Development of 8x8 All-terrain Vehicle with Individual Wheel Drive

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Abstract: In this article, we consider the problem of developing a rational competitive design of a multifunctional all-terrain vehicle (MATV) with 8x8 axle configuration. Empirical dependencies are proposed to calculate weight-size parameters of these vehicles, such as power and power-to-weight ratio, payload, maximum speed, average ground pressure depending on full vehicle weight. Key dependencies are provided to calculate hydrostatic transmission (HST) parameters used to determine hydraulic unit sizes and connection diagrams. Various HST control algorithms are analyzed in order to increase efficiency and reduce fuel consumption. The results show that the right HST control algorithm can increase efficiency by 10%, and reduce fuel consumption by 18%. General view of the developed MATV is provided.

1 INTRODUCTION

Most of the Russian territory is characterized by rather poor road infrastructure. These un- and underdeveloped areas are hard to reach but very promising in terms of mineral and hydrocarbon production. A study shows that individuals and companies in Russia purchase around 700 – 750 new vehicles annually. The market is dominated by 4x4 and 6x6 all-terrain vehicles. 8x8 modifications account for just 20% of all sales, but they are as good off-road as tracked vehicles, and less destructive to the tundra soil. Individual wheel drive and the right control algorithms for each wheel ensure the best cross-country abilities, highest efficiency and lowest emissions.

Therefore, in this article we consider the problem of developing a rational competitive design of a 8x8 vehicle with individual wheel drive. Possible algorithms for power distribution flow control in hydrostatic transmission are analyzed.

2 CALCULATION OF WEIGHT-SIZE PARAMETERS

We have analyzed the key parameters of current multiaxial all-wheel drive vehicles with 8x8 axle configuration and obtained basic relations for weight, power and speed characteristics (Barahtanov et al., 2015) Table 1 contains regression equations for all-terrain vehicles, trucks and special purpose vehicles.

Recommended parameters for the developed all-terrain vehicle are listed in Table 2. Full vehicle weight served as an initial parameter. The reason for such choice is that all-terrain vehicles with 8-9 t full weight have an insignificant market share in Russia.

All analogs of the developed multiaxial vehicle on ultra low pressure tires are equipped with manual transmission (reducers, cardan shafts, etc.) But it is not enough for cross-country conditions. Such vehicles require infinitely variable automatic transmission combining individually regulated power actuators for each wheel with automatic control system. Efficient torque adjustment helps each wheel to achieve maximum traction on low-load-bearing capacity soils. Skid control system for each wheel ensures maximum traction force and minimum road resistance.

Current multiaxial wheeled vehicles are equipped with electromechanical (for example, NEMTT-AZ by Oshkosh, 6x6 multipurpose vehicle by QinetiQ, 8x8 experimental prototype BAZ-M6910E) and hydrostatic transmission (HST). The best-known Russian vehicle with hydrostatic transmission is three-axle vehicle «Gidrohod-

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Table 1: Regression equations for design parameters of 8x8 vehicles.

Dependencies	Vehicle type	Formula
Engine power from full vehicle weight, [kW - t]	All-terrain	Pe = 15 Ma + 13
	Trucks	Pe = 4 Ma + 135
	Special purpose	Pe = 13 Ma + 21
Power-to-weight ratio from full vehicle weight, [kW/t - t]	All-terrain	pe = 27-5 ln(Ma)
	Trucks	
	Special purpose	
Payload from full vehicle weight, [t - t]	All-terrain	Mг = 0,3 Ma
	Trucks	Mг = 0,8 Ma - 9,1
	Special purpose	Mг = 1
Maximum speed from full vehicle weight, [km/h - t]	All-terrain	Va = 38 Ma0,3
	Trucks	Va = 80
	Special purpose	Va = 38 Ma0,3
Average ground pressure from full vehicle weight, [kPa - t]	All-terrain	p = 0,6 Ma + 5,4
	Trucks	p = 1,.3Ma + 25,1
	Special purpose	p = 1,6 Ma + 14

49061» developed by the Central Scientific Research Automobile and Automotive Engines Institute «NAMI» (Belyakov et al., 2018). In Russia, the most common type of infinitely variable automatic transmission is hydrostatic transmission.

