HYDROSTATIC TRANSMISSIONS
CALCULATION FOR MOBILE MACHINES
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1. INTRODUCTION

During developing time of mobile machines on wheels the hydrostatic systems were used first only for power supply of working attachments-manipulator. However in latest decade, on same types of machines more and more hydrostatic transmissions are used for movement system. Leading manufactures of hydraulic components have already developed hydrostatic transmissions for movement of mobile machines on wheels in range of weight from 3000 to 30000 kg, that corresponds the power 30 to 300 kW. Solutions of hydraulic transmissions are mostly with modular design and contain integrated within, following elements:

- elementary components for energy transformation and energy transmission (hydraulic pumps and hydraulic motors),
- hydrostatic systems for movement control,
- hydrostatic system for braking,
- hydrostatic systems for regulation, control and stable maintaining of moving characteristics of mobile machines.

2. ENGINEERING SOLUTIONS

As a rule, hydrostatic transmissions on the mobile machines on wheels are in form of closed hydraulic circuit system, most frequently with axial piston hydraulic motors with constant or variable specific flow. Operating pressure in systems is in range of 35 to 45 MPa.

Depending of way of energy transmission from hydraulic motors to wheels there are following solution variants of transmission executive parts [1][2][4]:

- shaft of hydraulic motor (4) (Fig.1a) is connected directly to the wheel hub,
- hydraulic motor (4) (Fig.1b) is indirectly connected to the wheel hub, through reducing gearbox (5),
- hydraulic motor (4) (Fig.1,c), is connection to the wheels through gearbox (5), universal shafts (6) and driving axles (7).

![Fig.1. Mobile machines on wheels with hydrostatic transmission for movement [3].](image-url)
As power producing members of transmissions are used most frequently diesel engines whose mechanical parameters of power $N_h$ hydraulic pumps transform into hydraulic form of power, defined by appropriate pressure $p$ and by flow $Q$.

Hydraulic motors with executive part of transmission the parameters of hydraulic form of power transform into appropriate drawing force $F$ and movement velocity $v$ of mobile machine.

General and elementary criterion for regulation of drawing characteristics of mobile machine can be expressed by equation:

$$N_h = p \cdot Q = F \cdot v = \text{const} \quad (1)$$

In contemporary solutions of hydraulic transmission for movement of mobile construction machines assumed criteria of regulation (equation 1) are realized by means of digital electronic system.

By appropriate sensors (9) (Fig.1c) [1][2] measured are parameters of driving, transforming and transmitting, transmission components.

In microcontroller (10) monitored parameters are processed according to appropriate software that in fact represents previously assigned regulating criteria.

Deviations of real (measured) and previously assigned parameters are transformed inside microcontroller into the signals that act on the characteristics of transmission components.

By this way of regulation are achieved the following capabilities of hydrostatic transmissions:

- automatic regulation of drawing characteristics by changing of specific flow of hydraulic pumps and hydraulic motors beside great fuel savings and noise decreasing, even in higher movement velocities.
- continual decreasing of movement velocity (by inch pedal), for reason of directing more power for needs of working attachments - manipulators on machine.
- regulation of Limiting Load of driving engine.
- prevention of drive wheels skidding.

3. CALCULATION

General conceptual solution of transmission for movement on construction mobile machines for which is calculated consist of following: diesel engine (1) [3] (Fig.2), coupling (2), hydraulic pump (3) with variable specific flow, hydraulic motor (4) with variable specific flow, transmission gearbox (5), cardan shaft (6), driving axle (7) and wheel (8).

Starting parameters that are assigned when the transmission calculation is performed belong to the following set of values [3][4]:

$$P_n = \left\{ N_h, n_m, F_{max}, v_{max}, v_{max}, r_d \right\} \quad (2)$$

where is: $N_h$ - maximal power that diesel engine transfers to the hydraulic pump; $n_m$ - number of revolutions of diesel engine power; $F_{max}$ needed maximal drawing force of machine; $v_{max}$ - maximal operating velocity of machine; $v_{max}$ - maximal transporting velocity of machine; $r_d$ - dynamic radius of wheel.

