Simulation diagnostics of power train mechanical drives

N I Ovchinnikova, V V Bonnet and A V Kosareva
Irkutsk State Agricultural University named after A.A. Ezhevsky, Molodezhny settlement, Irkutsk distrikt, Irkutsk region, 664038, Russia

E-mail: bonnet74@mail.ru

Abstract. Mechanical drives have become the most widely used in design of agricultural machinery. In comparison to drives of machinery applied in other sectors of national economy, they are distinguished by their design features, performance, and cost-performance ratio. In this regard, diagnostics of mechanically driven parts of agricultural machinery is a key to the overall harvester diagnostics. In practice, health of drives is tested with subjective assessment methods, as a rule. The authors suggest application of a kinematic method for diagnostics of agricultural machinery drive trains during their operation; this method implies analysis of position changes and movement of mating parts: wear of parts and backlash of mating drive parts may be assessed by establishment of geometric parameters of diagnostics (linear and angular movements). The total transmission backlash may be established by dynamic torque appearing in transient states of mechanism operation; such total backlash characterizes dynamic errors in movement of an outlet member, which is a result of dependence of equivalent moment of inertia and drag torque from the velocity transmission error. Such diagnostics of potato harvester transmission allows checking of backlashes in separate sections of the chain, as well as assessment of quality of its components adjustment and maintenance. The research data were used for evaluation of overall engineering state of the harvester and determination of dynamic parameters of its components drives.

1. Introduction

High performance of agricultural machinery depends on its technical condition allowing reduction of work, labour costs and increase of agricultural yield. Any production process in the agriculture may be represented as functioning of a complicated system which is characterized by different failures occurring for a variety of reasons [1, 2]. To study the reasons of production failures, the most common is a systematic approach allowing revealing possibilities for increase of various production processes efficiency.

The authors paid considerable attention to reliability of machines [3, 4] during their study of production processes. Machine-tractor aggregates (MTA) may operate for a rather long time without significant deterioration of performance given their correct operation and due maintenance [5, 6, 7]. As practice shows, the trouble-free life of machines and their aggregates is shorter than the life period guaranteed by the manufacturer. The main reasons of such short life period are premature groundless maintenance and low culture of MTA operation in real farm conditions [8].

Considering machine harvesting of potato, it should be noted that harvesters are not quite suitable for operation in severe climatic conditions which is evidenced by their low reliability level [9-13].
Dynamic overloads caused by potato yield, size and shape of fields, and foreign matters on fields jeopardise technical condition of machine aggregates.

Mechanical drives have gained wide use in design of potato harvesters: they are simple in design and reliable in operation, having high serviceability, low cost and high performance index, which makes them high in demand for designing of drive units. Mechanical drives of agricultural machinery differ from those used in machines of other sectors of national economy due to peculiarities of design and operation of agricultural vehicles. That is why diagnostics of mechanical drives of operating parts in potato harvesters is the most significant part of diagnostics of the whole machine.

Health of potato harvesters is determined with subjective assessment methods with the help of measuring devices, as a rule [14-18], by determination of variations between diagnostic parameters and their rated values. Though, these diagnostic methods have not gained widespread use for agricultural machinery, regardless a great number of engineered devices and instruments. The main reason for this is high cost of applied equipment which is intended mostly for measurements of insignificant number of diagnostic parameters and is ill-adapted for field conditions.

2. Materials and methods

We suggest application of kinematic method during operation of agricultural machinery for diagnostics of its power train. This method allows testing of geometric parameters (linear and angular movement) during position change and movement of mating parts. These parameters help to determine wear of parts and backlash of mating parts. This method also involves measurement of total transmission backlash for determination of kinematic pair condition without its disassembling. Using this parameter, dependence of angular play from wear of mating parts is determined.

