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ECOLOGY - VEHICLE AND ROAD SAFETY - EFFICIENCY

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APPLICATION OF HYDROSTATIC TRANSMISSION IN MOBILE MACHINE

ABSTRACT: Hydrostatic transmissions are widely used in the field of mobile machines in construction, mining, agriculture, forestry, both to start working bodies (multipliers) that perform technological operations, and for motion drives. In the first part of the paper, hydrostatic power transmissions and their classification are described, followed by an explanation of the working principles of hydraulic pump and hydraulic motor. In the second part of the paper, the application of the hydrostatic transmission in different mobile machines is presented. The third part represents the most crucial segment, where the calculation to obtain the key parameters for hydrostatic transmission design is presented. Finally, the main components of the hydrostatic transmission are selected.

KEYWORDS: hydraulic pump, hydraulic motor, calculation, hydrostatic transmission

INTRODUCTION

The hydraulic power transmission is carried out by means of liquids, which are most often mineral hydraulic oils and non-flammable fluids for hydraulics. In the components of these transmissions, the mechanical energy of the working fluid is converted into its fluid energy and vice versa. Depending on the principle of operation of these hydraulic devices for energy conversion, hydrostatic and hydrodynamic power transmissions are distinguished. In hydrostatic transmissions, the energy converters are a volume pump at the input and a volume hydro-motor or hydraulic cylinder at the output [1].

Compared to others, hydraulic drives have a significantly lower mass and smaller aggregate dimensions, and therefore have a low inertia; the rotational mass of hydraulic motors of rotational action is several times smaller than the rotational mass of electric motors of the same power. They make it possible to achieve a stepless change of the output speed, convert rotary motion into translational and translational into rotary motion; constructively, it simply

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ensures the protection of hydro aggregates from overloading. Disadvantages include the high price of aggregates, the complexity of exploitation, and a relatively short service life [1].

In recent years, the progress has been made in the development and practical application of hydrostatic transmission and management in all branches of economy. Hydrostatic transmissions (HST) are particularly widely used in the field of mobile machines in civil engineering, mining, agriculture and forestry, wind turbines, etc. These hydrostatic systems are intended for movement of working organs (manipulators) which perform technological operations and also as driving power [2].

When we talk about the global hydrostatic transmission market, it was at 5.1 billion USD in 2023. and is predicted to reach 7.9 billion USD by 2032 (Figure 1). This sector has a strong presence in the North American market, especially the United States and Canada in the agricultural sector. Technological improvements and the deployment of modern machinery drive the market in this area even further.

When we talk about the application of hydrostatic transmisisons in the EU, Germany, France, the United Kingdom, Italy, and Spain are leading the way. The increase of building and mining operations, notably in Eastern European nations, is driving market growth in Europe. Adoption of hydrostatic transmissions is further aided by stringent rules encouraging energy efficiency and environmental practices [3].

