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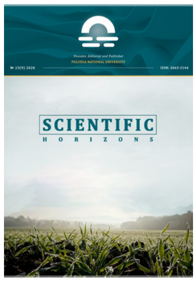

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Forecasting the technical condition of hydraulic transmissions of agricultural machines based on kinematic viscosity and pressure indicators of oil

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Abstract. Maintenance of the technical condition of hydrostatic transmission of agricultural machines is not fully provided by the existing repair and maintenance system of Ukraine, which determines the search for available methods for early detection of hydraulic drive malfunctions. The purpose of the study was to synthesise a method for predicting the technical condition of the hydraulic transmission of modern agricultural machines by controlling the dynamics of changes in the values of the empirical dependence of pressure on the kinematic viscosity of oil in conditions of insufficient material and technical equipment of the production base. Generally accepted methods were applied to achieve this goal: analysis-synthesis, induction, observation, experiment, graphic method. As a result of the study, the author's hypothesis was confirmed, according to which the change in the kinematic viscosity of the working fluid relative to the initial value is determined by the current state of the hydraulic transmission, which is controlled by pressure measurement. Based on the identified shortcomings and problems of the current system of maintenance and repair, a methodology was proposed that provides for monitoring the operational indicators of agricultural machines and the kinematic viscosity of working fluid samples taken from their hydraulic transmissions. Kinematic viscosity values for constructing the predictive model were obtained by the capillary method and calculated using the Walter formula, and the dependence of viscosity on influencing factors was determined by bilinear interpolation. A regression model of pressure from kinematic viscosity was obtained by the least squares method, and the exponent was used as an approximating function. Based on the results of testing the models according to the Fischer criterion, their adequacy was confirmed, and the deviation of the theoretical values of the controlled parameters calculated using the most accurate

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model from the empirical ones was 0.34% for pressure and 1.3% for kinematic viscosity. The practical value of the study lies in the fact that the results allow reducing unproductive time costs associated with the downtime of equipment, due to emergency failures of hydraulic transmission units and contribute to the adaptation of the planned preventive maintenance system for agricultural machinery to the needs of the Ukrainian agro-industrial complex

Keywords: combine harvester; hydrostatic transmission; reliability; diagnostics; working fluid properties

INTRODUCTION

The innovative level of design features of hydrostatic gears, with which modern agricultural machines are equipped, causes increased requirements for monitoring their technical condition. Conducting diagnostic measures is usually reduced to identifying the causes of the loss of performance of the hydraulic transmission and the machine in general. This approach leads to unplanned downtime of equipment since resource diagnostics, which are regulated by the existing planned preventive system, do not provide for the possibility of predicting changes in the technical condition of the diagnostic object.

The main tasks of the planned preventive system (PPS) of technical maintenance and repair (TMR) of agricultural machinery, in accordance with the explanation of its essence in a study by Konovaliuk *et al.* (2013) is to maintain the components of the machine in good condition and increase their service life, the solution of which is regulated by the manufacturers of the equipment in the relevant regulatory-technical documentation. According to the studies by Zakharchuk (2019) and Petrov (2020), there is an increase in the number of processing areas per unit of equipment, and the trend of the permanent increase in imports of post-warranty equipment determines the problem of oversaturation of the Ukrainian machine and tractor fleet of the agro-industrial complex (AIC) with machines of the post-warranty period, which require special attention to monitoring their technical condition.

Considering the hydrostatic transmission of a modern agricultural machine as an object of PPS, in the conditions of the repair and maintenance base of Ukraine, the volume of work of which, according to Molodyk *et al.* (2009), has decreased by 5 times since the 90s of the 20th century and continues to decrease, which substantially increases the critical level of the problem of monitoring and restoring the operability of hydraulic machines, the official repair of which can only be conducted with the involvement of repair and maintenance bases of the manufacturer, the material-technical support of which today does not meet the needs for repair of the AIC of Ukraine.

Guo *et al.* (2017) estimated the durability of a modern hydraulic machine has a highly embedded resource, which, depending on the operating conditions and considering the seasonality of their load as part of an agricultural machine, can exceed 10 years of operation, but the average age of the machine and tractor fleet of most production enterprises eliminates this advantage.

Reducing the number of potential resource failures of hydrostatic transmission is possible due to the involvement of the forecasting component in the process of implementing regular maintenance regulations. Andrenko *et al.* (2018) define the concept of forecasting as a solution to the probabilistic problem of determining the behaviour of the system and its state in the future, depending on the factors of influence. Given the complexity of reproducing such studies, the paper presents three forecasting methods that are currently not relevant in practice and require their adaptation to the conditions of the repair and maintenance base of Ukraine: by constructing curves of reliability changes, Markov approximation, and the method of expert assessments. The presented methods of forecasting changes in the technical condition for their implementation in the context of modern hydrostatic transmission are not currently used due to the substantial influence of information uncertainty regarding the dynamics of changes in the resource of modern hydrostatic transmission units. According to studies by foreign researchers, the level of development of the subject on predicting the technical condition of hydraulic transmission units for agricultural machinery could not be estimated due to the complexity of access to relevant information.