Given a stated rotation angle $\phi_1$ of an inlet member in a perfect transmission, the outlet member rotates by a corresponding angle $\phi_n$ which is pro rata to angle $\phi_1$ in time and to the reduction ratio $i$ [19]:

$$\phi_n = f(\phi_1, i, t)$$  \hspace{1cm} (1)

This dependence is violated in real transmission due to inaccuracies in manufacturing of parts, rotation supports, bodies, shafts and other transmission components, and inaccuracies in assembling and elastic strains of transmission components occurring under transmitted loads:

$$\phi_1 = \phi_n + \Delta \phi_n$$  \hspace{1cm} (2)

where $\Delta \phi_n$ – describes the level of theoretical connection disturbance (velocity transmission error) between positions of inlet and outlet components of transmission under a definite value of the rotation angle $\phi_n$ of the driven member.

The velocity transmission error appears at the beginning of the forward motion, because the driven member remains motionless during rotation of the driving member till backlash of mating parts establishes, and elastic strain of these transmission components occurs. Further on, the velocity transmission error will acquire the form of function $\Delta \phi_{n,np} = f_1(\phi_n)$, during forward motion and change of the angle $0 < \phi_n < \phi_n^p$ and function $\Delta \phi_{n,fp} = f_n(\phi_n)$ during backward action.

Difference of velocity transmission errors during forward motion and backward action is a "lost motion" (backlash):

$$U_\phi = f_n(\phi_n) - f_1(\phi_n).$$  \hspace{1cm} (3)

We suggest applying a dynamic torque occurring during transient states of mechanism operation to determine total backlash in transmission of two-row potato harvester KPK-2-01.
The essence of the method is as follows: each member possesses finite rigidity, i.e. they strain under loads, while there are backlashes in mating parts; consequently, shaft torque would stepwise rise while transmission components become engaged.

The torque required for drive of \( i \)-component of the machine is calculated by the equation [20]:

\[
M_i = M_{ci} + J_i. \tag{4}
\]

where \( M_{ci} \) - is dead-weight load, involving friction of \( i \)-component of transmission; \( J_i \) - is the moment of inertia of \( i \)-component of transmission driven to the driveshaft.

If there is \( n \) number of rotating parts with inertias \( J_1, J_2, J_3, ..., J_n \) and angular velocities \( \omega_1, \omega_2, \omega_3, ..., \omega_n \), their total dynamic action would reduce to a single inertia normalized to the angular rate of the inlet shaft. Then, the following condition is fulfilled during rotation:

\[
J \omega_i^2 = \frac{J_1 \omega_1^2}{2} + \frac{J_2 \omega_2^2}{2} + \frac{J_3 \omega_3^2}{2} + ... + \frac{J_n \omega_n^2}{2}. \tag{5}
\]

The total inertia moment driven to the inlet shaft of the mechanism is determined as follows:

\[
J = J_1 + J_2 \left( \frac{\omega_2}{\omega_1} \right)^2 + J_3 \left( \frac{\omega_3}{\omega_1} \right)^2 + ... + J_n \left( \frac{\omega_n}{\omega_1} \right)^2. \tag{6}
\]

If acceleration \( \frac{d\omega}{dt} \neq 0 \) is changed, the drive would overcome dynamic moments, and the equation of total load would be:

\[
M_{\text{sum}} = \sum_{i=1}^{n} \left( M_{ci} + J_i \frac{d\omega_i}{dt} \right). \tag{7}
\]

The torque of the harvester driveshaft will increase till all drive components are engaged. When the torque reaches its maximum, the angle matches up with the total transmission backlash (lost motion). When comparing the torque dynamics and the corresponding section of the kinematic scheme, we can determine backlashes by separate units and parts of transmission.

To assess technical condition of transmission aggregates, it is suggested to use the ability of mechanisms to establish variable disturbing torque at even rotation of the inlet member, i.e. its inner vibration activity, as a dynamic criterion. The vibration activity is determined by the torque \( M_{\text{var}} \), affecting the drive; it appears during additional acceleration \( \Delta \varepsilon \).