Table 2: Recommended vehicle parameters.

Parameter	Recommended value
Full weight, t	8-9
Payload, t	min. 3
Power-to-weight ratio, kW/t	max. 15
Maximum speed, m/s	min. 70
Average ground pressure, kPa	10.2-10.8

3 MATHEMATICAL MODEL OF THE VEHICLE WITH HYDROSTATIC TRANSMISSION

HST parameters are determined basing on the traction-speed calculation. The ability rating is calculated from the following dependence (Belyakov et al., 2018):

$$D_{\max} = \frac{\sum M}{G_a r_{\text{кс}}} = \frac{i_{\text{рм}} \eta_{\text{рм}} \left[\left(p_{\text{н}}^{\max} - p_{\text{п}} - \Delta p_{\text{пот}} \right) q_{\text{м}}^{\max} \eta_{\text{мм}} \right] z_{\text{м}}}{2\pi 10^2 G_a r_{\text{кс}}}$$

vehicle speed is calculated from the formula (Belyakov et al., 2018):

$$V_{\text{к}\max} = 0.377 \frac{\omega_{\text{e}\max} z_{\text{н}} q_{\text{н}}^{\max} \eta_{V\text{н}}^{P_{w\max}} r_{\text{кс}}}{i_{\text{рн}} i_{\text{рм}} \left(2 - \eta_{V\text{н}}^{P_{w\max}} \right) z_{\text{м}} q_{\text{н}}^{\min}}$$

where V – vehicle speed; $Z_{\text{н}}$; $Z_{\text{м}}$ – number of pumps, motors; ω_e – angular velocity of the motor; $q_{\text{н}}$; $q_{\text{м}}$ – pump volume, motor volume; $r_{\text{кс}}$ – rolling radius; $p_{\text{н}}$ – pump pressure; $\Delta p_{\text{пот}}$ – pressure drop in the hydraulic circuit; $p_{\text{п}}$ – charge pressure; $G_{\text{а}}$ – vehicle weight; $i_{\text{рн}}$, $i_{\text{рм}}$ – pump, motor reducer ratios, $\eta_{\text{рп}}$; $\eta_{\text{н}}$, $\eta_{\text{м}}$, $\eta_{\text{рм}}$ – efficiency factor of pump reducer, pump, motor, motor reducer.

Calculation results helped to define typical sizes of hydraulic units and connection schemes (SHuhman et al., 2007). We have selected a hydrodifferential scheme with individual control, two 125 cm3 pumps and eight 107 см3 motors. Transmission scheme is shown in Figure 1.

A Matlab/Simulink model has been developed for initial HST configuration and adjustment. The basic equations for hydraulic unit parameters are given below.

For the pump:

– torque $T_{\text{н}} = p_w q_{\text{н}} \left(2\pi\eta_{\text{н}} \right)^{-1}$,

– discharge $Q_{\text{н}} = q_{\text{н}} \omega_{\text{н}} \eta_{V_{\text{н}}}$.

For the motor:

– torque $T_{\text{м}} = p_w q_{\text{м}} \eta_{\text{м}} \left(2\pi \right)^{-1}$,

– discharge $Q_{\text{м}} = q_{\text{м}} \omega_{\text{м}} \eta_{V_{\text{м}}}^{-1}$.

