UDC 629.225 DOI: 10.30977/AT.2219-8342.2024.55.0.05

Modeling of limitations on the use of hydraulic motor-wheels in transmissions of mobile machines

Avrunin G.[1], Podrigalo M.[1], Podrigalo N.[1], Fidrovskaya N.[1], Moroz I.[1], Yatsunskyi P.[2]

[1] Kharkiv National Automobile and Highway University, Ukraine
[2] Lviv Polytechnic National University, Ukraine

Annotation. Problem. The development of mobile machines with increased movement speeds requires constructive solutions for the creation of appropriate transmissions, particularly the analysis of the possibility of creating hydraulic stepless transmissions using hydraulic motors of various types. ***Goal.*** *Increasing the technical level of transmissions of utility, construction and road vehicles and multi-axle high-speed vehicles with the help of advances in modern hydrostatic transmissions.* ***Methodology.*** *The transmissions of mobile machines are considered from the point of view of the possibility of using multi-cycle radial-piston hydraulic motors in them as gearless hydraulic motor-wheels. According to the traction-speed characteristics, the values of the torques and rotation frequencies of the hubs were calculated, and the hydraulic motor-wheels were selected according to the corresponding working volumes. As an example, calculations of the dynamics of the hydraulic drive transmission of a cleaning utility vehicle were carried out using the VisSim application program package, where the universal characteristic of the gerotor hydraulic motor was used to determine the hydromechanical efficiency in the modes from displacement to maximum rotation frequency.* ***The results.*** *Positive results were obtained in terms of increasing the speed of mobile machines when using hydraulic motor-wheels of radial piston multicycle action in transmissions instead of gerotor hydraulic motors, axial-piston hydraulic motors with planetary gearboxes, hydraulic transmissions with cardan shafts and mechanical transmissions.* ***Originality.*** *New calculated data on the initial characteristics of transmissions with a hydraulic drive were obtained, the possibilities of modeling dynamic processes in the transmission hydraulic drive depending on the action of external factors regarding the load, speed and properties of the working fluid were shown. It was established that for multi-axle vehicles with a maximum speed of up to 100 km/h, the use of electric or hydraulic motor-wheels requires the addition of planetary gearboxes with reducers or multiplier frames.* ***Practical meaning****. Recommendations for the use of radial-piston gearless hydraulic motor-wheels in mobile machines in order to improve their technical level are given.*

Key words: *vehicle, transmission, hydraulic motor-wheel, torque, rotation frequency, dynamic calculations, VisSim package*

Introduction

The basis for the creation of new equipment, in particular road construction machines, tractors and other mobile machines, is the constant analysis of the achievements of the world's leading man-ufacturers. At the same time, it is necessary to pay attention not only to the technical characteristics of machines, but also to new components related to transmission units and technological equipment, which include hydraulic devices [1] in the form of pumps, hydraulic motors, hydraulic equipment, working fluid and means of its conditioning. The results of the analysis of the technical level of modern hydraulic motors according to the information sources of their manufacturers were the impetus for conducting real research. The main limitation of the use of high-torque radial-piston hydraulic motors was low rotation frequency, which did not allow such hydraulic motors to be installed in vehicles at a speed of more than 30 km/h without multipliers (mechanical gears with increased rotation frequency at the output). Such hydraulic motors abroad were classified as low-speed high-torque (LSHT).

Analysis of publications

The prospects for the importance of LSHT hydraulic motors are demonstrated by the company "Rexroth-Bosch Group" (Germany), which has the largest range of axial-piston hydraulic motors of the A2FM and A6VM(E) series in combination with planetary gearboxes, but at the same time produces radial-piston hydraulic motor-wheels MCR a fairly wide range of standard sizes in terms of working volumes and structural designs in terms of regulation and braking systems, as well as the most powerful "Hagglunds" hydraulic motors in the world [2, 3].

Analysis of the characteristics of LSHT hydraulic motors of the "Poclain Hydraulics" company (France) showed that over the past 20 years, the designers have managed to significantly increase their technical level [4–6].

In the table 1 shows the main parameters of hydraulic motors of the MS series and the latest MHP20/27 development of approximately the same working volumes V_1, in particular, the values of the maximum rotation frequency n, pressure p, torque T, output power P and mass m are given. To compare hydraulic motors, let's turn to the indicators, to which there are many references in the literature [7], in particular to such specific indicators as the ratio of mass to torque k_T and power k_P, as well as the speed indicator C_n. A significant improvement in the specific parameters of the MHP20/27 series hydraulic motor was achieved due to an increase in pressure from 45 MPa to 50 MPa and a more than doubled rotation frequency. In terms of speed C_n, the advantage is more than doubled. In addition, hydraulic motors have a wide range of adjustment of the working volume up to four, an increased number of adjustment steps, and there are designs of hydraulic motors with built-in parking and working brakes.

Table 1. Technical characteristics of hydraulic motors of the company "Poclain Hydraulics"

Code of the hydraulic motor	V_1 [cm³]	n [rpm]	T [Н.м] / p [МПа]	P [кВт]	m [кг]	k_T [m/N.m]	k_P [m/kW]	C_n^*
MS18-6	1091/545	172/172	7806/45	70/47	160	0.02	2.3	1.4
MS18-2	2099/1049	145/100	15018/45	70/47	160	0.01	2.3	1.0
MS25-8	2004/1002	145/145	14339/45	90/60	270	0.018	3.0	1.5
MS25-2	3006/1503	115/130	21508/45	90/60	270	0.012	3.0	1.5
MHP20-7	1416/354	342/435	11257 /50	200/175	240	0.021	1.2	3.0
MHP20-9	1821/455	273/350	14477/50	200/160	240	0.017	1.2	2.7
MHP27-7	1893/473	254/316	15049/50	215/125	240	0.016	1.1	2.5
MHP27-9	2712/678	182/228	21560/50	185/125	240	0.011	1.3	2.0

Notes: 1. Rotational frequencies and power are given for hydraulic motors with adjustable working volume (MS18 and MS25 with two stages, MHP20 and MHP27 with four stages) at the maximum and minimum (underline) values of the working volume; 2. The torque is calculated as theoretical at the maximum working volume and the value of the pressure drop under the line; 3. The mass of MS hydraulic motors is shown in the configuration with a parking brake, MHP hydraulic motors with parking and working brakes; 4.*) –Dimensions of technical level coefficients: $C_n = n \cdot V_1^{1/3}$ [rpm· cm·10^{-3}].