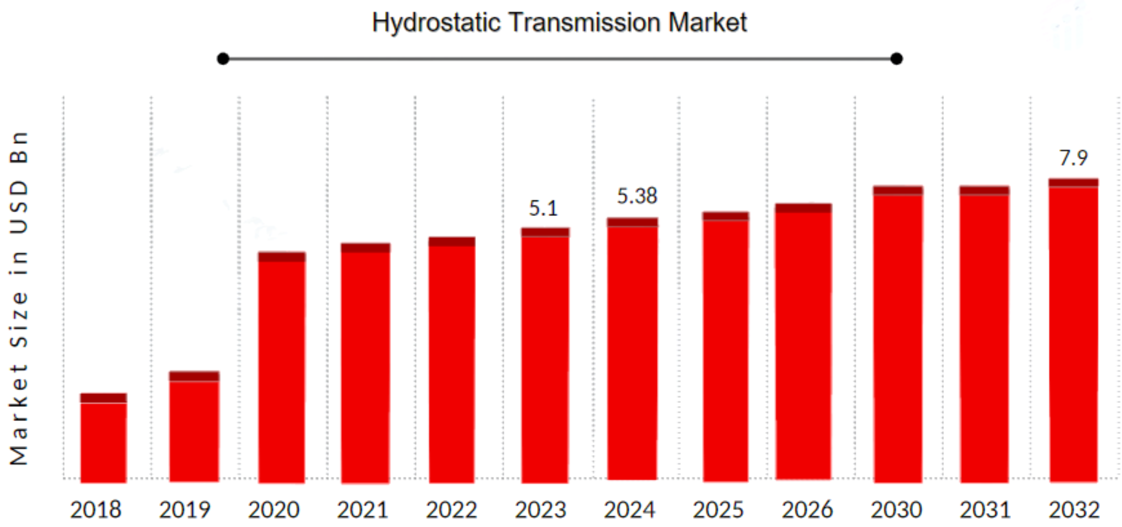
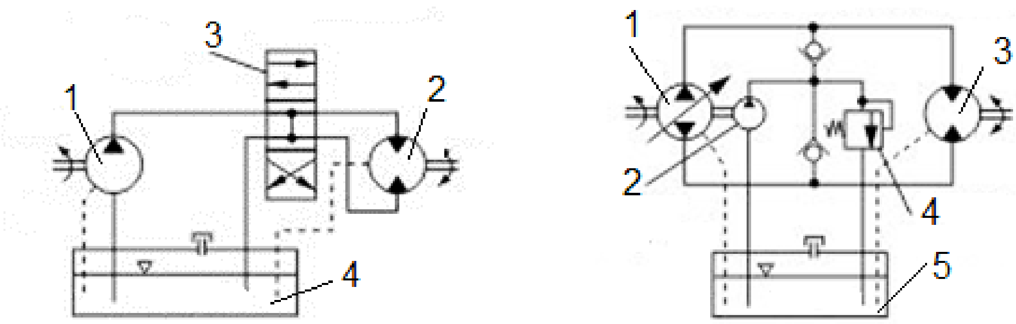


Figure 1 The global hydrostatic transmission market [3]

Configuration of hydrostatic transmission

There are four types of hydrostatic transmission, two with open circuit and two with closed circuit. In open-loop circuit transmission (Figure 2, a), the working fluid enters the regulating pump through the reservoir, then passes through the hydraulic motor and finally reaches the reservoir, or rather, returns to it. In a closed-loop circuit, (Figure 2, b) the path of fluid movement is continuous, so the fluid flows along a constant path from the output of the control pump to the input of the control motor and vice versa [2]. An open circuit is not used in vehicles, because it cannot be reversed; and lacks braking. It is used for conveyor belts where load is resistant and where rotation in one direction is possible.



a) b)

Figure 2 Scheme of the hydrostatic transmission

a) open-loop hydraulic circuit, 1 - hydraulic pump, 2 - hydraulic motor, 3 – directional valve, 4 – oil tank
b) closed-loop hydraulic circuit, 1 - hydraulic pump, 2 - feed pump, 3 - hydraulic motor, 4 - pressure regulator, 5 – oil tank [4]

The configuration of the hydrostatic transmission can be with a pump with a constant (or variabile volume), and with a hydraulic motor with a constant (Figure 2, a) or variable working volume. HST with constant displacement pump and motor is cheap, but its application is limited, mainly because other types of power transmission are inefficient. The most widespread configuration of hydrostatic transmission consists of a regulating pump (Figure 2, b) and a regulating motor with a variable working volume. Theoretically speaking, this arrangement provides an infinite number of torque and speed ratios. With the throttle motor at maximum operating volume, the variable output volume of the throttle pump directly changes the speed and power output, while the torque remains constant. By reducing the working volume of the engine at the full working volume of the control pump, the speed of the control motor increases to its maximum value, the torque changes inversely with the speed, and the power remains constant.

Figure 3 shows the working characteristics of the hydrostatic transmission. Range 1 covers changing the angular speed of the motor by varying only of displacement of the hydraulic pump from zero to maximum values, while the working volume of the engine is fixed at its maximum value. Range 2 starts when the pump reaches its maximum move. To obtain higher values for the angular velocity, engine displacement must be reduced. Within this range, the system ensures constant power and flow, while hydraulic torque is proportional to engine volume move.