Insufficient development of this subject in the conditions of the Ukrainian research complex is partly explained by the adaptability of hydraulic equipment under study only for outdated hydraulic machines GST-90, GST-112, the resource for the failure of which, according to the information provided by Voitov (2018), does not exceed 1000 operating hours and is not sufficient for conducting such studies. In turn, the construction of an available forecasting method is reduced to finding and extrapolating the empirical dependence of pressure on factors influencing it.

Since the indicator of the working fluid pressure in the system reflects the energy efficiency of the hydraulic machine, according to the studies by (Biluš *et al.*, 2021) and Koralewski (2011) is obtained by providing a balance between its mechanical and volumetric efficiency, which is largely determined by the kinematic viscosity of the working fluid. In a study, conducted by Zamiruddin *et al.* (2020), the dependence of the oil film thickness on the viscosity of the working fluid was confirmed, the relationship between which is described by a positive correlation. In turn, a decrease in kinematic viscosity causes a deterioration in the lubricating properties of the oil, a change in the temperature regime due to an increase in the volume of throttling of the working fluid, a decrease in the productivity and service life of the axial piston hydraulic machine, etc.

Since during the circulation of the working fluid in the hydraulic system, it is prone to loss of its quality properties, the features of changing which are described in the textbook (Boichenko *et al.,* 2019), which lead to ageing of the working fluid and indicate a stochastic relationship between pressure and kinematic viscosity for further development of a method for predicting the state of the hydraulic drive.

Considering the fact that the degradation of the physico-chemical properties of the oil occurs during its operation, the catalyst for changes in the properties of the oil and its kinematic viscosity is the time and intensity of its operation, which is noted in a study by Majdan *et al.* (2019). In accordance with this, a working hypothesis was proposed according to which the loss of productivity of hydraulic machines can be tracked by the dynamics of changes in the pressure of hydraulic transmission, which is determined by the dependence of the kinematic viscosity of the working fluid on the intensity of operation and the technical condition of hydraulic transmission units.

Based on the above material, the purpose of the study was formulated: synthesis of a method for predicting the technical condition of hydraulic transmission of imported agricultural machines by controlling the dynamics of changes in the values of the empirical dependence of pressure on the kinematic viscosity of oil in conditions of insufficient material and technical equipment of the production base of the AIC of Ukraine.

MATERIALS AND METHODS

Measurements of the dynamics of pressure changes together with the established factors of influence on it were conducted during the performance of maintenance, which provides for the replacement of working fluid and filter elements on agricultural machines belonging to various agro-industrial enterprises of Ukraine, in accordance with the methodology developed in the laboratory of the Dnipro State Agrarian and Economic University (DSAEU). The developed methodology for predicting the operability of hydrostatic transmission included the selection of controlling factors and equipment for their monitoring, justification of the plan, and procedure for conducting studies.

The capillary method was chosen to determine kinematic viscosity ν of the working fluid, the procedure for which is described in European Pharmacopoeia 10 (2019). This method is based on Poiseuille's law, the application of which is to determine the time of flow of a certain volume of liquid under the influence of gravity through a calibrated glass capillary viscometer at a constant temperature.

The choice of this method is determined by its availability and low complexity of implementation. An experimental setup based on the BPR-3 viscometer was developed to apply the method, d=0.92 mm, which additionally includes a water circulation and heating system (Fig. 1).

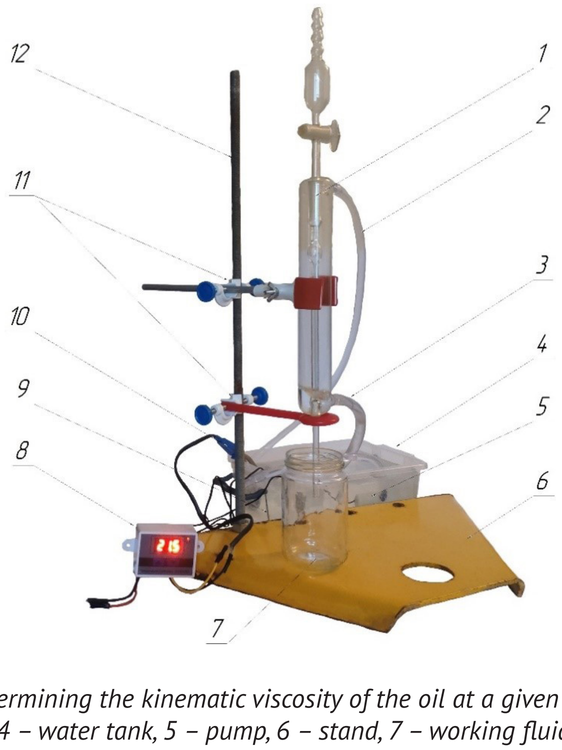


Figure 1. *Installation for determining the kinematic viscosity of the oil at a given temperature: 1 – viscometer, 2 – feed tube, 3 – drain tube, 4 – water tank, 5 – pump, 6 – stand, 7 – working fluid sample tank, 8 – thermostat, 9 – temperature sensor, 10 – electric heater, 11 – viscometer holders, 12 – rod*

The flow time of the working fluid sample is determined three times. Based on their arithmetic mean, kinematic viscosity is calculated using the formula:

$$\nu = \frac{g}{9.807} \cdot t \cdot k\,, \tag{1}$$

where g=9.80884 (m/s^2) – acceleration of gravity at the place where the kinematic viscosity of the liquid is measured; t – arithmetic mean of the liquid flow time (s); k=0.1716 (mm^2/s^2) – calibration constant of the viscometer.