It should be noted that the comparison of the hydraulic motor of the MHP20-1416 series with the hydraulic motor of the MHP11-1401 series [8], that is, of approximately equal working volumes, gives significantly different values of the maximum rotation frequencies. For the MHP20-1416 hydraulic motor, this value is 435 rpm, and for the MHP11 hydraulic motor it is 202 rpm, that is, less than twice. Such a difference emphasizes the high level of constructive achievements of the specialists of the "Poclain Hydraulics" company. In recent years, the values of the maximum rotation frequencies of multi-cycle radial-piston hydraulic motors of the MSR model of the "Rexroth-Bosch Group" company have also significantly increased [2].

Axial-piston hydraulic motors have stepless regulators for changing the working volume in designs with an inclined disk or a cylinder block, but the need to use a planetary gearbox somewhat reduces the efficiency of such a hydraulic motor-reducer. Thus, a review of achievements in the field of high-torque radial-piston hydraulic motors shows the prospects of this direction of motor-wheel application.

Such increased speed indicators of hydraulic motors of the MHP series of the "Poclain Hydraulics" company lead to a conclusion regarding the assessment of their use in the modernization of transmissions of mobile machines in use and prospective developments. At the same time, a decision was made to consider serial transmissions of machines with a speed of up to 40 km/h (tractors, road construction and communal cleaning machines), as well as the creation of transmissions for vehicles with high speed and maneuverability. The high-speed transmission must have a traction-speed characteristic with a force of up to 500 kN when shifting and provide a vehicle speed of up to 100 km/h with a reduced traction effort. One of the modern trends in the construction of structural diagrams of such transmissions is the rejection of cardan gears and the use of motor-wheels for rotating the hubs.

Purpose and Tasks

The purpose of the article is to improve the technical level of transmissions of utility, construction and road vehicles and multi-axle high-speed vehicles with the help of advances in modern volumetric hydraulic drives.

Tasks of the article are to analyze the possibility of using high-torque radial-piston hydraulic motors as gearless hydraulic motor-wheels by conducting static calculations of hydraulic transmissions and modeling dynamic processes in the full range of speed-traction characteristics of the vehicle. The hydraulic drive of the transmission of the cleaning utility vehicle was chosen as the object of dynamic research.

Materials and Method

Tractor transmissions use mechanical transmissions with hydraulic gear shifting drives without power interruption, stepless two-flow transmissions with parallel power flow using a hydrostatic transmission, and hydrodynamic transmissions with complex torque transformers [9]. The disadvantage of transmissions with complex hydraulic transformers is the need to additionally create a speed reducer using mechanical gears or hydrostatic transmission, which significantly complicates the transmission. At the same time, hydrostatic transmission with high-torque hydraulic units are used in mobile machines, which consist of axial-piston hydraulic motors with planetary gearboxes or high-torque hydraulic motors. The latter include gerotor hydraulic motors and radial-piston single-cycle (eccentric) and multi-cycle action (with profile cam-copier).

In multi-cycle radial piston hydraulic motors, the forces on the main bearings of the shaft are reduced to a minimum with the kinematic balance of the piston groups due to the optimal selection of the number of pistons and the working profiles of the copier, and the piston groups also underwent significant modernization [7].

To reduce the radial and axial dimensions of hydraulic motors, miniature designs of piston groups appeared, in which the formation of torque was achieved in the presence of lateral loads on the piston. In such piston groups of the "piston-roller" type, the latter performs a rotational movement relative to the bore in the piston and along the profile. An increase in the high wear resistance of the piston group when the piston rubs against the side wall of the cylinder and the roller on the surface of the piston and the copier is achieved due to new materials, coatings and the use of hydrostatic unloading in the "piston-roller" pair.

In fig. 1 presents structural diagrams of loaders with full-flow transmissions with a hydrostatic drive, that is, transmissions in which, unlike two-flow hydromechanical transmissions, the pump and hydraulic motor (hydromotors) create the full power of the transmission. For example, in mobile machines, in particular loaders, a transmission of two hydraulic machines is used a pump 2 and a hydraulic motor 1, which has an adjustable working volume and rotates the cardan shafts of the driving axles DA (a) through a gearbox. Such a transmission is installed in the Weidemann-9080 loader [10, 11]. The transmission with hydraulic motor-wheels has a multi-machine scheme in which one or two pumps rotate the hubs of the driving wheels with the help of hydraulic motors. In the TS-10KHTZ crawler tractor-bulldozer, the hubs of the two driving sprockets are rotated by axial-piston hydraulic motor-wheels with adjustable working volume with planetary gearboxes [12]. The same scheme is used in the wheeled forklift Linde H20, but only with one pump and two axial-piston hydraulic motors with an inclined disk and a constant working volume [13]. Four gerotor hydraulic motor-wheels with a constant working volume are used in the transmission of the "Nilfisk MV4500" utility cleaning machine [14, 15].

When using radial-piston hydraulic motors 11-14 of single-cycle or multi-cycle operation, it is possible to abandon the intermediate gearbox, and with the help of hydraulic motor designs with adjustable working volume, reduce the setting power of the pumping unit and the drive internal combustion engine (b). Rejection of cardan shafts significantly simplifies the layout of the machine in relation to the location of the pump with the drive internal combustion engine relative to the driving hubs of the machine with the help of high-pressure hoses.