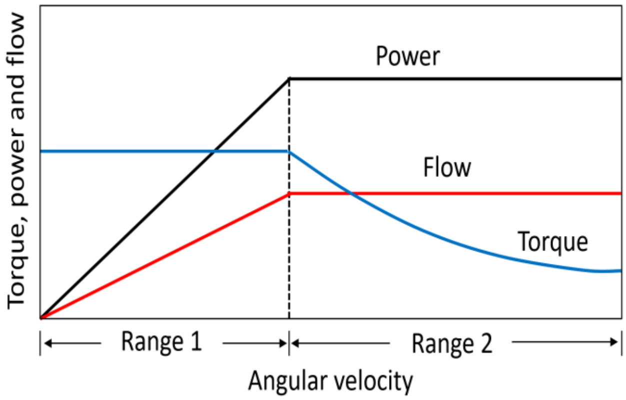


Figure 3 Operational characteristics of the hydrostatic transmission [5]

APPLICATION OF HYDROSTATIC TRANSMISSION

Hydrostatic transmission is widely used in agriculture. It is used in tractors, all types of self-propelled machines such as combine harvesters for sugar cane, sugar beet harvesters, silage harvesters, sprayers, telescopic manipulators, silo mixers, etc. Hydrostatic transmission is the most modern, but also the most expensive transmission and is used mainly in special agricultural machines. In order to achieve cost reduction, manufacturers of agricultural machinery apply hydro-mechanical transmissions with less or greater use of reducers and mechanical drive bridges [4]. At the beginning of the 2000's, the most commonly applied type of transmission was with rear-wheel drive only, with one variable-flow piston-axial pump and one two-flow piston-axial motor connected to a mechanical drive bridge (Figure 4).

Figure 4 Mechanical drive bridge with attached hydraulic motor and reducers [6]

Figure 5 shows the hydrostatic drive solution with a speed reducer between the hydraulic motor and the wheel. This a hydrostatic circuit consists of a piston-axial pump, a two-flow piston-axial hydraulic motor with an inclined axis and a speed reducer. The most common transmission ratio in such reducers is i = 35 - 45. An integrated parking brake or an active disc brake are installed in the reducer. The big advantage of this type of hydrostatic system is its price. Two-flow piston-axial engines have a price of about 60% lower compared to high-torque piston-radial low-speed engines, while the reducers are from mass production, slightly modified to meet the needs of the machine manufacturer [7].

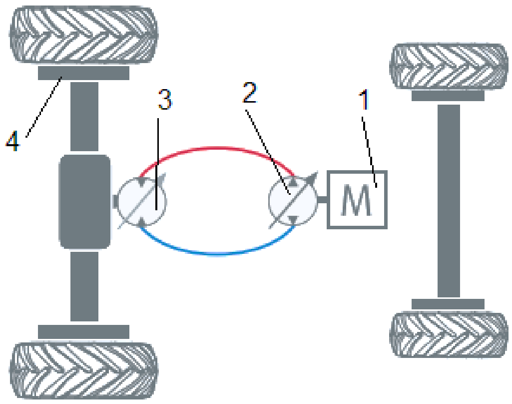


Figure 5 *Classic hydrostatic drive system with a speed reducer*
(1 - power unit, 2 - piston-axial pump, 3 - piston-axial hydraulic motor, 4 - reducer) [7]

One example of the use of hydrostatic transmission in a combine harvester is shown in Figure 6. This harvester uses a diesel engine, a variable-displacement hydraulic pump with mechanical-hydraulic control, and a constant displacement hydro-motor connected to a three-speed gearbox. Gear ratios are adjusted for different conditions of use such as harvesting, moving around the field, as well as the road. In the cabin, there is a mechanical-hydraulic controller, with which the operator of the machine regulates the operation of the hydro-pump.

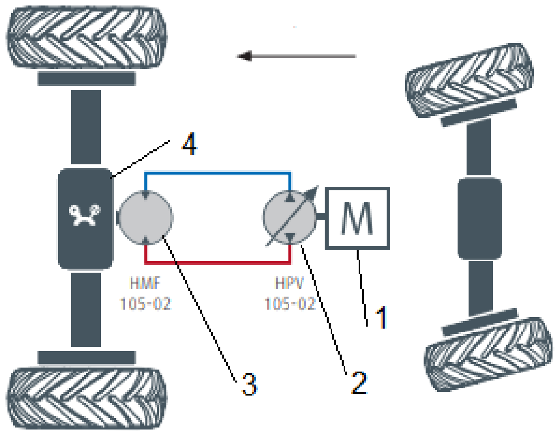


Figure 6 Hydrostatic transmission for combine harvesters
(1 - diesel engine, 2 - hydraulic pump, 3 – hydro-motor, 4 - gearbox) [7]

Hydrostatic transmission is also used to drive sugarcane harvester. In Figure 7, the concept with two hydraulic circuits is shown and works without a transfer mechanism with a distributor. The power unit drives two variable displacement hydraulic pumps, which transmit hydraulic power, each separately, to variable displacement hydraulic motors that drive the tracks.