Two constant temperature programmes were determined to reduce the influence of the human factor on the expression of the viscosity-temperature characteristics of the working fluid when setting the thermostat: T_1=40°C and T_2=60°C, and the calculation of the kinematic viscosity value at an arbitrary temperature is conducted according to the analytical Walter formula presented in the ASTM D341 (2020) standard:

$$log_{10}\left(log_{10}(\nu_T + 0.7)\right) = A - B \cdot log_{10}T\,, \tag{2}$$

where ν_t – kinematic viscosity of the liquid at temperature T (mm^2/s); T=t+273.15 – liquid temperature, (K); A, B – coefficients determined based on experimentally obtained kinematic viscosity values ν_1 and ν_2 at temperatures T_1 and T_2.

$$A = log_{10}\left(log_{10}(\nu_{T1} + 0.7)\right) + B \cdot log_{10}T1\,, \tag{3}$$

$$B = \frac{log_{10}\left(log_{10}(\nu_{T2}+0.7)\right) - log_{10}\left(log_{10}(\nu_{T1}+0.7)\right)}{log_{10}\frac{T1}{T2}}\,. \tag{4}$$

Formula (2) was converted to the following to find the value of the kinematic viscosity from it:

$$\nu_t = 10^{10^{(A - B \cdot log_{10}T)}} - 0.7\,. \tag{5}$$

The working fluid pressure values were measured in compliance with the temperature requirements specified in the regulatory-technical documentation for the machine using an electronic diagnostic device (Fig. 2), which was developed and calibrated independently of the current study. The principle of its operation is based on reading pressure values using piezoresistive sensors, which are installed in the structurally provided technological holes of the volumetric hydraulic machine, and the temperature of the liquid in the hydraulic system through digital sensors, which are fixed to the couplings of high-pressure hoses at the point of their connection with the hydraulic pump.

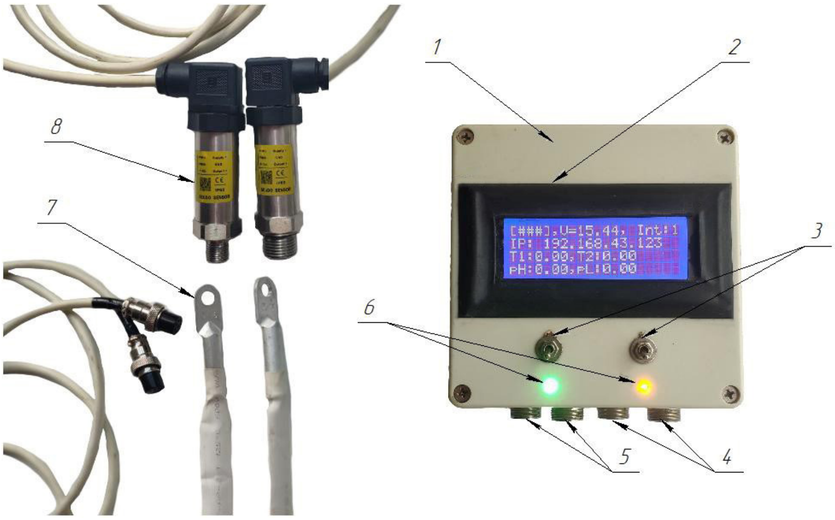


Figure 2. *Appearance of the device for measuring the pressure and temperature of the working fluid: 1 – computing unit, 2 – display, 3 – toggle switches, 4 – temperature sensor ports, 5 – pressure sensor ports, 6 – workflow indicators, 7 – temperature sensors, 8 – pressure sensors*

The operating time and fuel consumption of each technical system was recorded using the built-in computer, the main features of which are described in the TUCANO 500 configuration instructions (2018). The obtained data was grouped with the previously obtained diagnostic parameters of the machine and entered in the spreadsheet on the personal computer.

Notably, due to the unmanageability of the controlled parameters, which were selected as factors of the working fluid pressure response function, the construction of models was conducted based on the results of a passive experiment, which, accordingly, will mean a deterioration in the predictive properties of models, but according to Lapach (2020), the use of a passive experiment is allowed if it is impossible to conduct an active full factor experiment. In turn, due to the insufficient amount of information about the mechanism of the processes of changing the state of the working fluid and the operability of hydraulic system units (the dynamics of which is individual for each machine), it was decided to apply the cybernetic approach of the "black box", which is fully described in the study (Obod *et al.,* 2019).

As a result of the study of the relationship of controlled factors, the decomposition of an empirical dependence of pressure on the kinematic viscosity of the working fluid was conducted, according to which a four-level hierarchical structure of dependencies of controlled factors was formed, in which factors of the subsequent level are determined by factors of the previous level (Fig. 3), and the desired mathematical model will be a nested superposition of functions of the form:

$$p(\nu(i(t_c, V_c), t_3)), \tag{6}$$

where p – regression dependence of pressure on kinematic viscosity (MPa); ν – regression dependence of kinematic viscosity on the intensity of machine operation and total machine operating time t_s (mm²/s); i – formula for the intensity of machine operation; t_s – car operating time per season (operational hours); V_s – fuel consumed per season (L).