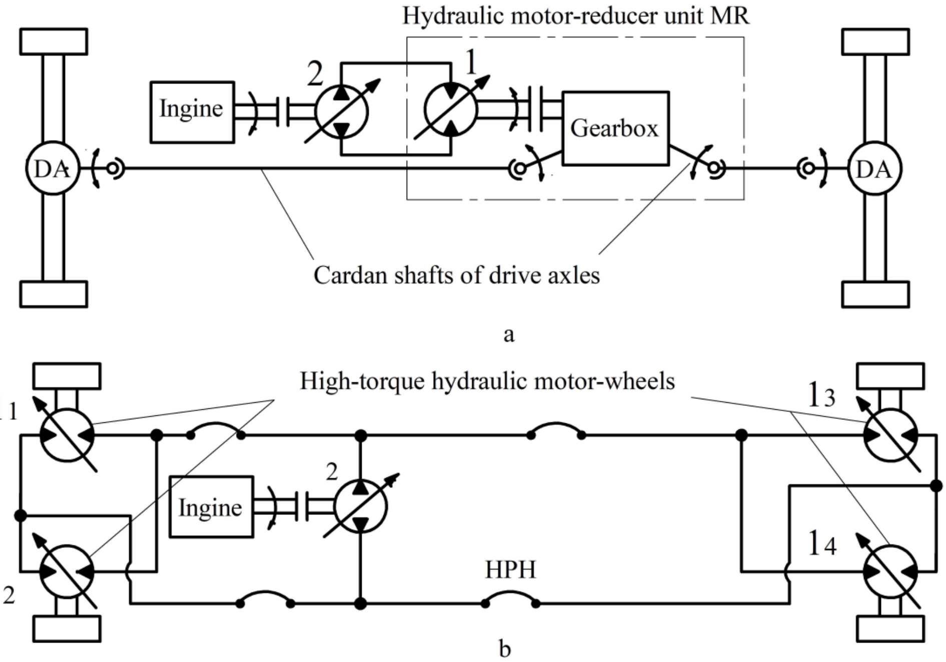


Fig 1. Transmissions of mobile machines with a full-flow hydrostatic transmissions: a – with a hydraulic motor and wheel drive gearbox; b – with high-torque hydraulic motor-wheels

The research methodology consists of an analysis of the requirements for traction-speed characteristic of the vehicle and calculation of the static and dynamic characteristics of the hydraulic transmission. During the static calculation, the maximum values of the torque and rotation frequency of the driving hubs, the output power of the transmission are determined, and the values of the hydraulic motors and their power supply pump, which are required for the working volume, are selected. All these values make it possible to preliminarily find the efficiency of the hydraulic drive and the parameters of the oil-cooler. Dynamic calculations provide for the determination of the pressure in the hydraulic drive and the frequency of rotation of the driving wheels depending on time and give the opportunity to simulate these parameters at various cyclograms in relation to the external load on the driving wheel, changes in the intensity of the pump supply, the moment of inertia of the load and the modulus of elasticity of the working fluid.

The initial data is based on a hypothesis regarding the possibility of creating hydraulic transmissions with hydraulic motor-wheels of multi-cycle action in all considered mobile machines.

At the first stage, the transmissions of vehicles with a movement speed of up to 40 km/h were considered, in particular, the "Nilfisk MV4500" utility cleaning machine, the H20-Linde forklift and the Weidemann-9080 and T-156B front loaders produced by KhTZ [16].

Table 2 shows the initial data of vehicles and the results of calculation of transmissions for them using radial-piston hydraulic motor-wheels (HMW) of multi-cycle action. When calculating the initial parameters of transmissions, in particular, the values of the hydraulic parameters of the hydraulic motor-wheels, the appropriate formulas are used [7, 9]:

rotation frequency of the hydraulic motor-wheel (hub):

$$n_{hmw.max} = 60\frac{v_{max}}{\pi \cdot d_{tire}} = 60\frac{10^3}{3600}\cdot\frac{v_{max}}{\pi \cdot d_{tire}} = 5.3\frac{v_{max}}{d_{tire}}, \text{ rpm}, \quad (1)$$

where v_{max} – the maximum speed of the car, km/h; d_{tire} – outer diameter of the tire, m;

the maximum torque of the hydraulic motor-wheel, which ensures the movement of the machine with the maximum traction force:

$$T_{hmw.max} = 10^3 F_{max} \frac{d_{tire}}{2 \cdot z}, \text{ N.m}, \qquad (2)$$

where F_{max} – traction force of the machine, kN; z – the number of hydraulic motor-wheels;

working volume of the hydraulic motor:

$$V_{hmw} = \frac{2\pi \cdot T_{hmw.max}}{\Delta p_{м} \cdot \eta_{hmw.hm}}, \text{ cm}^3, \qquad (3)$$

where $\Delta p_{м}$ – pressure drop on the hydraulic motor, MPa; $\eta_{hmw.hm}$ – hydromechanical efficiency of the hydraulic motor.

Table 2. Initial data and calculation results of mobile transmissions machines with radial-piston hydraulic motor-wheels

Parameters, dimension	Type of transport and technological means:			
	Nilfisk MV4500	H20-Linde	Weidemann- 9080	T-156B
d_{tire} [м/z]	0.812/4	0.456/2	1304/4	1.605/4
v_{max} [km/h]	32	18.5	40	30.14
$n_{hmw.max}$ [rpm]	209	215	163	99.7
$T_{hmw.max}$ [Н.м]	562	1619	5705/10432*	12038
Code HMW	MCR3-A220	MCR3-A400	MHP20	MHP27
$V_{hmw.catalog}$ [cm^3]	160/80/2	400/200/2	1821/354/4	2434/608/4
$\Delta p_{м.operating} / \Delta p_{maxTSP}$ [MPa]	17/40	31/40	20/37*/50	37/50
m_{hmw} [kg]	28	28	180	240
$n_{hmw.max.TSP(V_{min})}$ [rpm]	620	350	350	252
$v_{max.possible}$ [km/h]	95	30,2	86	76

Notes: 1.*) – The mass of the car with a trailer; 2. $\Delta p_{м.operating} / \Delta p_{maxTSP}$ – calculated pressure of the HMW at the given value of the torque $T_{hmw.max}$, under the line is the maximum pressure of the HMW according to the catalog; 3. m_{hmw} – mass of hydraulic motor-wheel;
4. $n_{hmw.max.TSP(V_{min})}$ – the maximum frequency of rotation of the HMW at its minimum working volume according to the catalog; 5. In the notation of working volumes of HMW, their minimum values and the number of adjustment steps are given under dashes, respectively.