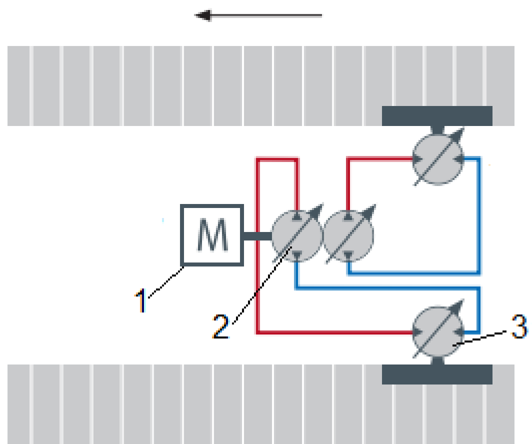
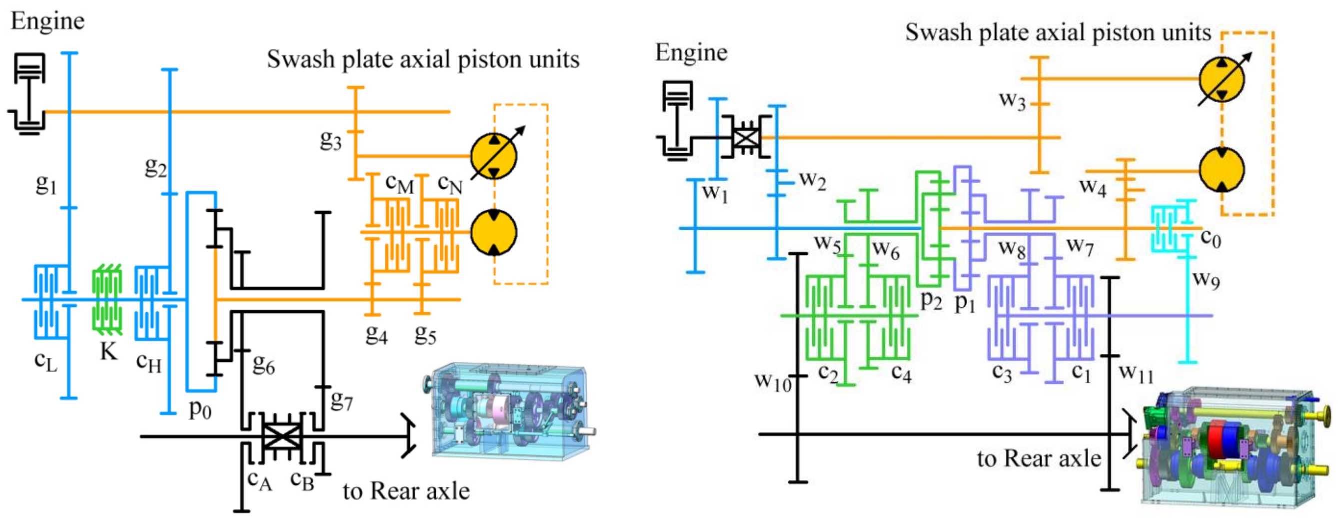


Figure 7 Hydrostatic transmission at sugarcane harvester
(1 – diesel engine, 2 - hydraulic pump, 3 - hydraulic motor) [7]

When we talk about tractors, manual transmission, hydrostatic (HST) and hydro-mechanical transmission (HMT) are used today. HST and HMT transmission are continuously variable transmissions and can operate the engine with high thermal efficiency independently of the vehicle speed in the transmission range, thereby reducing fuel consumption and exhaust gases. In addition, being able to automatically control the gear ratio increases the driver's work efficiency, and finally, they are environmentally friendly and highly efficient [8]. In order to improve the comfort of driving a tractor with HST, this transmission is often combined with a planetary gearbox (Figure 8) [9].



a) b)

Figure 8 Powertrain of hydrostatic power-split transmission
(a) Standard HMT, (b) Simpson HMT [9]

CALCULATION OF HYDROSTATIC TRANSMISSION

The most important assumption for setting up a satisfactory solution to the problem is the previous system procedure of planning and execution of the hydrostatic system. When designing the hydrostatic system, the requirements and parameters of the function of the members of the kinematic chain of the machine that the actuators of the hydrostatic system should strengthen are first analyzed in detail. For the correct selection and definition of hydrostatic components, it is necessary to know their characteristics: principles, methods and conditions of operation, basic parameters and transmission functions, methods of installation and maintenance, prices and methods of delivery.