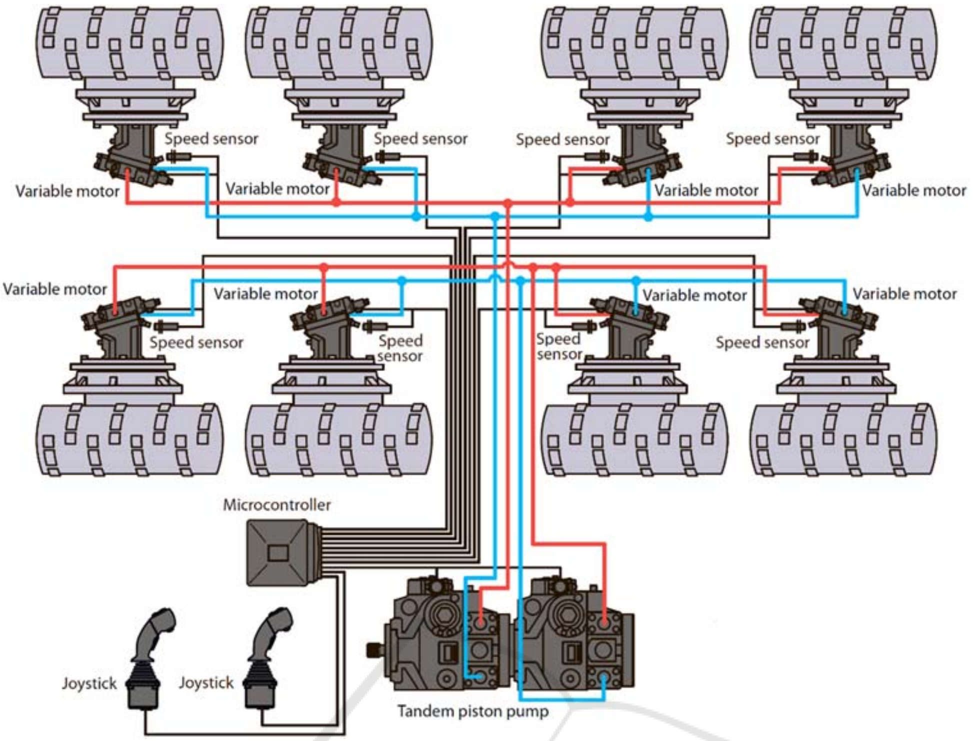

Figure 1: Structural transmission scheme.

p_w – pressure drop of the working fluid in pumping and draining lines of hydraulic units, $\eta_{V_{\text{н}}}$, $\eta_{V_{\text{м}}}$ – volume efficiency factor of the pump and the hydraulic motor.

Torque distribution on motor shafts is calculated from the following formula (Belyakov et al., 2018):

$$T_{\text{м}1} : T_{\text{м}2} : T_{\text{м}3} : \ldots \approx q_{\text{м}1} : q_{\text{м}2} : q_{\text{м}3} : \ldots$$

Angular velocities of hydraulic motors are calculated from the dependence (Belyakov et al., 2018):

$$Q_{\text{н}} \approx q_{\text{м}1}\omega_{\text{м}1} + q_{\text{м}2}\omega_{\text{м}2} + q_{\text{м}3}\omega_{\text{м}3} + \ldots$$

Torque from the hydraulic pump applied to the drive wheel is used to overcome rolling resistance, accelerate the wheel and implement traction. The general equation of wheel dynamics is given below:

$$I_k \cdot \dot{\omega}_k = T_{\text{м}} i_{\text{м}} \eta_{\text{м}} - T_{\text{сопр}}$$

The rotation resistance torque is determined by the rolling resistance torque and the torque generated by the tangential component of the wheel-soil interaction force:

$$T_{\text{сопр}} = T(R_z) + T(R_x).$$

A model from the works (SHuhman et al.,2007); (Belousov et al., 2013); (Kurmaev, 2009) served as a basis for HST operation model for multiaxial vehicle.

The calculations presented above make it possible to analyze the HST parameter control algorithms in order to achieve maneuverability, cross-country ability and power efficiency targets in off-road conditions reflecting the factors that influence vehicle operational parameters. Slip control ensures maximum traction force and minimum rolling resistance.

To select rational settings for HST control system, we have analyzed various control algorithms (Lepeshkin, 2012); (Gorelov et al., 2012); (Kotiev et al., 2012); (Gorelov et al., 2011); (Serebrennyj, 2009):

- slip control algorithm for the side wheels based on the known linear velocity of MATV chassis' center of inertia;
- «high-threshold» control algorithm for the side wheels of MATV chassis (with angular acceleration limitation);
- slip control algorithm based on the average rotation velocity of MATV chassis' side wheels.