After choosing from the catalog the working volume $V_{hmw.catalog}$ of the hydraulic motor, determine the actual pressure drop in the hydraulic drive of the transmission:

$$\Delta p_{м.operating} = \frac{2\pi \cdot T_{hmw.max}}{V_{hmw.catalog} \cdot \eta_{hmw.hm}}, \text{ MPa}. \qquad (4)$$

Using the value of the maximum speed of rotation of the hydraulic motor-wheels according to the catalog and at the minimum working volume $n_{hmw.max.TSP(V_{min})}$, the maximum possible speed of the machine is found:

$$v_{max.possible} = \frac{n_{hmw.max.TSP(V_{min})} \cdot d_{tire}}{5.3}, \text{ km/h}. \qquad (5)$$

We will also give the formulas needed to calculate the transmission, in particular the output power of the hydraulic motor-wheel:

$$P_{hmw} = \frac{T_{hmw} \cdot n_{hmw}}{9550}, \text{ kW}; \qquad (6)$$

and the theoretical flow rate of the pump (or pumps) of the hydraulic transmission:

$$q_2 = 10^{-3} n_2 \cdot V_{hmw} \cdot z, \text{ lpm}. \qquad (7)$$

According to the results of preliminary calculations by traction-speed characteristic, it was established that the class of machines in question requires transmissions to create traction forces of up to 60 kN and speeds of up to 40 km/h, with the prospect of increasing it. To implement these requirements, a HMW with a torque of up to 12 kN.m and a hub rotation frequency corresponding to the speed is required. For example, to increase the speed of T-156B loaders, it is necessary to have hydraulic motor-wheels with a rotation frequency higher than 100 rpm, and for loaders of foreign production, the frontal Weidemann-9080 is higher than 163 rpm, for the fork H20-Linde is higher than 215 rpm. It goes without saying that the rotation frequencies of the hubs are related to the diameters of the used wheels of transport and technological vehicles. Therefore, we will consider modern possibilities of hydraulic motor-wheels, based on the above requirements as basic. Based on the results of this review, that is, the specific characteristics of hydraulic motor-wheels in terms of torques and rotation frequencies, it is possible to draw a conclusion about the possibility of practical application of hydraulic motor-wheels. Such data are given in the lower part of the table using radial piston hydraulic motors of the companies "Rexroth-Bosch Group" (hydraulic motors MCR3) and "Poclain Hydraulics" (hydraulic motors MHP).

It was established that these hydraulic motors make it possible to increase the speed of the machines in question by 1.6-3 times, which is quite a significant indicator. Rejection of intermediate planetary gearboxes also helps to increase the efficiency of the hydraulic motor-wheels, and the equipment with brakes for parking and working modes simplifies the manufacturing technology of the hydraulic transmission. Attention should also be paid to the use of a radial-piston hydraulic motor with an adjustable working volume instead of a gerotor in the transmission of the "Nilfisk MV4500" machine. Such a transition helps to reduce the installed capacity of the axial piston pump, more precisely, to reduce its working volume when designing the transmission due to the fact that increasing the speed of the machine is achieved by reducing the working volume of the hydraulic motor and meets the requirements of the of vehicles.

Next, we will consider the possibility of using hydraulic motor-wheels in high-speed machines and work in difficult road conditions. The following transmission requirements are set for a multi-axle vehicle: maximum traction force when moving uphill F_{max} = 440 kN, maximum speed up to v_{max} = 90 km/h ($n_{hmw.max}$ = 469 rpm), number of driving wheels z = 8, maximum torque of one wheel $T_{hmw.max}$ = 28 kN.m, diameter of the driving wheel d_{tire} = 1.02 m.

In fig. 2 presents the structural diagrams of the transmissions of the vehicle with motor-wheels, which must fulfill the following requirements. At the same time, we will consider hydraulic and electric motors as motor-wheels.

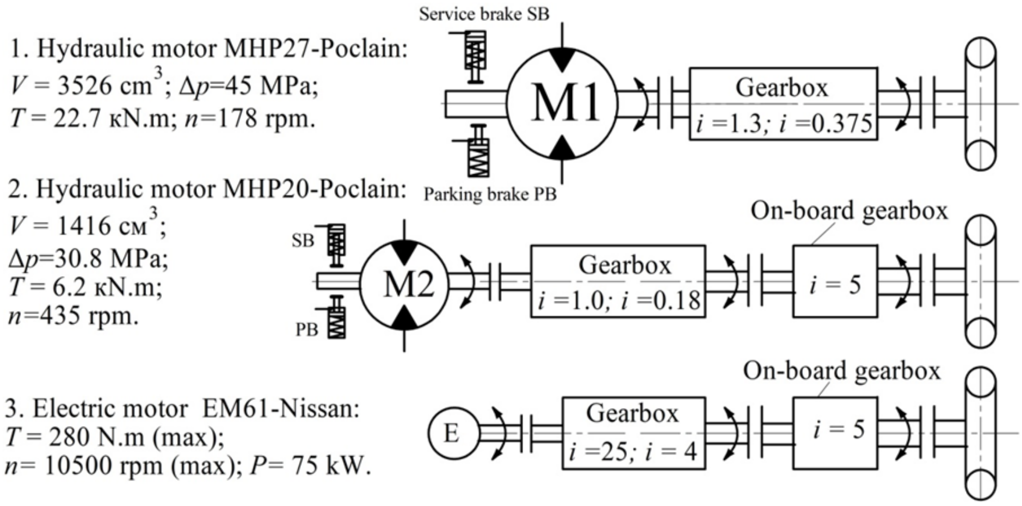


Fig. 2. Variants of motor-wheel application in a multi-axle vehicle

High-torque radial-piston hydraulic motor-wheels of multi-cycle action with step-by-step regulation of the working volume allow to create a transmission in two versions. In the first version with the hydraulic motor M1, it is possible to abandon the on-board gear and limit yourself to the use of a gear box with steps i = 1.3 in the displacement mode i = 0.375 (multiplication gear) at maximum speeds. The MHP27-Poclain (M1) wheel hydraulic motor with a working volume of 3526 cm^3 provides a displacement torque of 22.7 kN.m at a pressure of 45 MPa, and to achieve the maximum speed of the vehicle, a multiplying gear is used and the working volume of the hydraulic motor is reduced in four times.