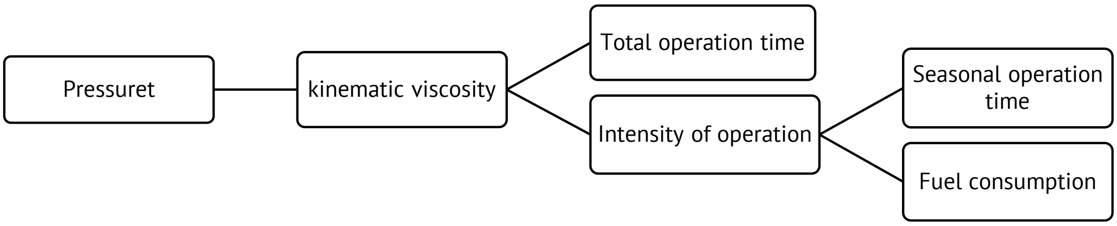


Figure 3. *Theoretical hierarchy of relationships between controlled parameters*

According to Formula (6), the solution to the problem involves consistently finding functional dependencies in descending order of their nesting level: operating intensity, kinematic viscosity, pressure. The formula for the intensity of operation of the machine (7) was determined in terms of the share of fuel consumption and operating time for the current season. This function was introduced to reduce the complexity of calculating the coefficients of the kinematic viscosity regression equation by reducing the number of predictors.

$$i(t_c, V_c) = \frac{V_c}{t_c}. \tag{7}$$

The kinematic viscosity formula $\nu(i, t_s)$ was decided to be calculated by the method of bilinear interpolation. However, its application requires compliance with certain conditions, namely, the presence of four points with coordinates corresponding to the predictors of the desired dependence, which form a rectangle whose sides are parallel in pairs to the abscissa or ordinate axes. Since the conditions for applying the method are violated due to the presence of an insufficient number of points, and the satisfaction of the condition for placing these points will be probabilistic, therefore, to ensure permanent compliance with the requirements of applying the method, an algorithm for converting the initial data in accordance with the requirements for applying bilinear interpolation for three arbitrary points was proposed, the procedure for which is presented below.

It is necessary to draw vertical perpendiculars to the abscissa axis through the existing three points, the abscissa value of which is minimum or maximum, and through the points, the ordinate value of which is minimum or maximum, draw horizontal perpendiculars to the ordinate axis to determine the vertices of a rectangle on the Cartesian plane, the coordinates of which will correspond to the values of the predictors of the function $\nu(i, t_s)$, and each such vertex will correspond to a single value of kinematic viscosity. As a result of the intersection of these lines, a rectangle with vertices at the points will be formed: $(i_{min}, t_{s.min})$, $(i_{min}, t_{s.max})$, $(i_{max}, t_{s.min})$, $(i_{max}, t_{s.max})$.

Finding the applicat for the formed points, the values of which correspond to the kinematic viscosity, is primarily reduced to finding the general equation of the plane in three-dimensional space:

$$A \cdot i + B \cdot t + C \cdot \nu + D = 0, \tag{8}$$

where A, B, C – coefficients of the equation.

According to the theoretical material on linear algebra and analytical geometry, which is systematised in the Osadcha manual (2020), it is possible to find the coefficients of equation (8) through a third-order determinant, the elements of which correspond to the differences of certain controlled parameters that are represented on one of the axes of a three-dimensional Cartesian coordinate system, the lower index of which corresponds to the maintenance number at which the diagnostic parameter was obtained:

$$\begin{vmatrix} i - i_1 & t - t_1 & \nu - \nu_1 \\ i_2 - i_1 & t_2 - t_1 & \nu_2 - \nu_1 \\ i_3 - i_1 & t_3 - t_1 & \nu_3 - \nu_1 \end{vmatrix} = 0. \tag{9}$$

Substituting the values of the controlled parameters obtained for the last three maintenances and identifying the determinant (9) on the left side of the expression, after reducing such terms, the desired general equation of the plane is obtained.

According to the geometric interpretation of kinematic viscosity, its value corresponds to the applicator of the intersection point of the perpendicular omitted to the XOY plane and plane (8). It is necessary to substitute each of the four points formed at the beginning of the algorithm into equation (8) and solve it with respect to ν to find the desired applicates.

The model of the relationship between pressure and kinematic viscosity in accordance with the volume of observations of the dynamics of changes in controlled parameters at the initial stage was determined by the LaGrange polynomial of the 2nd degree, which in turn assumed the simplicity of its application and a low error of the formula, and minimising the influence of the Runge phenomenon in the current order of the polynomial, which Belanger (2017) conducted studies on to eliminate.