We have simulated MATV movement on various surfaces and performed virtual tests on high adhesion roads followed by low adhesion roads, and tests on high adhesion surfaces with alternating low adhesion surfaces. The most challenging surface for HST control system is the «mixed» road surface with random parameter setting. For simulation, we have set a combination of snow and soil surfaces with characteristics assigned according to the normal law of distribution. Examples of wheel slip changes for MATV simulation w/o control system (on the left) and w/ control system (on the right) are indicated in Figure 2. Changes in efficiency, power demand and fuel consumption for MATV simulation w/ control system are shown in Figure 3.

The curves in Fig. 2 and 3 show that implementation of control system reduces slipping, increases efficiency, and cuts power loss related to movement and fuel consumption. In this case, the most relevant characteristics are efficiency and fuel economy. Now we shall determine which control algorithm is more suitable for the developed MATV.

4 EFFICIENCY AND FUEL ECONOMY EVALUATION

To evaluate power efficiency, we use the value equal to the ratio of «effective» traction work applied to the wheels to the «performed» work of

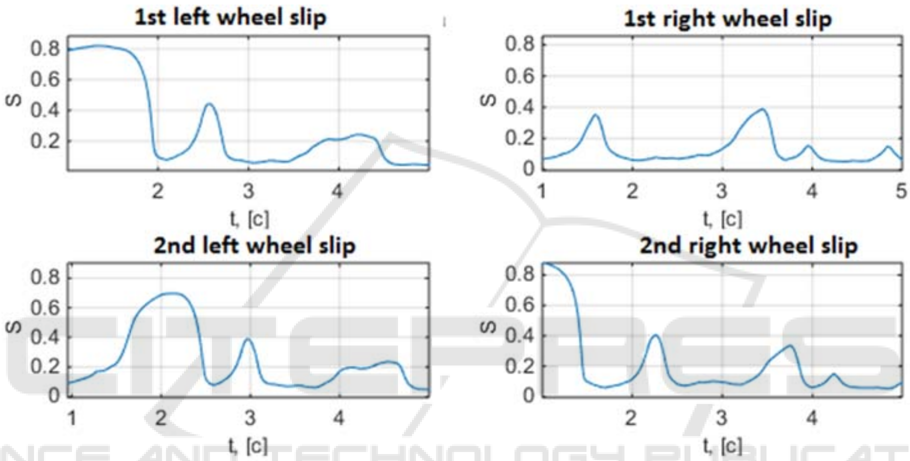

Figure 2: Examples of wheel slip curves for MATV simulation w/o control system (on the left) and w/ control system (on the right).

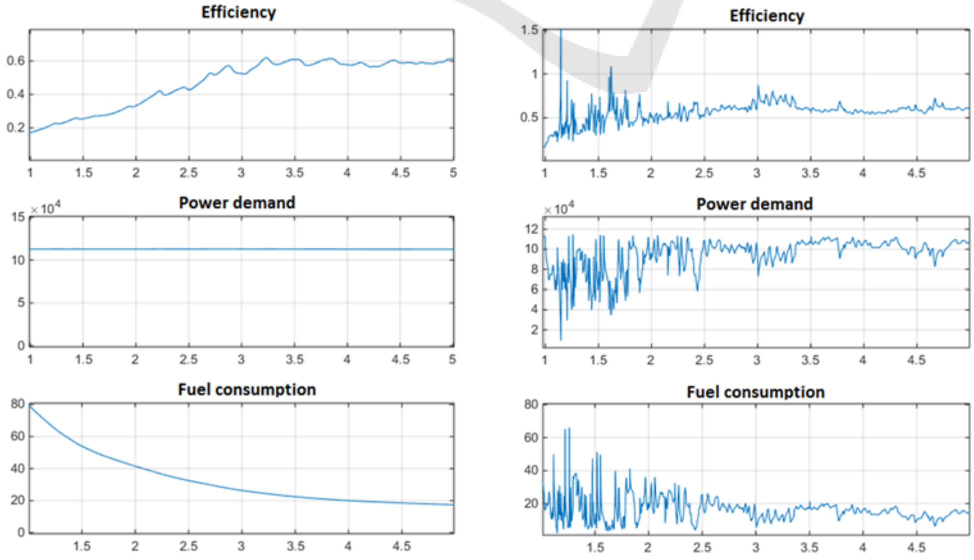

Figure 3: Examples of efficiency, power demand and fuel consumption curves for MATV simulation w/o control system (on the left) and w/ control system (on the right).

the input torque.