In the second variant, the hydraulic motor M2 with a reduced working volume of MHP20-Poclain to 1416 cm^3 can be used, but it requires the preservation of the on-board gear (i = 5) and the gearbox with i = 1.0 and i = 0.18. The hydraulic motor develops a torque of 6.2 kN.m at a pressure drop of up to 31 MPa, that is, it has a significant reserve in terms of durability, since the maximum pressure for the hydraulic motor is 50 MPa.

Hydraulic motor-wheels are delivered complete with brakes of parking PB and of service SB types, which simplifies the production of the vehicle.

In connection with the limitations of existing electric motors for such a torque, a combination in the form of "electric motor-two-stage gearbox-on-board gearbox" is proposed. When using an electric motor with a torque of 250 N.m, the traction-speed characteristic requirements in shifting mode are solved using the maximum gear ratio i = 125, during high-speed transport, the gear ratio must be reduced to i = 20 with the help of a gearbox.

A feature of the designs is the step-by-step adjustment of the working volume of the hydraulic motor, in order to work out the traction-speed characteristics of the transmission, the introduction of synchronization of the adjustment modes of the hydraulic motor and the pump is required. Such a function can be performed by an electronic unit with simultaneous adjustment of the pump supply using feedback from the speed of the mobile machine and the pressure in the hydraulic drive.

It should also be noted that in the hydraulic schematic diagram of the transmission, it is necessary to provide means to prevent wheel slippage, and the company "Poclain Hydraulics" [17] has a lot of experience in this direction.

As an example of a dynamic analysis of a hydraulic transmission, consider the utility vehicle "Nilfisk MV4500". The transmission consists of four "DANFOSS" OMSB gerotor hydraulic motors with a working volume of 200 cm^3. Hydraulic motors with a mass of 18 kg develop a maximum final torque of 2600 N.m at a pressure of 30 MPa and have a rotation frequency of up to 240 rpm. Hydraulic motors are equipped with a built-in drum brake. The operation of the transmission in a closed circuit of the circulation of the working fluid is provided by an axial piston pump with a maximum working volume of 64.7 cm^3, a rotation drive from an internal combustion engine with a frequency of up to 3100 rpm and an output power of 83 kW. The hydrostatic transmission provides the maximum transport speed of the machine of 32 km/h, and in technological mode up to 19 km/h. It should be noted that, in principle, such a gerotor hydraulic motor, which has a maximum rotation frequency of 400 rpm, makes it possible to increase the speed of the machine to 61,2 km/h.

In fig. 3 shows the calculation scheme for determining the dynamic characteristics of the "Nilfisk MV4500" hydrostatic transmission. The designations of the parameters are given when considering the mathematical model.

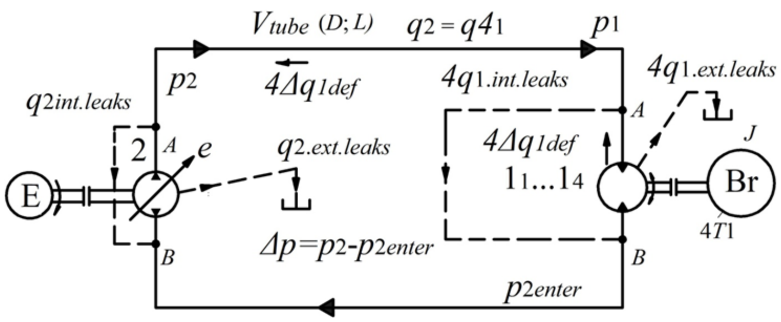


Fig. 3. Calculation diagram of the hydrostatic transmission of the "Nilfisk MV4500" machine

The mathematical model of the change in the dynamic characteristics of the hydrostatic transmission considers time-dependent parameters: the frequency of rotation of the hydraulic motor-wheels, the pressure in the hydraulic system, the speed of the machine and its useful power. We will use the mathematical model of transmissions with hydraulic motors, built on the basis of Pascal's law and the continuity equation for the working fluid, as well as Newton's third law of mechanics [11]. At the same time, assumptions are made: the bulk modulus, temperature, density, and viscosity of the liquid are constant values; the moment of inertia is assumed to be constant; wave processes in the pipelines are not taken into account due to their small length (the pump and hydraulic motors are connected by fairly short high-pressure hoses); the pressure at the output of the hydraulic motor (at the drain) is equal to the pressure developed by the feed pump and is assumed to be constant.

Thus, the expressions for the pressure drop $\Delta p_{\text{м}}$ [MPa] and the frequency of rotation of the hydraulic motor n_1 [rpm] have the form:

$$\Delta p_1 = \int_0^t [q_{2\text{т},e}(t) - 10^{-3} V_1(t) \cdot n_1(t) - \\ -C_{(1+2).leaks} \cdot p_2(t)] \frac{K_{\text{т}}}{V_{tube}} d, \quad (8)$$

$$n_1 = \int_0^t \frac{3.6 \cdot 10^3}{J_1} \times \\ \times \left[\frac{1}{2\pi} V_{1,i}(t) \cdot (p_2 - p_{2entr}) \cdot \eta_{1.hm} - T_1 \right] dt, \quad (9)$$

where $q_{2\text{т},e} = q_{2\text{т}} \cdot e$ – pump supply (flow) at a given relative angle of rotation of the inclined disc, which deviates in both directions from the neutral position in relative values $e = 0 \ldots \pm 1$, l/min; $q_{2\text{т}} = 10^{-3} V_2 \cdot n_2$ – theoretical pump supply with maximum working volume V_2 [cm^3] and rotation frequency n_2 [rpm] without taking into account leaks, l/min; V_1 – working volume of the hydraulic motor, cm3; $C_{(1+2).leaks}$ – coefficient of total external and internal fluid leaks of the hydraulic motor Δq_{1leaks} and pump Δq_{2leaks}, l/(MPa.min); V_{tube} – volume of liquid in the inlet (high-pressure) cavity (pipeline) of the hydraulic motor with internal diameter D [mm] and length L [m], dm3; $K_{\text{т}}$ – the modulus of elasticity of the liquid, which causes its deformation flow Δq_{def} in the pipeline with a volume of V_{tube}, MPa; J – final moment of inertia, reduced to the shaft of the hydraulic motor, kg.m2; p_2 і p_{2entr} – the pressure in the pump injection and fluid drain lines, respectively, MPa; $\eta_{1.hm}$ – hydromechanical efficiency of the hydraulic motor; T_1 – torque of resistance (external load), N.m.