Upon the basis of assigned parameters $E_n$ needed is to define the sizes of transmission components expressed by the following set of values:

$$E_n = \left\{ p_{max}, q_{p \text{ max}}, q_{m \text{ max}}, q_{m \text{ min}}, i_m, i_m, \right\} \quad (3)$$

where is:

- $p_{max}$ - maximal pressure of the hydrostatic system;
- $q_{p \text{ max}}$ - maximal specific flow of hydraulic pump;
- $q_{m \text{ max}}$ - maximal specific flow of hydraulic motor;
- $q_{m \text{ min}}$ - minimal specific flow of hydraulic motor;
- $i_m$ - gearbox transmission ratio in operating velocity of machine;
- $i_m$ - gearbox transmission ratio in transporting velocities of machine; $i_o$ - transmission ratio of driving axles.

Maximal pressure $p_{max}$ is the main parameter of hydrostatic system. Value of this pressure prescribes the choice of transmission concept in other terms, the choice of types of hydraulic pump and hydraulic motor.

Size of hydraulic pump is defined according to input hydraulic power $N_h$. For the hyperbolic form of regulation of pump parameters (pressure and flow) (Fig.3) can be written equation:

$$N_h = \frac{p_{max} Q_{min}}{60 \eta_p \eta_{pm}} = \frac{p_{min} Q_{max}}{60 \eta_p \eta_{pm}} = \frac{p Q}{60 \eta_p \eta_{pm}} \quad (4)$$

where is: $p_{min}, Q_{max}$ - pressure and flow of start of pump regulation; $p_{max}, Q_{min}$ - pressure and flow of end of pump regulation; $p, Q$ pressure and flow inside the range of pump regulation; $\eta_p, \eta_{pm}$ - volumetric and mechanical pump efficiency ratio.
By introducing the range of regulation as ratio:

\[ e = \frac{p_{\text{max}}}{p_{\text{min}}} \]  

(5)

can be calculated maximal pump flow:

\[ Q_{\text{max}} = \frac{60 \cdot N_{\text{h}} \cdot e}{\eta_p \eta_{\text{pm}}} \]  

(6)

according which is calculated pump maximal specific flow:

\[ q_{p_{\text{max}}} = \frac{1000 \cdot Q_{\text{max}}}{\eta_{p} \eta_{\text{pm}}} \]  

(7)

where is:

\[ Q_{\text{max}} \text{ [l/min]}, q_{\text{p max}} \text{ [cm}^3\text{]}, n_{\text{p}} \text{ - pump number of revolutions for the first step of calculation can be taken } n_{\text{p}} = n_{\text{ar}} \]

On the basis of calculated value selected is from the manufacturers catalogue the size of hydraulic pump.

Size of hydraulic motor is defined from defined condition that maximal drawing force \( F_{\text{max}} \) of machine is achieved at:

- maximal pressure \( p_{\text{max}} \) of pump,
- maximal specific flow \( q_{\text{m max}} \) of hydraulic motor,
- transmission ratio of gearbox \( i_{\text{m1}} \) that is used in operating velocities.

Needed maximal torque \( M_{\text{max}} \) on wheels at maximal drawing force:

\[ M_{\text{max}} = r d F_{\text{max}} \]  

(8)

On the basis of maximal torque of hydraulic motor:

\[ M_{\text{m max}} = \frac{(p_{\text{max}} - p_{o}) l_{\text{m max}}}{2 \pi} \eta_m = \frac{M_{\text{max}}}{\eta_{\text{m}} l_{\text{m1}} l_{\text{m}} l_{\text{o}}} \]  

(9)

Calculated is needed maximal specific flow of hydraulic motor:

\[ q_{\text{m max}} = \frac{2 \pi M_{\text{max}}}{(p_{\text{max}} - p_{o}) l_{\text{m1}} l_{\text{m}} l_{\text{o}}} \]  

(10)

where is:

\[ q_{\text{m max}} \text{ [cm}^3\text{]}, M_{\text{m max}} \text{ [Nm]}, p_{o} \text{ [MPa]} \text{ - pressure value in return line of hydraulic motor; } \eta_m \text{ mechanical efficiency ratio of hydraulic motor; } \eta_{\text{m}}, \eta_{\text{o}} \text{ - efficiency ratio of gearbox and driving axles.} \]

On the basis of calculated value \( q_{\text{m max}} \), selected is from the manufacturers catalogue the size of hydraulic motor.