The results obtained using this algorithm provide sufficient conditions for applying the bilinear interpolation method to construct an empirical dependence of kinematic viscosity on the operating intensity and overall operating time of the machine. The calculation of the function-response values was conducted according to the approach described by Chapra and Raymond (2015):

$$F(i,t) = \frac{1}{(i_{max}-i_{min})(t_{3.\max}-t_{3.\min})}\left[i_{max} - i \;\; i - i_{min}\right]\begin{bmatrix}\nu_{11} & \nu_{12}\\ \nu_{21} & \nu_{22}\end{bmatrix}\begin{bmatrix}t_{3.max} - t\\ t - t_{3.min}\end{bmatrix}, \tag{10}$$

where $\nu_{11}=\nu(i_{\min}, t_{3.\min})$, $\nu_{12}=\nu(i_{\min}, t_{3.\max})$, $\nu_{21}=\nu(i_{\max}, t_{3.min})$, $\nu_{22}=\nu(i_{\max}, t_{3.max})$.

Checking the adequacy of forecasting using this formula showed unsatisfactory results of approximation accuracy, and therefore, using the least squares method (LSM), it was determined that the optimal function for describing models is an exponential function of the form (11), the coefficients of which are obtained from the system of linear equations (12).

$$f(x) = a_1 \cdot e^{a_2 \cdot x}, \tag{11}$$

where a_1, a_2 – undefined coefficients

$$\begin{cases} a_1 \cdot n + a_2 \cdot \sum_{i=1}^{n} x_i = \sum_{i=1}^{n} y_i \\ a_1 \cdot \sum_{i=1}^{n} x_i + a_2 \cdot \sum_{i=1}^{n} x_i^2 = \sum_{i=1}^{n} x_i \cdot y_i \end{cases}. \tag{12}$$

Since function (11) is not linear with respect to its coefficients, it is necessary to reduce it to a linear form and perform substitutions, the substitution of which in the system (12) allows finding the coefficients a_1, a_2 and the LSM model.

$$\ln y = \ln a_1 + a_2 \cdot x \tag{13}$$

$$\begin{cases} a_1' = \ln a_1 \\ y' = \ln y \end{cases}. \tag{14}$$

RESULTS AND DISCUSSION

Increased attention to monitoring the technical condition of hydraulic systems (HS) by the value of the working fluid pressure, in contrast to monitoring its supply, is explained by the structural adaptability of hydraulic machines provided by technological holes through which mechanical or electrical pressure monitoring sensors are connected, and the installation of a flow meter in the HS circuit is accompanied by a number of problems, including: the need for depressurisation of the system, which causes a higher labour intensity, the possibility of violating the integrity of connections in the places where the flow meter is installed, soil contamination with oil; high cost of implementation. Therefore, monitoring the technical condition by the working fluid pressure value is a priority, since it does not require substantial material and labour costs with a satisfactory level of its information content.

According to the user's instructions for the Comia C6/C8 combine harvester (2020), the regulations for conducting periodic maintenance of which are similar to most agricultural machines of the world market leaders, the procedures for maintaining the technical condition of the HS are limited to organoleptic inspection of tightness, oil level and surface contamination, and the preliminary assessment of the technical condition is reduced to monitoring such diagnostic parameters as pressure and flow of working fluid, the permissible deviation of which is not regulated by the documentation.

The DSTU 2193-93 (1994) standard established the permissible deviation of operability for the total efficiency and feed rate, which should not decrease by more than 15% and 7% relative to the initial values, respectively. However, the problem of establishing a correlation between the total efficiency and the working fluid pressure makes this technical requirement time-consuming and financially expensive to implement. In practice, the operation of the hydraulic transmission is stopped only if it is impossible for it to perform its functions in full, which, on the example of Lexion combine harvesters, corresponds to a pressure threshold of 40 MPa for the 90R130/100 hydraulic pump, the nominal pressure value of which, according to the official manufacturer's catalogue (2016), is 45 MPa.

Observations on the dynamics of changes in controlled parameters took place during four seasons of operation for each machine equipped with hydraulic transmission, except for the first one, the object of study of which failed due to an emergency failure due to an operational factor. A certain number of observations is established in accordance with the rules of forecasting, namely, the extrapolation period for the future should not exceed a third of the observation period described by Batsamut (2020). An additional fourth observation was performed to evaluate the accuracy of the obtained empirical dependencies.

Immediately before implementing regular maintenance, diagnostic parameters for monitoring the technical condition of hydrostatic gears and machine operation indicators, shown in Table 1, were recorded.

Table 1. *Indicators of controlled parameters of the study objects*						
No. of object	**Object experiment**	**Season**	**Total operating time, operating hours**	**Pressure, MPa**	**Temperature, °C**	**Fuel consumption, L**
1	Tucano 480	1	4193.60	41.74	50.81	162177.00
		2	4638.40	41.68	49.01	179389.00
		3	-	-	-	-
		4	-	-	-	-
2	Tucano 570	1	4578.35	41.95	50.44	169444.00
		2	5144.50	41.62	49.15	190425.00
		3	5716.65	41.16	49.47	211600.00
		4	6250.80	40.98	47.03	231403.00
3	Lexion 560	1	6797.92	41.91	47.99	242727.00
		2	7351.52	41.74	47.77	262520.00
		3	7883.12	41.21	48.86	281531.00
		4	8446.72	41.13	49.71	301658.00
4	Lexion 560	1	6071.16	41.89	49.96	247292.00
		2	6674.80	41.77	51.33	271911.00
		3	7249.44	41.70	50.69	295357.00
		4	7813.08	41.62	51.19	318294.00
5	Lexion 580	1	4501.22	41.67	47.88	190383.00
		2	5060.24	41.52	46.30	214034.00
		3	5572.26	41.32	46.67	235738.00
		4	6129.28	41.29	46.17	259290.00
6	Lexion 580	1	4952.91	41.33	51.94	185246.00
		2	5443.9	41.09	51.09	203625.00
		3	5921.89	40.61	47.60	221529.00
		4	6405.88	40.42	46.20	239619.00

Source: *compiled by the authors*

The results of determining kinematic viscosity based on working fluid samples that were removed from hydraulic transmissions after scheduled maintenance work are presented in Table 2.