The given equations show that when evaluating the dynamic characteristics of the hydraulic drive, the time-varying and predetermined parameters are: the moment of resistance of the external load T_1; pump supply $q_{1\text{т},e}$; the working volume of the hydraulic motor V_1 and the efficiency of the pump and the hydraulic motor.

To solve differential equations (8) and (9), we use the VisSim application program package [9, 18] and choose the Runge-Kutta integration method of the fourth order with discreteness $\Delta = 0.001\,\text{c}$.

We will also write down the formulas for calculating leakage coefficients due to the value of the volumetric efficiency of the pump:

$$\eta_{2V} = \frac{q_2}{q_{2\text{т}}} = \frac{q_{2\text{т}} - \Delta q_{2leaks}}{q_{2\text{т}}} = 1 - \frac{\Delta q_{2leaks}}{q_{2\text{т}}}; \\ \Delta q_{2leaks} = q_{2\text{т}}(1 - \eta_{2V}); \\ C_{2.leaks} = \frac{\Delta q_{2leaks}}{p_2 + p_{2entr}} = \frac{q_{2\text{т}}(1 - \eta_{2V})}{p_2 + p_{2entr}}. \quad (10)$$

and volumetric efficiency of the hydraulic motor:

$$\eta_{1V} = \frac{q_{1\text{т}}}{q_{1\text{т}} + \Delta q_{1leaks}}; \\ \eta_{1V} \cdot q_{1\text{т}} + \eta_{1V} \cdot \Delta q_{1leaks} = q_{1\text{т}}; \\ \Delta q_{1leaks} = q_{1\text{т}} \left(\frac{1}{\eta_{1V}} - 1 \right); \quad (11) \\ C_{1.leaks} = \frac{\Delta q_{1leaks}}{p_2 + p_{2entr}} = \frac{q_{1\text{т}}}{p_2 + p_{2entr}} \left(\frac{1}{\eta_{1V}} - 1 \right),$$

where $Q_{\text{мт}} = 10^{-3} V_{\text{м},i} \cdot n_{\text{м}}$ – theoretical consumption of a hydraulic motor with a working volume [cm3] at its rotation frequency [rpm], l/min;

For input into the VisSim block diagrams, we will present the value of the final leakage coefficient of the pump and the hydraulic motor in the following form:

$$C_{(1+2).leaks} = C_{1.leaks} + C_{2.leaks} = \\ = \frac{q_{1\text{т}} \left(\frac{1}{\eta_{1V}} - 1 \right) + q_{2\text{т}}(1 - \eta_{2V}) \cdot}{p_2 + p_{2entr}} \quad (12)$$

In fig. 4 shows the oscillograms for calculating the dynamics and modeling of the hydrostatic transmission of a utility vehicle, which consist of oscillograms with parameter assignments: 1 – pump feed; 2 – external load (torque on the hub); 3 – hydromechanical efficiency of the hydraulic motor, and oscillograms based on the results of differential equation calculations: 4 – frequency of rotation of the hydraulic motor-wheel; 5 and 6 – pressure and useful power of the hydraulic drive, respectively. If the value of the pump supply and the torque of the hydraulic motor is the result of the traction-speed calculation according to the technical characteristics of the utility vehicle, then the value of the hydromechanical efficiency is taken from the universal characteristics of the gerotor hydraulic motor according to the data of the catalog [19]. To determine the hydromechanical efficiency according to the data on the torque graph at a constant pressure drop $\Delta p = 21$ MPa and at different values of the rotation frequency of the hydraulic motor, we use the following formula:

$$\eta_{hmw} = \frac{2\pi \cdot T_{hmw}}{V_{hmw} \cdot \Delta p}. \qquad (13)$$

In fig. 5 shows the dependence of the pressure fluctuation in the hydrostatic transmission on the time of increase of the shifting moment of the utility vehicle. At a set pressure value of 23 MPa, the shift modes are characterized by an increase in pressure up to 33 MPa (a), 24.5 MPa (b) and practically no increase in pressure (c). All these regimes were simulated when the pump flow rate increased to 50 l/min in 3 s, and the load increased in 0.001 s (a), 0.01 s (b), and 0.1 s (c). Undoubtedly, the data on the increase in torque during displacement need experimental verification.

In fig. 6 shows graphs of pressure fluctuations in the hydrostatic transmission at three values of the elastic modulus K_T of the working fluid: a – 500 MPa; b – 750 MPa; c – 1500 MPa. The last value corresponds to air cleaned of undissolved particles. All oscillograms are given at the same value of the load torque increase in the hydraulic motor of 0.001 s. The set pressure value is 23 MPa, and extreme values reach 38 MPa (a), 37 MPa (b) and 33 MPa (c). Also, the time of pressure fluctuations changes from 0.05 s to 0.02 s, that is, more than twice and which makes it possible to draw a conclusion about thorough cleaning of the working fluid during the operation of the hydrostatic transmission.