In this part, the calculation of hydrostatic transmissions is described, which is used to drive wheeled tractors and crawler tractors, and based on which the choice of hydro-pump and hydro-motor is then made. First, it is necessary to calculate the parameter values of individual components that are within this transmission. Some of the quantities are hydraulic power, maximum pump flow, specific flow, etc. The general scheme of the hydrostatic transmission used in the calculation is shown in Figure 9.

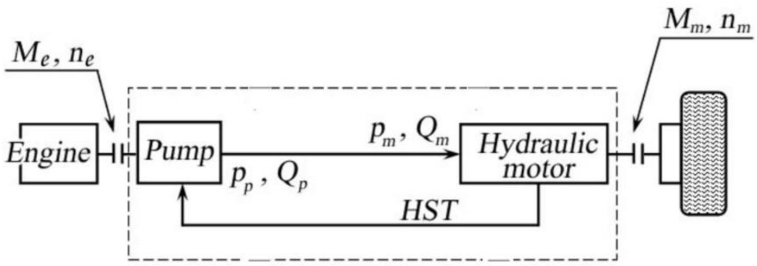


Figure 9 Model of hydrostatic transmission [10]
M_e, n_e - torque and motor shaft speed; M_m, n_m - torque and rotational speed of the hydraulic motor shaft; p_p, Q_p - pump pressure and flow rate; p_m, Q_m - pressure and supply to the hydraulic motor

For wheeled tractor, the circulation of the working fluid is in a closed circuit. This type of hydraulic drive consists of a power unit, specifically a diesel engine, a hydraulic pump with a variable working volume, which drives a hydraulic motor with a constant working volume, and which is connected via a two-stage mechanical gearbox to the drive bridge, which drives the wheels and transmits power to the ground.

The basic equations for torque and flow of hydraulic pump and hydraulic motor are given by equations 1-4.

$$M_p = \frac{\Delta p \cdot q_p}{2 \cdot \pi \cdot n_p} \tag{1}$$

$$M_m = \frac{\Delta p \cdot q_m \cdot \eta_m}{2 \cdot \pi} \tag{2}$$

$$Q_p = q_p \cdot n_p \cdot \eta_{vp} \tag{3}$$

$$Q_m = \frac{q_m \cdot n_m}{\eta_{vm}} \tag{4}$$

where are: Δp - pressure difference across hydraulic motor/pump (Pa); Q_p, Q_m- flow rate of hydraulic pump/motor (l/min); M_p, M_m- torque of hydraulic pump/motor (Nm); n_p, n_m– number of revolutions of pump/motor (rpm), q_p, q_m– specific flow rate of hydraulic pump/motor - displacement (cm^3/rev); η_{vp}, η_{vm}- volumetric efficiency.

Table 1 gives the initial data for the calculation of hydrostatic transmission for wheeled and crawler tractors, and Figure 10 shows the calculation flow.

Table 1 Basic data for calculation

Wheeled Tractor	
Vehicle weight [kN]	42.8
Wheel radius [mm]	590
Nominal speed of pump [min^{-1}]	2100
Maximum vehicle speed [km/h]	25
Type of road	macadam
Maximum ascent [º]	15

Crawler tractor	
Mass of tractor [t]	7.5
Engine power [kW]	120
Maximum flow of pump [l/min]	250
Maximum working pressure [MPa]	40
Maximum vehicle speed [km/h]	10
Maximum required traction force of one track [N]	2590