Since the velocity transmission error is a function of rotation angle of the driving member \( \Delta \varphi = f (\varphi_1(t)) \), additional velocity may be obtained by its differentiation [19, 21]:

\[
\Delta \omega = (\Delta \varphi)'_1 = \frac{d\Delta \varphi}{dt} = \frac{d\Delta \varphi}{d\varphi_1} \cdot \frac{d\varphi_1}{dt} = \frac{d\Delta \varphi}{d\varphi_1} \cdot \omega_1. \tag{8}
\]

By its differentiation we get additional acceleration:

\[
\Delta \varepsilon = (\Delta \varphi)''_1 = \frac{d^2 \Delta \varphi}{dt^2} = \frac{d^2 \Delta \varphi}{d\varphi_1^2} \cdot \frac{d\varphi_1}{dt} + \frac{d\Delta \varphi}{d\varphi_1} \cdot \frac{d^2 \varphi_1}{dt^2} = \frac{d^2 \Delta \varphi}{d\varphi_1^2} \cdot \omega_1^2. \tag{9}
\]
As $\frac{d^2\phi_1}{dt^2} = 0$ at constant rotation speed of the inlet member, then the following result may be obtained:

$$\Delta\varepsilon = \frac{d^2\Delta\phi}{d\phi_1^2} \cdot \omega_1^2.$$ \hspace{2cm} (10)

Hence, the variable torque affecting the drive is determined as follows:

$$M_{\text{var}} = J \cdot \Delta\varepsilon = J \omega_1^2 \frac{d^2\Delta\phi}{d\phi_1^2}.$$ \hspace{2cm} (11)

Considering that the inertia moment of the harvester parts is constant, while the inlet shaft rotates at constant speed, then the vibration activity of mechanical drives of the harvester would depend on additional angular acceleration $\Delta\varepsilon$, which is proportional to second derivatives of the velocity transmission error, i.e. technical condition of the unit transmission.

3. Results of the study, their discussion.

The following results presented in figure 1 were obtained during the study performed on the theoretical background and in compliance with the method of "simulation" diagnostics of potato harvester mechanical drives.

Shaft torque variation was determined with the help of strain measurement. If the driveshaft of the harvester transmission rotates for a long time, the torque resistance occurring at the shaft rises stepwise up to a definite value of $M_{\text{sum}}$ equal to the friction force of all components of the drive.

![Figure 1](image-url)

**Figure 1.** Dynamics of torque changes on the drive shaft of the transmission of the potato harvester.
Further on, its value starts to change, and the variable disturbing torque \( M_{\text{var}} \) appears. At even rotation of the inlet member, inner vibration activity of the drive appears. This value describes dynamic errors of the inlet member motion and results from dependence of the reduced moment of inertia and the drag torque from the velocity transmission error. At that, the rangeability of the torque is directly proportional to the drive rotation speed, while these values may be negative if rotation speed exceeds \( n \geq 100 \, \text{min}^{-1} \).

Application of this parameter for assessment of transmission technical condition is based on its comparison with performance standard (obtained during rotation of an adjusted harvester drive \( M_{\text{var}} = 25\ldots30 \, \text{Nm при частоте } n = 2 \, \text{min}^{-1} \)).

Since the potato harvester transmission involves a large number of different mating parts in units and aggregates (or components), as well as different operating parts engaged both in parallel and in sequence during rotation, it is impossible to determine a definite mating part of the drive, where there is a backlash, using variation of the torque.

In support of this, a scaled up dynamics line of the torque rise is given in the figure. To find out technical condition of transmission units and aggregates, torque variations were grouped by sections of the kinematic chain. In this case, there is a possibility to analyze them during diagnostics. Besides, separate sections of the kinematic chain may be removed during the shaft rotation for more reliable results.

4. Conclusion

We suppose that assessment of technical condition of mechanical drives in operating parts of potato harvester KPK-2-01 on the basis of their lost motion and vibration activity is the most acceptable method. Kinematic method of diagnostics allows reduction of dynamic loads on transmission components and related drive parts, prevention of overloads, providing the required service life and diffusing external manifestations of transmission oscillations (jerks, vibrations, etc.). Besides, simulation diagnostics of the harvester mechanical drives allows determination of technical condition of overload release clutches in operating parts and the moment of their action. In this case, simulation of the clutch operation involves locking of its outlet shaft and the operating part where it is installed.