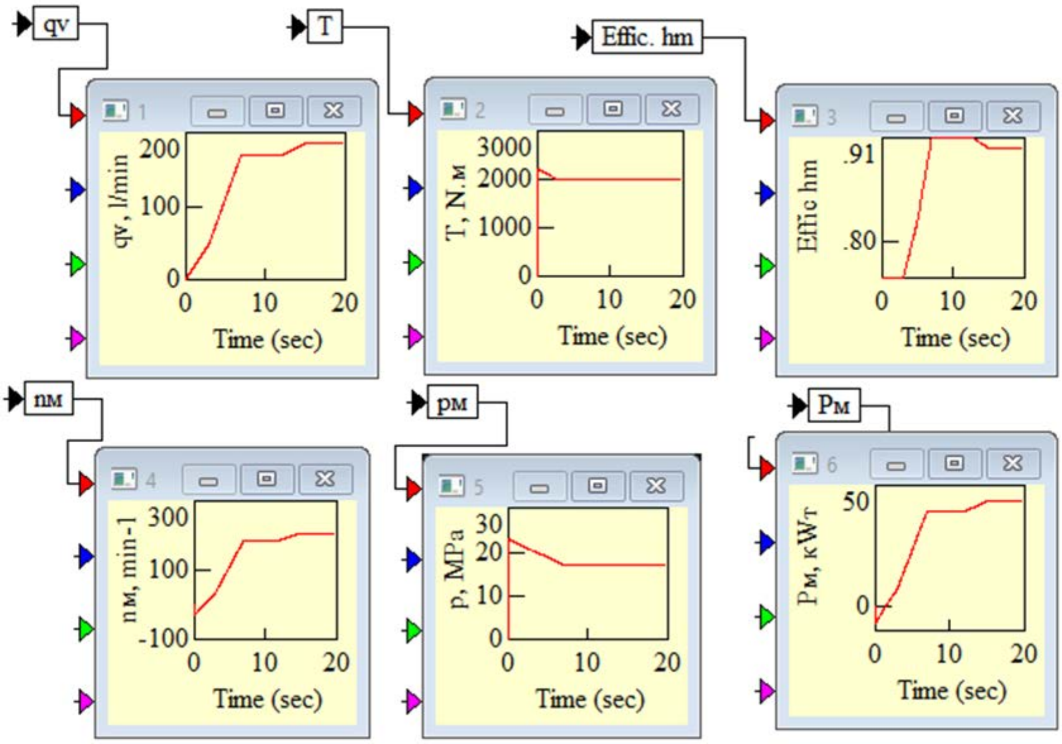
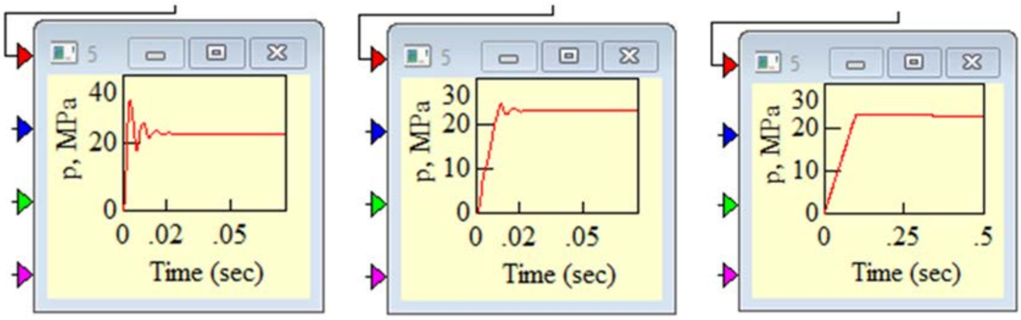


Fig. 4. Oscillograms of dynamic calculations of hydrostatic transmission communal cleaning machine



a b c

Fig. 5. Pressure fluctuations in the hydrostatic transmission depending on the time of torque growth when moving the communal cleaning machine

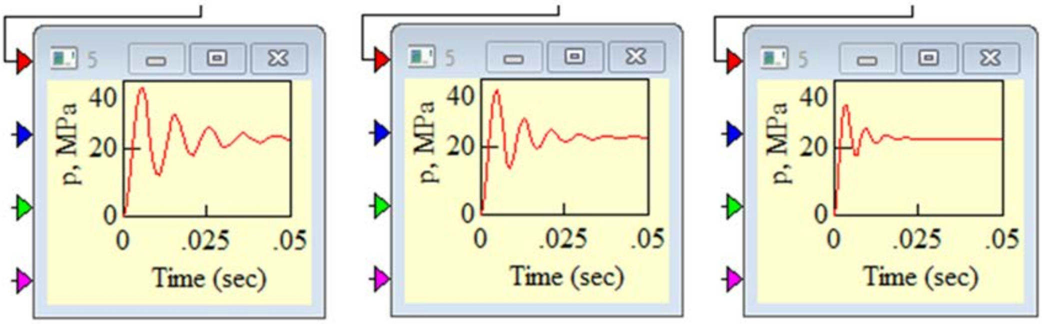


Fig. 6. Pressure fluctuations in the hydrostatic transmission depending on the modulus of elasticity of the working fluid

Conclusion

Analysis of modern achievements in improving the speed characteristics of radial-piston hydraulic motor-wheels and calculations of hydrostatic transmission for wheeled tractors, loaders, and cleaning utility vehicles make it possible to draw a conclusion about the prospects of this direction.

For mobile machines with a traction force of up to 60 kN and a maximum speed of more than 40 km/h, in particular wheeled tractors and loaders, it is possible to use radial-piston hydromotor-wheels in the gearless version. For multi-axle vehicles with a traction force of up to 440 kN and a speed of more than 90 km/h a hydraulic motor-wheel combination with a two-speed foam gearbox is required, and transmissions with electric motors have the same disadvantages.

Modeling the dynamics of the hydrostatic transmission with the help of calculations in the VisSim package made it possible to establish modes of pressure fluctuations increased by 1.5-2 times relative to the established mode depending on the speed of the external load and the decrease in the modulus of elasticity of the working fluid when it is not purified from undissolved particles air.

Further actions regarding the practical use of radial-piston hydraulic motor-wheels in the hydrostatic transmissions of high-speed mobile machines should be based on the results of functional-cost analysis and experimental studies.