Table 2. *Kinematic viscosity indicators of working fluid samples*				
No. of object	**Season**	**Kinematic viscosity at 38°C, mm^2/s**	**Kinematic viscosity at 40°C, mm^2/s**	**Kinematic viscosity at 58°C mm^2/s**
1	1	45.48	42.20	23.30
	2	43.76	40.60	22.14
	3	-	-	-
	4	-	-	-
2	1	42.90	39.60	20.90
	2	40.90	37.70	19.80
	3	40.20	37.20	20.00
	4	39.40	36.50	19.70
3	1	39.80	37.60	23.70
	2	39.40	37.20	23.30
	3	37.00	34.80	21.40
	4	36.10	34.00	21.10

Table 2, Continued

No. of object	Season	Kinematic viscosity at 38°C, mm^2/s	Kinematic viscosity at 40°C, mm^2/s	Kinematic viscosity at 58°C mm^2/s
4	1	41.20	38.20	21.00
	2	38.70	36.00	20.30
	3	38.40	35.80	20.22
	4	38.40	35.80	20.22
5	1	44.30	40.80	21.40
	2	42.80	39.50	20.90
	3	40.90	37.70	19.70
	4	40.00	36.80	19.10
6	1	39.30	36.30	19.40
	2	37.70	34.90	18.80
	3	35.90	33.30	18.20
	4	35.70	33.10	18.20

Source: *compiled by the authors*

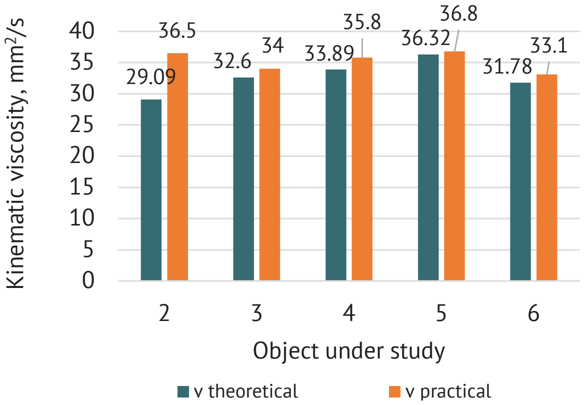
Table 3 shows the theoretical values of the desired controlled parameters calculated according to the research methodology, based on which an assumption is made about the technical condition of the research object at the time of performing the next maintenance.

Table 3. *Predicted values of controlled parameters of study objects*

No. of object	Intensity of operation, L/operating hours	Viscosity, mm^2/s	Pressure, MPa
1	-	-	-
2	37.05193991	29.09	39.04
3	35.76750601	32.60	40.67
4	40.79360815	33.89	41.61
5	42.35878058	36.32	41.15
6	37.46030481	31.78	40.28

Source: *compiled by the authors*

From the graphical interpretation of the comparative characteristics of theoretical and practical values of viscosity and pressure of the working fluid (Fig. 4) it can be seen that the accuracy of the approximation is satisfactory and sufficient to confirm the working hypothesis. Moreover, the resulting calculation error is largely due to the poorly defined intensity of machine operation, and to a lesser extent, the influence of undetected factors.



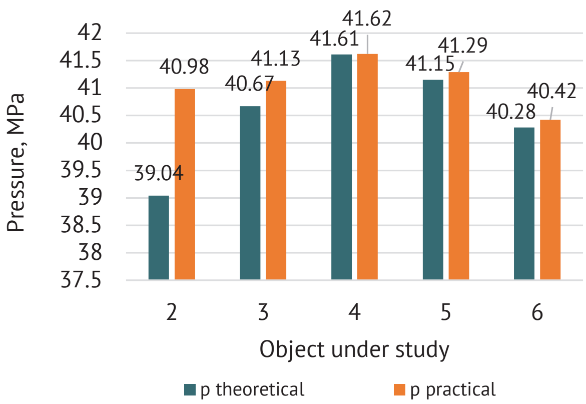


Figure 4. *Comparative characteristics of the values of theoretical and operational indicators: 1) kinematic viscosity; 2) pressure*

The mathematical statistics apparatus was used and the prediction results were compared with the control values obtained during the fourth maintenance to check the adequacy of the developed models. Statistical indicators of the substantiality of models are shown in Table 4.