Efficiency of MATV wheel drive control algorithms should be estimated in HST operation simulation w/o the parameter control system. This will ensure qualitative assessment.

Since the estimated parameters take on different values at any time, they should be considered as an integrated measure in the course of vehicle movement. Otherwise, dependencies for the variable processes will be defined based on the following dependencies:

– for efficiency

$$K_{\text{эф}}^{\text{инт}} = \int_T K_{\text{эф}}\, dt$$

where $k_{\text{эф}}$ – efficiency factor at any time, T – total movement time.

– for fuel economy

$$Q_{\text{эф}}^{\text{инт}} = \int_T Q\, dt$$

Changes in efficiency and fuel consumption on the «mixed» road surface w/ HST control system using different control algorithms are presented on the diagram in Fig. 4.

5 DATA ANALYSIS

Basing on the results of computer simulation, we can judge the efficiency of the developed control algorithms for the hydrostatic wheel drive. The higher variability of the surface parameters, the higher the HST control system efficiency. For example, for step change of the parameters typical for the high adhesion surface followed by a low adhesion area, increase in efficiency and drop in fuel consumption amount to just tenths of a percentage point. For the high adhesion surfaces with alternating low adhesion surfaces, efficiency is increased by 3-5 %, and fuel consumption is reduced by 8-14 % depending on the selected control algorithm. For the «mixed» surface, efficiency is increased by 5-10 %, and fuel consumption is decreased by 11-18 % depending on the selected control algorithm.

It should be noted that for actual operating conditions of MATV the most suitable surface is the «mixed» one. It means that the developed control algorithms will not just boost maneuverability, but also increase HST efficiency by 10% and reduce fuel consumption by 18%.

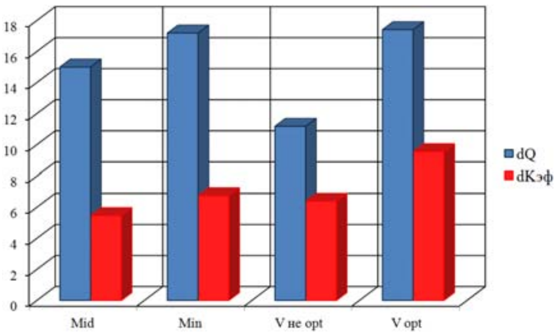

Figure 4: Incremental efficiency factor and decremental fuel consumption diagram for the «mixed» road surface w/ HST control system using different control algorithms.

Figure 5: General view of MATV.

6 PRACTICAL IMPLEMENTATION

The calculations served as a basis for MATV development. General view of the vehicle (Belyakov et al., 2018);y(Belyakov et al., 2015) is presented in Fig. 5. The technical characteristics correspond to the calculations. The vehicle will be manufactured by LLC Transmash (http://www.transmashnn.ru/).

7 CONCLUSIONS

- layout schemes and design options for 8x8 vehicles have been analyzed.
- statistical dependencies for multiaxial vehicles, boundaries of rational parameters for development of a competitive MATV have been obtained: full weight 8-9 t, min. payload 3 t, max. power-to-weight ratio 15 kW/t, average ground pressure 10.2-10.8 kPa.
- implementation of infinitely variable hydrostatic transmission in the Russian vehicles has been

motivated.

- various HST control algorithms have been analyzed: algorithm based on the known linear velocity of center of inertia, «high threshold» algorithm for the side wheels of MATV chassis (with angular acceleration limitation), algorithm based on the average rotation velocity of the side wheels.
- the results have showed that depending on the selected control algorithm and operating conditions, efficiency increases by 10 %, and fuel consumption falls by as much as 18 %.
- theoretical research presented in the paper has been implemented in the MATV manufactured by LLC Transmash.

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