear is stopped

\[
u_{bh}^a = \frac{\omega_h}{\omega_b} = \frac{n_h}{n_b} = \frac{1}{u_{bh}^a} = \frac{z_b}{z_b + z_a} \tag{3}
\]

where \( z_b \) and \( z_a \) are the number of teeth of the ring and sun gear, respectively.

\[
u_{bh}^a = \frac{63}{63 + 30} = 0.677
\]

\( \eta_{ph}^a \) – efficiency of the planetary mechanism in the transmission of torque from the ring gear to the carrier when the sun gear is stopped. According to various sources [2–4] \( \eta_{ph}^a = 0.99–0.96 \).

Hence \( T_a = T_b \times (0.677 \times 0.975 - 1) = -0.34T_b \)

\[
T_a = \frac{30 \times 0.34 \times N_{PTO} \cdot H_M}{\pi n_{PTO}} \tag{4}
\]

The frequency of rotation of the shaft \( n_{PTO} \) coincides with the frequency of rotation of the carrier with the drum and is (for different types of PTO) 545 or 1000 r/min. The drive power \( N_{PTO} \) of various agricultural machinery ranges from 5 to 37 kW [5].
The magnitude of the circumferential force on the drum with its radius of 0.08 m will be:

\[ F_{td} = \frac{220.5}{0.08} \approx 2760 N \]

Based on the amount of circumferential force, the tape performance is calculated.

2.2 Tape parameter determination

In accordance with the calculations, the friction force \( F_{fp} \) between the tape and the inclusion drum must be at least 2760 N. Taking into account the safety factor [6], the friction force \( F_{fp}^S \) must be at least 4140 N. force of pressing the tape to the drum inclusion is determined by the dependence:

\[
F_{fp} = \frac{F_{fp}^S}{f_\alpha}, N
\]

where \( f \) is the coefficient of friction between the friction strip and the inclusion drum is 0.2–0.4; \( \alpha \) – angle of the drum tape, rad. For tape design is used \( \alpha = 5.76 \) rad.

With the minimum value of the friction coefficient, the value of the clamping force will be:

\[
F_{fp} = \frac{4140}{0.2 \times 0.357} = 3120 N
\]

One of the reserves to reduce the clamping force of the tape is to increase the angle of coverage of the drum tape. However, this requires a change in the design of the tape. The most rational is to change the method of clamping the tape.

3. The design of the drive electromagnets

We have developed a design for controlling the activation of the power take-off mechanism using electromagnets (Fig. 4) [7]:

![Figure 4 - Mechanism of the inclusion of a drive with electromagnets](image)

1 - shaft; 2 - inclusion drum; 3 - tape; 4 - electromagnets; 5 - switching device

The clamping force of the tape, with four electromagnets, will be 780 N per one magnet. The PTO design allows you to mount electromagnets on brake bands and install connectors for electrical wires on the rear wall of the PTO housing. The switch-on device is configured so that the drive is turned on for an optimal period of time.

In an electromagnet, a large part of the magneto motive force of the magnetization winding is applied to the air gap with a friction strip of the tape. Therefore, at any other point of the magnetic circuit the bulk energy density of the magnetic field will be less by several orders, i.e. with an acceptable
approximation it is possible to assume that all the energy of the magnetic field of the winding goes to the work of attracting the tape with an electromagnet to the drum or its braking.

The bulk density of the energy of the magnetic field is [8]:

\[
\frac{dW}{dV} = \frac{BH}{2} = \frac{\mu_0 H^2}{2},
\]

where \( B \) – the magnetic induction, \( \text{T} \); \( H = \frac{B}{\mu_0} \) – magnetic field strength, \( \text{A/m} \); \( \mu_0 = 4\pi \cdot 10^{-7} \text{H/m} \) – absolute magnetic permeability of the air gap; \( dV = Sdx \) – the elementary volume of the air gap, \( \text{m}^3 \), in which the magnetic energy is concentrated, \( J \); \( S \) – cross-sectional area of the magnetic circuit, \( \text{m}^2 \); \( dx \) – infinitely small length of the magnetic circuit air gap, \( \text{m} \); \( F \) – electromagnet traction force.

If the magnetization of the electromagnet core does not reach the saturation point, then the magnetic field strength in the air gap \( H \approx Iw/\pi x \), where \( Iw \) – the magneto motive force (MMF) of the electromagnet winding, \( \text{A} \); \( x \) – the thickness of the tape frication layer (\( x \approx 4 \text{ mm} \)).

Then

\[
\frac{dW}{dV} = \frac{Fdx}{Sdx} = \frac{F}{S} = \frac{\mu_0 (Iw)^2}{2x^2}.
\]

Thus, the winding of the DC electromagnet coil should provide MMF

\[
Iw = x \sqrt{\frac{2F}{\mu_0 S}}.
\]

We will calculate the electromagnet coil voltage that is powered from a constant voltage source at nominal voltage \( U = 12 \text{ V} \) (the minimum voltage at which it can work \( U_{\text{min}} = 10.8 \text{ V} \)); the design of such a coil is shown below (Fig. 5).