Conflict of interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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Avrunin Grygoriy[1], PhD (Engineering), Assoc. Prof. Department of Construction and Road-Building Machinery,
e-mail: griavrunin@ukr.net,
Phone.: +38 050-596-62-53,
ORCID: https://orcid.org/0000-0002-0191-3149
Podrigalo Mikhail[1], DSci (Engineering), Department Technology of mechanical engineering and machine repair,
e-mail: pmikhab@gmail.com,
Phone.: +38 (050) 301-16-58,
ORCID: https://orcid.org/0000-0002-1624-5219
Podrigalo Nadia[1], DSci (Engineering), Assoc. Prof. Department of Computer Graphics,
e-mail: pnm2018@ukr.net,
Phone.: +38 (050) 501-51-01,
ORCID: https://orcid.org/0000-0003-2426-0336
Fidrovska Natalia[1], DSci (Engineering), Professor Department of Construction and Road-Building Machinery,
e-mail: nfidrovskaya@ukr.net
Phone.: +38 (099) 790-55-34
ORCID: https://orcid.org/0000-0002-5248-273X
Moroz Irina[1], Senior Lecturer Department of Higher Mathematics.
e-mail: irinamoroz1@ukr.net,
Phone.: +38 (050) 700-67-95,
ORCID: https://orcid.org/0000-0001-5950-2089
Yatsunskyi Petro[2]. PhD (Engineering) Department of Design Machine and Automotive Engineering,
e-mail: petro.p.yatsunskyi@lpnu.ua
Phone.:+38 (068) 017-66-70
ORCID: orcid.org/0000-0002-1609-7009

[1] Kharkiv National Automobile and Highway University Yaroslava Mudrogo str., 25, Kharkiv, Ukraine, 61002
[2] Lviv Polytechnic National University, Profesorska str., 1, Lviv, Ukraine, 79013

Моделювання обмежень щодо застосування гідромотор-колес в трансмісіях мобільних машин

Анотація. Проблема*. Створення мобільних машин з підвищеними швидкостями пересування вимагає конструктивних рішень щодо створення відповідних трансмісій, зокрема аналізу можливості створення гідравлічних безступеневих трансмісій з використанням гідромоторів різних типів.* ***Мета.*** *Підвищення технічного рівня трансмісій комунальних, будівельно-дорожніх машин та багатовісних швидкісних транспортних засобів за допомогою досягнень в сучасних об'ємних гідроприводах.* ***Методологія.*** *Розглянуті трансмісії мобільних машин з точки зору можливості використання в них радіальнопоршневих гідромоторів багатоциклової дії в якості безредукторних гідромотор-колес. Згідно тягово-швидкісних характеристик розраховані значення крутних моментів та частот обертання маточин і обрані гідромотор-колеса за відповідними робочими об'ємами. В якості приклада проведені розрахунки динаміки гідроприводної трансмісії прибиральної комунальної машини за допомогою пакету прикладних програм VisSim, де використали універсальну характеристику героторного гідромотора для завдання гідромеханічного ККД на режимах від зрушування до максимальної частоти обертання.* ***Результати.*** *Отримали позитивні результати щодо підвищення швидкості мобільних машин при застосуванні гідромотор-колес радіальнопоршневої багатоциклової дії в трансмісіях замість героторних гідромоторів, аксіальнопоршевих з планетарними редукторами гідромоторів, гідравлічних трансмісій з карданними валами і механічних трансмісій.*
Оригінальність. *Отримані нові розрахункові дані щодо вихідних характеристик трансмісій з гідроприводом, показані можливості моделювання динамічних процесів в гідроприводі трансмісії залежно від дії зовнішніх факторів щодо навантаження, швидкоді і властивості робочої рідини. Встановлено, що для багатовісних транспортних засобів з максимальною швидкістю до 100 км/год використання мотор-колес електричного або гідравлічного типів потребує доповнення планетарними коробками передач з редукторами або мультипликаторами.* ***Практичне значення.*** *Приведені рекомендації щодо застосування радіальнопоршневих безредукторних гідромотор-колес в мобільних машинах з метою підвищення їх технічного рівня.*

Ключові слова: *транспортний засіб, трансмісія, гідромотор-колесо, крутний момент, частота обертання, динамічні розрахунки, пакет VisSim*

Аврунін Григорій Аврамович[1], к.т.н., доцент кафедри будівельних і дорожніх машин ім. А. М. Холодова,
e-mail: griavrunin@ukr.net,
тел.: +380 50-596-62-53,
ORCID: https://orcid.org/0000-0002-0191-3149
Подригало Михайло Абович[1], д.т.н. професор кафедри технології машинобудування і ремонту машин,
e-mail: pmikhab@gmail.com,
тел.: +38 (050) 301-16-58,
ORCID: https://orcid.org/0000-0002-1624-5219
Подригало Надія Михайлівна[1], д.т.н, доцент кафедри комп'ютерної графіки,
e-mail: pnm2018@ukr.net,
тел.: +38 (050) 501-51-01,
ORCID: https://orcid.org/0000-0003-2426-0336
Фідровська Наталія Миколаївна[1]**,** д.т.н., професор кафедри будівельних і дорожніх машин,
e-mail: nfidrovskaya@ukr.net
тел.: +38 (099) 790-55-34
ORCID: https://orcid.org/0000-0002-5248-273X
Мороз Ірина Іванівна[1], старший викладач кафедри вищої математики,
e-mail: irinamoroz1@ukr.net,
тел.: +38 (050) 700-67-95
ORCID: https://orcid.org/0000-0001-5950-2089
Яцунський Петро Петрович[2]**,** доцент кафедри проєктування машин та автомобільного інжинірингу,
e-mail: petro.p.yatsunskyi@lpnu.ua
тел.: +38 068-017-66-70
ORCID: orcid.org/0000-0002-1609-7009

[1] Харківський національний автомобільно-дорожній університет, вул. Ярослава Мудрого, 25, м. Харків, Україна, 61002.
[2] Національний університет «Львівська політехніка», вул. Професорська 1, м. Львів, Україна, 79013.