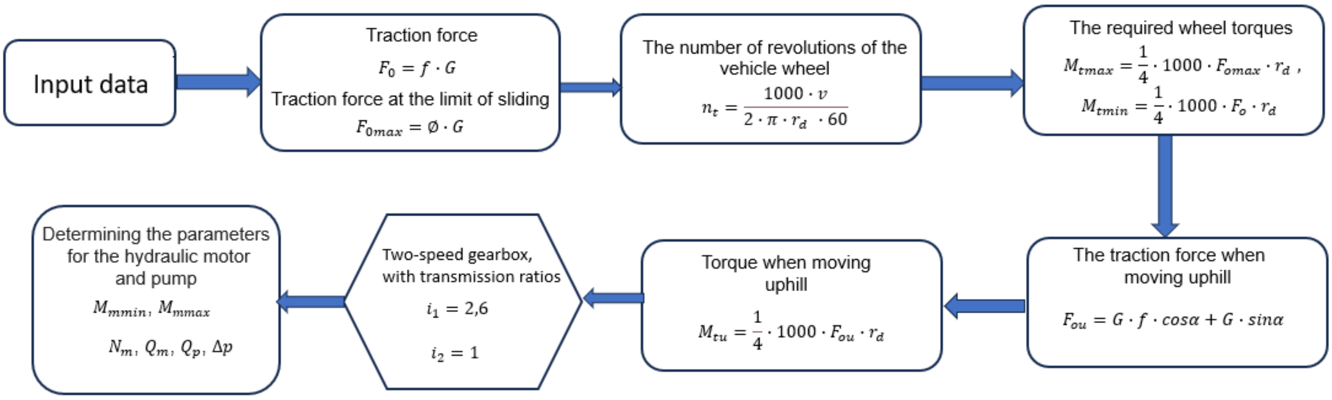


Figure 10 Calculation flow for wheeled tractor

After obtaining the necessary parameters, the pump and motor are selected. The hydraulic motor and hydraulic pump, based on the data obtained from the calculation, were adopted from the catalog of the manufacturer "Bosh Rexroth", model MCR-F, and the hydraulic pump AA4VG Series 32 (Table 2).

For the crawler tractor used a hydrostatic transmission system with two open circuits (Figure 11), consisting of: diesel engine, elastic coupling, toothed distributor, hydraulic pumps, distributors, modular drive transmission with an integrally connected hydraulic motor and planetary reducer to which the caterpillar's drive sprocket is attached. The calculation is based on the maximum required torque on the output shaft of the drive reducer, i.e. the maximum required torque on the drive sprocket of one caterpillar. It is necessary to first calculate the maximum required traction force of one caterpillar.

Table 2 Technical data on the hydraulic pump and motor from the manufacturer's catalog [11]

Radial piston hydraulic motor „*Bosh Rexroth MCR-F*“	
Displacement	$565\ cm^3/rev$
Maximum torque	$4047\ Nm$
Maximum pressure	$450\ bar$
Maximum number of revolutions	$385\ min^{-1}$

Axial piston pump „*Bosh Rexroth AA4VG Series 32*“	
Displacement	$40\ cm^3/rev$
Nominal pressure	$400\ bar$
Maximum pump flow	$160\ l/min$
Maximum pressure	$450\ bar$

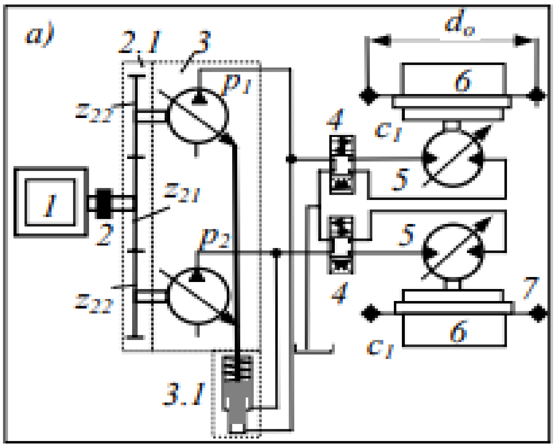


Figure 11 Functional scheme of transmission with two open hydrostatic circuits [12]
(1 – diesel engine, 2 – elastic coupling, 2.1 – gear distributor, 3 – hydraulic pump, 3.1 – collective distributor, 4 – flow regulator, 5 – hydromotor, 6 – reducer, 7 – sprocket)