Summarizing results of the study undertaken, it should be noted that simulation diagnostics of the potato harvester transmission allows considerable increase of reliability of values of release clutch action moments, as well as their accurate adjustment. Comparing side lashes in separate sections of the chain with their standard values (determined by terms of reference), quality of adjustment and maintenance of the chain section may be established. The data obtained as a result of the study were used for assessment of the overall technical condition of the harvester and determination of dynamic parameters of its components drive.

References

[1] Ovchinnikova N., Kosareva A., Bonnet V 2019 Analysis of functioning of potato-terminal technological system based on probability-statistical approach IOP Conf. Ser.: Earth and Environ. Sci. 341 012129

[2] Ovchinnikova N I et al 2019 A simple semi-Markov model of functioning of agricultural cleaning and transport system Journal of Physics: Conference Series. 2019. 1333 032061

[3] Terskih I P, Ovchinnikova N I and Bonnet V V 2003 Improving the reliability of the technological system of potato harvesting man-machine-environment-transport Equipment in agriculture 4 7–9

[4] Bonnet V V 2001 The impact of the technical condition of the potato harvester on the reliability and efficiency of the technological process: dissertation (Novosibirsk) p 198

[5] Zavrazhnov A I, Vedishhev S M, Glazkov Ju E, Prohorov A V, Milovanov A V and Hol'shev N V 2019 Operation of the machine and tractor Park (Tambov: Publishing center FGBOU VO «TGTU») p 224

[6] Zangiev A A, Shpi'l'ko A V and Levshin A G 2008 Operation of machine and tractor equipment (Moscow: Koloss) p 320
Kosareva A V, Ovchinnikova N I 2017 Improving the reliability of the ergatic system with transport security in crop production due to reservation of its elements Herald IrGSHA 80 111–8

Andreev O P 2020 Scientific bases of effective use of machine-tractor units (Moscow: Autograph LLC) p 115

Chkhetiani A A 2011 Analysis of modern technologies for the cultivation of potatoes and the design of potato harvesters Technical Sciences - from theory to practice Proc. 4th Int.scientific-practical conf. (Novosibirsk: SibAK [SibAC]) pp 110–5

Korolev A E 2017 Reliability of potato harvesters Tekhnicheskie nauki [Technical Sciences] 10 398

Krygina E E, Parshin I A and Dudukin S A 2018 Ways to increase the efficiency of potato harvesters in difficult conditions Molodoj uchenyj [Young scientist] 42 39–42

Melem V V, Stepanov N V and Bonnet V V 2019 Theoretical study of the design parameters of the working body of the chain haulm shredder Agrarnyj nauchnyj zhurnal [Agrarian Scientific Journal] 7 84–8

Pshechenkov K A, Mal'cev S V and Smirnov A V 2018 Potato harvesting Sel'skij mekhanizator [Rural machine operator] 9 8–13.

Anan’in A D, Mihlin V M, Gabitov I I, Negovora A V and Ivanov A S 2008 Diagnostics and maintenance of machines (Moscow: Academy) p 432

Kapustin V P and Glazkov Ju E 2010 Technological maintenance of agricultural machines (Tambov: Publishing center FGBOU VO «TGTU») p 12

Kapustin V P and Glazkov Ju E 2010 Agricultural machines: setting and adjustment (Tambov: Publishing center FGBOU VO «TGTU») p 196

Korneev V M, Novikov V S, Kravchenko I N, Ochkovskij N A and Petrovskij D I 2018 Technology of repair of cars, ed B M Korneeva (Moscow: INFRA-M) p 314

Taratorkin V M and Golubev I G 2017 System of maintenance and repair of agricultural machines and mechanisms (Moscow: Academy) p 378

Vul'fson I I, Erihov M L, Kolovskij M Z and Pejsah Je E 1996 Mechanics of machines, ed G A Smirnova (Moscow: Higher school) p 511

Dunaev P F and Lelikov O P 2009 Design of machine components and parts (Moscow: Academy) p 496

Prudnikov A Yu, Bonnet V V and Loginov A Yu 2019 Automated system for processing diagnostic parameters of asynchronous motors for poultry house ventilation systems IOP Conf. Ser.: Earth Environ. Sci. 315 032019