Table 4. *Estimation of the substantiality of pressure regression dependences on kinematic viscosity*

No. of object	MAPE	η	R^2	SE	F-statistics	α– reliability
1	-	-	-	-	-	-
2	0.047%	0.912	0.832	0.005540	4.955	0.1
3	0.01%	0.995	0.990	0.001250	97.6067	0.1
4	0.00777%	0.956	0.914	0.000955	10.5812	0.1
5	0.000505%	0.990	0.990	0.000056	11372.4191	0.1
6	0.018%	0.988	0.977	0.001940	41.5973	0.1

Source: *compiled by the authors*

The values of the mean absolute percentage error (MAPE) do not exceed 0.047%, which indicates a successful choice of the exponent as a function for approximating the pressure dependence on kinematic viscosity. The value of the coefficient of determination R^2 is within [0.832; 0,99], this confirms the high compliance of the developed models with the original data.

Empirical correlation relationship η, which is used to measure the strength of the correlation dependence of kinematic viscosity and pressure, changes within the interval $0 \leqslant \eta \leqslant 1$, the smaller the deviation η from one, the stronger the response (pressure) depends on the feature factor (kinematic viscosity). The deviation of the calculated values of η for models does not exceed 0.088, which at the qualitative level on the Cheddock scale corresponds to a very high correlation strength.

The measure of variation in the factual data around the model is the standard regression error indicator (*SE*), which does not exceed 0.005, which theoretically causes high prediction accuracy. However, the influence of random operational processes on the values of response functions and their additional extrapolation minimises the substantiality of this statistical indicator. But comparisons of theoretical and practical values of the controlled parameters showed a deviation of 4.73% for pressure and 20.3% for kinematic viscosity of the least accurate model No. 2, a deviation of 0.34% for pressure and 1.3% for kinematic viscosity of the most accurate model No. 5.

The hypothesis of the substantiality of models was tested according to Fischer's F-criterion at the substantiality level α=0.1. Based on the results of this, the adequacy of models for objects No. 3, 5, and 6 was confirmed and refuted for objects No. 2, 4. Possible discrepancies in the accuracy of the models may be due to measurement error and the influence of random factors (which in the case of object No. 1 led to an emergency failure).

The obtained results of forecasting the technical condition of hydrostatic transmission according to the developed method confirmed the possibility of its practical application in the production conditions of agricultural enterprises. Notably, regardless of the accuracy of the forecast of the technical condition using this method, the possibility of an emergency failure of the hydraulic drive is not excluded, which can be caused by subjective and difficult-to-predict factors.

In accordance with the complexity of the search for papers relevant to the current study, an analogy was drawn with models for predicting the state of hydraulic machines for other diagnostic features at the qualitative level and it was established that the scientific and practical substantiality of the current study for improving the planned preventive system of maintenance and repair of agricultural machines is substantial, which is explained by the use of available equipment and the low labour intensity of its implementation.

Andrenko *et al.* (2018) provide a list of methods: based on reliability change curves, Markov approximation, and expert assessment method, which can theoretically be used to predict the technical condition of hydraulic drives. Forecasting based on reliability curves is based on an assessment of the maximum reliability of hydraulic drives and the probability of failure-free operation. This method provides for an analytical description of the probability of failure-free operation of the hydraulic drive and requires a substantial amount of bench studies, the results of which will not correspond to the actual operating conditions of the machine. Since the production of hydraulic equipment by different manufacturers may differ in resource to failure and their operation as part of agricultural machinery does not provide for a uniform load, this method can only be effective when operating in conditions that are close to bench conditions. Forecasting the characteristics of the hydraulic drive according to the Markov approximation is conducted on a similar principle, but the function of the probability of failure-free operation is determined by the equation of the Markov process, the determination of the coefficients of which is accompanied by substantial difficulties, since the dynamics of their change is described based on long-term observations of the quantitative change in the connection of structural and diagnostic features of the hydraulic machine, which means the need for periodic depressurisation of the HS and dismantling of the study object to perform direct diagnostics. The method of expert assessments based on the results of a survey of experts in the relevant industry is also accompanied by problems with its implementation: the optimal number of experts to reproduce the method is 5-10 and its application allows determining the weight of factors on the state of the hydraulic drive only at a qualitative level. According to the above disadvantages, the information content of this heuristic method when predicting the technical condition of hydrostatic transmission units is low, and its applicability is difficult in the Ukrainian repair and maintenance base conditions.

Based on the GO methodology and grey systems theory, the integrated HS prediction approach described by Liu (2018) is a solution for predicting systems with a small data sample and information uncertainty. The essence of the method is to determine the input and output signals that reflect the state of the hydraulic system, represent the units in the form of a GO model, and collect statistical information according to which the accuracy of the model is adjusted. Narrowing down the object of the study by this method to a hydraulic drive, the method is reduced to determining the factors of influence and their substantiality on the reliability of a hydraulic machine, which is a typical forecasting problem that is not solved by this method.