![Electromagnet coil in section](image)

**Figure 5 - Electromagnet coil in section:**

- \( h_w \) - winding thickness; \( D \) - coil diameter; \( l_c \) - coil length

Its geometrical dimensions are determined taking into account the PTO construction and correspond to the following values: \( h_w = 10 \text{ mm} \); \( D = 40 \text{ mm} \); \( l_c = 45 \text{ mm} \). In this case, the cross-sectional core area

\[
S = \pi \frac{(D - 2h)^2}{4} = 3.14 \cdot 10^{-4} \text{m}^2,
\]

and the required MMF according to (7) will be equal to

\[
Iw = 4 \cdot 10^{-3} \sqrt{\frac{2 \cdot 258.4}{4 \cdot 3.14^2 \cdot 10^{-11}}} \approx 4576A
\]

We calculate the average coil length (Fig. 5) \( l_a = 2\pi r_a = \pi (D - h_w) = 3.14(40 - 10) = 94.24 \text{mm} \).
Further, from Ohm’s law \( I = \frac{U_{\text{min}}}{R_c} \), where \( R_c = \rho \frac{l_w}{q_{cs} h_w \pi} \) – the active coil resistance, and \( \rho = 1.8 \times 10^{-11} \text{ Ohm} \cdot \text{m} \) – the copper resistivity, we find the wire cross section

\[
q_{cs} = \frac{l_w \rho l_w}{U_{\text{min}}} = \frac{4576 \times 1.8 \times 10^{-11} \times 94.25}{10.8} = 0.719 \text{ mm}^2
\]

From where the wire diameter \( d_w = 2\sqrt{q_{cs} / \pi} = 0.957 \text{ mm} \).

The closest copper winding wire produced to this section has a copper cross section \( q_{cs} = 0.712 \text{ mm}^2 \) and a nominal copper diameter \( d_w = 0.95 \text{ mm} \). The wire of the PEV-1 with such a cross section has a wire diameter taking into account the insulation \( d_l = 1.01 \text{ mm} \), the maximum allowable temperature for continuous operation \( \tau = 105 \degree \text{C} \), which corresponds to class Y of the heat resistance of insulating materials [9].

With the stacking factor \( k_s = 0.85 \), the filling factor of the winding space with copper will be equal to \( k_w = \frac{q_{cs}}{d_w^2} = 0.599 \).

We find the number of windings \( w \). By definition, the fill factor of the winding space with copper

\[
k_w = \frac{q_{cs}}{h_w l_w} w, \text{ from which } w = k_w \frac{h_w l_w}{q_{cs}} = 375.
\]

Next, we find the current value: \( I = I_{w w} = 12.2 \text{ A} \), the coil active resistance \( R_c = \frac{U_{\text{min}}}{I} = 0.885 \text{ Ohm} \), the power consumption \( P_c = I^2 R_c = 131.8 \text{ W} \) and if the heat transfer coefficient is \( k_{ht} = (8–14) \text{ W/m}^2 \), according to the Newton formula, we calculate the excess coil temperature over the external environment

\[
\Delta \tau = \frac{P_c}{k_w h_w \Delta t} = \frac{P_c}{k_w \pi D (l_c + D / 4)} = 1702.67\degree \text{C}.
\]

According to the results of calculations, an electromagnet of this design does not satisfy the requirements for the thermal resistance of wire insulation. It is necessary to change the electromagnet core (Figure 6):

![Figure 6 - The cross-sectional shape of the electromagnet core](image)

\( a \) - round section; \( b \) - elongated cross section

With the dimensions of the transverse core rectangular part of the elongated shape \( d \times 2d \), the coil temperature \( \Delta \tau \) will exceed the temperature of 200\degree \text{C} \), which corresponds to the class C of the insulation heat resistance [9–10].
4. Conclusions
To increase the braking efficiency of the drum of the planetary power take-off mechanism can be due to the application of force on the tape by electromagnets at four points, instead of one in the previous design. It can be used as a finished electromagnets, specially made according to the results of our calculations. The proposed design makes it possible to include electromagnets not simultaneously, but with some time offset, with a gradual pressing of the tape, starting with the portion of the tape closest to the axis of its suspension. The first is the upper left (see Fig. 4) electromagnet, latest – top-right. This improves the fit of the tape to the drum inclusion. In the transition from a mechanical device the drive enable to the electric device eliminates the operation of regulation, which reduces maintenance time and significantly improves the durability of the brake band.

References
[1]Ksenevich, I.P. Tractors of MTP-80 and MTP-82 / I.P. Ksenevich, S.L., Kustanovich, P.N. Stepanyuk and others; Under the general editorship of I.P. Ksenevich. - 2nd ed., revised and added. - M.: Kolos, 1984. - 254 p.
[2]Ivanov, M.N. Machine parts / M.N. Ivanov, V.A. Finogenov. - 11th ed., revised - M.: Higher school, 2007. - 408 p.
[3]Planetary gear. The directory/Under the editorship of V.N. Kudryavtsev and Yu. Kudasheva. - L.: Mechanical Engineering, 1977. - 536 p.
[4]Alexandrov, M.P. Brakes hoisting machines / M.P. Alexandrov; 3rd ed., added and revised - M.: Mechanical Engineering, 1976. - 383
[5]Regulatory reference material for the planning of mechanized operations in agricultural production: Collection. — Moscow: FGNU «Rosinformagrotekh», 2008. - 316 p.
[6]Alexandrov M.P. Lifting and transport machines. - 5th ed., revised and added – M.: Higherschool, 1979. - 558 p.
[7]Pat. №185594 Russian Federation. IPC B04K 17/28. Power take-off shaft / G.V. Redreev and others; patent holder of FSBEI HE «Omsk State Agrarian University. P.A. Stolypin». - №2018120959; declared. 06.06.2018; published 11.12.2018, bull. No. 35. – 2.
[8]Zilberman, G.E. Electricity and magnetism / G.E. Zilberman – M : Science, 1970. – 384 p.
[9]Ogonykov, V.G., EvtushenkoYu.M. Electrical insulation materials and insulation systems for electrical machines. In 2 books. / V.G. Ogonykov, Yu.M..Evtushenko – M : Publishing House MEI, 2012. – 304 p. (Book 2).
[10] Asanovich E. Z., V. A. Kolganova Highly heat-resistant electrical insulation. – M.: Energy atom published, 1988. – 264 s.