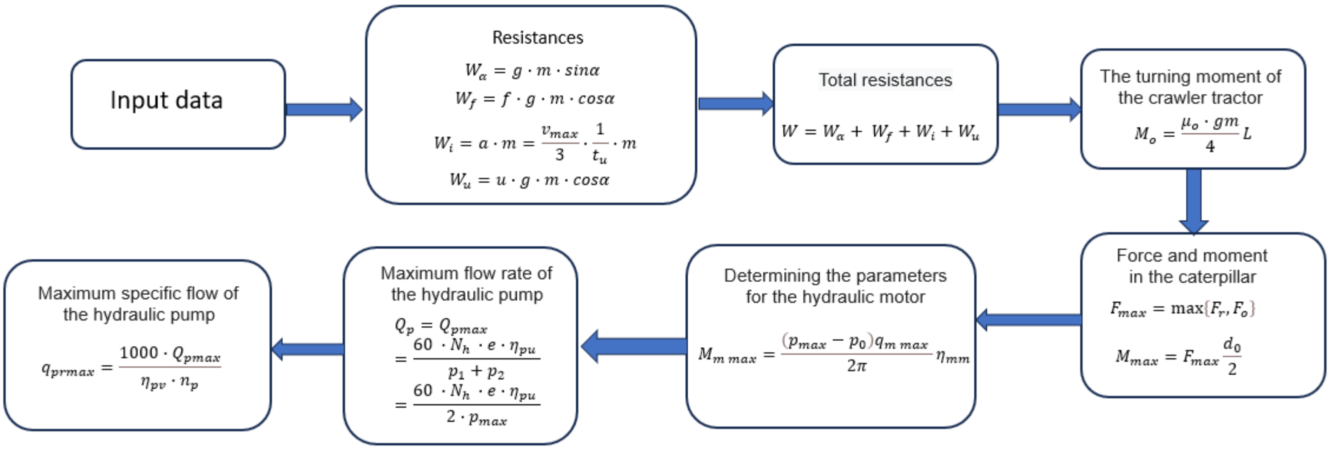


Figure 11 Calculation flow for crawler tractor

Based on the maximum specific flow determined by calculation, according to the manufacturer's catalog, the closest available value of the specific flow of the pump is adopted. If there is a significant difference between the magnitude of the required and available specific flow of the hydraulic pump, while maintaining the desired maximum flow of the hydraulic pump, the required gear ratio is determined from the power distributor. After that, the maximum number of revolutions of the hydraulic pump is determined through the ratio and checked in the manufacturer's catalog. The hydraulic motor and hydraulic pump were adopted, based on the data obtained from the calculation (Table 3):

- two piston-axial pumps from the catalog of the manufacturer "Danfoss", series 45, with frame E, and
- two hydraulic pump two hydraulic motors model A10VE manufactured by "Bosh Rexroth"

Table 3 Technical data on the hydraulic pump and motor from the manufacturer's catalog [11, 13]

Radial piston hydraulic motor "Bosh Rexroth A10VE"	
Displacement	$45\ \mathrm{cm}^3/rev$
Maximum torque	$250\ Nm$
Maximum pressure	$350\ bar$
Maximum number of revolutions	$5400\ min^{-1}$
	

Piston - axial pump "Danfoss"	
Displacement	$130\ cm^3/rev$
Nominal pressure	$310\ bar$
Maximum pump flow	$250\ l/min$
Maximum pressure	$400bar$
	

CONCLUSIONS

The paper presents a mathematical calculation that enables a preliminary calculation of the working volumes of hydraulic machines with further specification in accordance with standard values. The pressure produced by the pump is determined according to the load during the movement of the transport machine. The power of the drive motor should take into account both the movement of the vehicle and the possibility of creating special systems with a hydraulic drive.

The main disadvantages of the mechanical transmission are the sudden change in the transmission ratio due to the gearbox that works on the principle of toothed transmission, a small ratio of power per unit of mass, poor flexibility and the inability to regulate. On the other hand, the use of hydrostatic transmission in vehicles enables the achievement of large forces and moments with devices of small dimensions. Continuously variable transmission is also achieved within the entire working area, giving the best transfer measures between the drive motor and the wheels, which increases dynamic performance and reduces fuel consumption.

Further development of hydrostatic transmission components (primarily piston-axial hydraulic pumps and piston-radial hydraulic motors) as well as the integration of electronics and computers into these systems will dictate further directions of development of these systems. Some types of hydrostatic systems are the most acceptable with their price and will be used as basic systems for driving mobile machines for a long time. On the other hand, other types of hydrostatic systems presented in this paper are dominant in special agricultural machines (corn pickers, sugar beet harvesters), while the most modern hydrostatic systems are used in the most complex self-propelled agricultural machines (vegetable harvesters).

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