Methods described in the papers by Guo *et al.* (2020) and Li *et al.* (2021), based on forecasting by vibration oscillations and on the method of machine learning k-nearest neighbours, respectively, reflect current trends in the development of forecasting hydraulic machines in laboratory conditions, the implementation of which is accompanied by increased requirements for diagnostic equipment and the need to dismantle hydraulic drives. An attempt to integrate the first method into an agricultural machine equipped with a hydrostatic transmission will lead to a substantial loss of its information content due to the presence of other sources that affect the amplitude of vibrations. Integration of the second method will not lead to a loss of its efficiency, but the cost of operating equipment will substantially increase due to the need for expensive equipment, the installation of which occurs when the HS circuit is depressurised, which in turn will increase the labour intensity of the maintenance and the requirements for the qualification of equipment operators. Therefore, research on the development of available methods for predicting the technical condition of hydraulic drives of agricultural machines based on the pressure dependence on the working fluid parameters is the basis for improving the area of optimisation of the TOR system of hydraulic equipment.

CONCLUSIONS

The analysis of the features of ensuring the technical condition of hydraulic transmission drives of agricultural machines showed that the existing system of support and restoration of the working condition of hydraulic transmissions substantially depends on the equipment of the repair and maintenance base, which today does not meet the needs of industrial agricultural enterprises and leads to unplanned downtime of equipment during seasonal agrotechnical works. This state of affairs has determined the need to develop an affordable method for predicting the technical condition of the hydraulic transmission drive.

As a result of processing the data obtained during observations of the dynamics of changes in the performance indicators of agricultural machines and working fluid viscosity indicators, the working hypothesis of the study was confirmed and a method for predicting the technical condition of hydraulic transmission drives was proposed, which is based on monitoring and extrapolating the performance indicators of agricultural machines and the kinematic viscosity of working fluid samples. The accuracy of theoretical controlled indicators calculated using the proposed method has minor deviations from the models the substantiality of which has been confirmed, relative to empirical ones within the limits of [0.34%; 1.12%] for pressure and [1.3%; 4.12%] for kinematic viscosity. The proposed method creates sufficient requirements for forecasting the technical condition of the hydraulic transmission of agricultural machines for one season, with little labour intensity of its implementation, which does not provide for the dismantling of hydraulic machines and does not have a substantial impact on the maintenance work regulations.

Forecasting the technical condition of the hydraulic drive by the proposed method will allow owners of hydrofected equipment to respond in a timely manner to the dynamics of changes in its operability, which provides the following advantages: the ability to determine the need for repairs in the early stages of operation; prevent increased costs for eliminating emergency failures due to reducing the likelihood of their occurrence; reduce unproductive time spent associated with downtime of equipment; ensuring an economical mode of operation of machines. In addition, the implementation of this method is based on available equipment, which makes it highly important in the field.

Improving the quality of forecasting using this method is possible by creating conditions for conducting a complete factor experiment with an expanded set of Integral diagnostic features, which will allow more accurate tracking of patterns of changes in the functional parameters of the hydraulic drive and draw conclusions about the residual resource of hydraulic machines. Further prospects for applying the method consist in its adaptation to the regulations of the planned-preventive system for construction and road equipment equipped with hydrostatic transmission.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Прогнозування технічного стану гідравлічних трансмісій сільськогосподарських машин за показниками кінематичної в'язкості і тиску оливи

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Анотація. Підтримка технічного стану гідростатичної передачі сільськогосподарських машин не забезпечується наявною ремонтно-обслуговуючою системою України у повній мірі, що обумовлює пошук доступних методів для завчасного виявлення несправностей гідроприводів. Мета роботи полягала у синтезі методу прогнозування технічного стану гідравлічної трансмісії сучасних сільськогосподарських машин за контролем динаміки зміни значень емпіричної залежності тиску від кінематичної в'язкості оливи в умовах недостатнього матеріально-технічного оснащення виробничої бази. Для досягнення поставленої мети були застосовані загально-прийняті методи: аналіз-синтез, індукція, спостереження, експеримент, графічний метод. У результаті проведеного дослідження підтвердилася висунута автором гіпотеза за якою зміна кінематичної в'язкості робочої рідини відносно початкового значення визначається поточним станом гідравлічної трансмісії, контроль якої здійснюється за виміром тиску. На основі виявлених недоліків і проблем діючої системи технічного обслуговування і ремонту було запропоновано методику, яка передбачає контроль експлуатаційних показників сільськогосподарських машин і кінематичної в'язкості проб робочої рідини, взятих з їх гідравлічних трансмісій. Значення кінематичної в'язкості для побудови прогнозуючої моделі були отримані за капілярним методом і розраховувалися за формулою Вальтера, а залежність в'язкості від факторів впливу визначалась методом білінійної інтерполяції. Регресійну модель тиску від кінематичної в'язкості було одержано за методом найменших квадратів, в якості апроксимуючої функції використано експоненту. За результатами перевірки моделей за критерієм Фішера було підтверджено їх адекватність, причому відхилення теоретичних значень контрольованих параметрів, розрахованих за найбільш точною моделлю, від емпіричних склали 0,34 % для тиску і 1,3 % для кінематичної в'язкості. Практична цінність роботи полягає в тому, що результати роботи дозволяють зменшити непродуктивні витрати часу, пов›язані з простоєм техніки, внаслідок аварійних відмов агрегатів гідравлічних трансмісій і сприяють адаптації планово-попереджувальної системи технічного обслуговування сільськогосподарських машин до потреб українського агропромислового комплексу

Ключові слова: зернозбиральний комбайн; гідростатична передача; надійність; діагностування; властивості робочої рідини