Needed minimal specific flow \( q_{\text{m min}} \) of hydraulic motor is calculated from the condition that mobile machine achieves wanted transport velocity \( v_{\text{max}} \) at:

- maximal flow of pump \( Q_{\text{max}} \),
- minimal specific flow \( q_{\text{m min}} \) of hydraulic motor,
- transmission ratio of gearbox \( i_{\text{m2}} \) that is used at transport velocities of mobile machine.

For maximal flow of pump and maximal velocity of the machine:

\[ Q_{p_{\text{max}}} = \frac{q_{\text{m min}} q_{\text{m max}}}{1000 \eta_{\text{mv}}} \]  

(11)

Hydraulic motor will have maximal specific flow:

\[ q_{\text{m max}} = \frac{1000 \cdot Q_{p_{\text{max}}}}{\eta_{\text{m max}}} \eta_{\text{mv}} \]  

(12)

where is:

\[ n_{\text{m max}} \text{ - maximal revolution number of hydraulic motor.} \]

Maximal revolution number of hydraulic motor \( n_{\text{m max}} \) appears when mobile machine reaches maximal transporting velocity:

\[ n_{\text{m max}} = \frac{v_{\text{max}}}{r d} \frac{30}{\pi} i_{\text{m2}} i_{o} \leq n_{\text{md}} \]  

(13)

where is:

\[ n_{\text{md}} \text{ [min}^{-1}], v_{\text{max}} \text{ [m/s]}, r d \text{ [m]}, n_{\text{md}} \text{ - maximal permitted revolutions number of hydraulic motor that is given in motor manufacturer catalogue.} \]

Transmission gearbox and driving axles are produced by the specialized manufacturers. These components are selected according to maximal input torque. However, for driving axles selection must be prescribed also maximal static and dynamic load on each axle. For all components manufacturers offers available transmission ratios.

When transmission ratio of gearbox and driving axles are selected must be satisfied the following ratio:

\[ \frac{i_{\text{m1}}}{i_{\text{m2}}} = \frac{v_{\text{max}}}{v_{r_{\text{max}}}} \]  

(14)
4. DRAWING FORCE DIAGRAM

Drawing force diagram presents mutual dependence of drawing force machine movement velocity (Fig.4).

Movement velocity \( v_i \) and drawing force \( F_i \) for any working conditions in the pump regulation range and for any transmission ratio of gearbox can be calculated with equation:

\[
v_i = r_d \frac{n_m \pi}{i_{m2}} \frac{30}{60}
\]

(15)

\[
F_i = \frac{1}{i_d} M_m i_{m1} i_d n_m n_o
\]

(16)

In that case revolutions number of hydraulic motor \( n_m \) for any value of the specific flow of hydraulic motor \( q_m = [q_{\text{max}}, q_{\text{min}}] \) has value:

\[
n_m = \frac{1000 Q}{q_m} \eta_{\text{mv}}
\]

(17)

and torque \( M_m \) of hydraulic motor for any of the specific flow of hydraulic motor \( q_m = [q_{\text{max}}, q_{\text{min}}] \) has value:

\[
M_m = \frac{(p - p_o) q_m}{2\pi} \eta_{\text{mm}}
\]

(18)

![Drawing force diagram](image)

By pressure changing in the interval \( p = [p_{\text{min}}, p_{\text{max}}] \), along the calculation of appropriate pump flow (equation 4):

\[
Q = \frac{60 \cdot N_h}{p} \eta_{\text{p}} \eta_{\text{pm}}
\]

(19)

can be completely defined the drawing force diagram (Fig.4) of construction mobile machine.

5. CONCLUSION

Last decade is time of very dynamic development of hydrostatic components and hydrostatic system used for movement transmission on the mobile machines on wheels. In paper is presented procedure for the calculation of the elementary transmission parameters, on the basis of assigned parameters for the needed values prescribed for machines movements.

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