Selection of the combat vehicle individual wheel drive operation modes under required mobility criteria

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Abstract. With the development of the electric drive systems and vehicle on-board power sources the development of the combat vehicles with individually driven wheels is becoming a promising area. In the presented article, the authors illustrate an approach to selection of the requirements for power plants of such vehicles by an example of an 8x8 combat vehicle with full weight of 25 t. The approach is based on the use of the real-time driving simulator allowing the operator to drive the vehicle along typical routes and gather statistical data on the operation modes of the electric motors in the conditions close to the real operation conditions. The virtual driving for this purpose is performed along the routes which are generated from the known statistical data on the excitation inputs during the vehicle motion. The collected data can be used for the selection of the electric motor mechanical characteristics providing given mobility criteria of the vehicle and for the statement of the requirements for new electric motor specifications which would provide its most effective use on the vehicles being developed.

1. Introduction

The need to increase the mobility of the combat vehicles inevitably directs engineering teams towards experimenting with electric transmissions.

It is known that the operation of an electric motor is characterized by modes differing in duration, torque, rotor speed, currents, voltage, etc. In well-known applications (urban transport, conveyor drives, elevators, traction drives of the quarry machinery, etc.) the modes are standardized or converted to standardized ones. In the case of the traction drive of combat vehicles, the selection of the long and short-term modes of operation at the design stage in statistically specified driving conditions to ensure the required level of mobility is not possible without the use of mathematical modeling methods.

To solve this problem, a real time driving simulator was created. It using a mathematical model of the dynamics of flat curvilinear motion of a wheeled vehicle [1-11] which allows to simulate motion in "real time" on a computer controlled by a human (driver-operator).
2. Driving Simulator

In the mathematical model [5], the authors consider the wheeled vehicle as a solid body moving in the horizontal plane on a planar undeformed ground surface. The motion of the wheeled vehicle is the result of the translational motion of its center of mass and the rotational motion around the center of mass (figure 1). The principle of virtual displacements is used in the model to account for the redistribution of normal reactions from the action of the air resistance force, rolling resistance moments, acceleration of the center of mass and gravity. The wheels interact with the ground by means of an unilateral constraint.

![Figure 1. Planar motion of the wheeled vehicle.](image)

In accordance with the presented diagram of the vehicle motion (figure 1), the system of equations describing the planar motion of the wheeled vehicle has form (1). This system allows calculation of the current acceleration of the center of mass from the values of the forces and moments acting on the vehicle.

\[
\begin{align*}
    a_x &= \frac{dv_x}{dt} - \omega_y v_y = \frac{1}{m} \left( \sum_{i=1}^{n} R_{x,i} - P_w \right) \\
    a_y &= \frac{dv_y}{dt} + \omega_x v_x = \frac{1}{m} \left( \sum_{i=1}^{n} R_{y,i} \right) \\
    J_z \frac{d\omega_z}{dt} &= \sum_{i=1}^{n} M (R_{zi}) - \sum_{i=1}^{n} M (R_{xi}) - \sum_{i=1}^{n} M_{epi} \sin(\theta) + v_y \cos(\theta), \\
    v' &= \frac{dx'}{dt} = v_x \cos(\theta) - v_y \sin(\theta) \\
    v_y' &= \frac{dv_y'}{dt} = v_y \sin(\theta) \\
    \omega_z &= \frac{d\theta}{dt} \\
\end{align*}
\]
where \( m \) is the vehicle mass; \( J_z \) is the vehicle mass moment of inertia relative to the z-axis passing through the center of mass; \( a_x, a_y \) are the projections of the vehicle center of mass acceleration onto the \( x \) — and \( y \)-axes; \( v_x, v_y \) are the projections of the vehicle center of mass velocity onto the \( x \) — and \( y \)-axes; \( v'_x, v'_y \) are the projections of the acceleration of the vehicle center of mass onto the \( x' \) — and \( y' \)-axes; \( \frac{dv_x}{dt}, \frac{dv_y}{dt} \) — projections of the relative derivative of the velocity vector of the vehicle center of mass onto the \( x \) — and \( y \)-axes; \( \omega_z \) is the projection of the angular velocity vector of rotation of the vehicle onto the vertical z-axis; \( \theta \) is the rotation angle, in the fixed coordinate system; \( x', y' \) are the coordinates of the vehicle mass center in the coordinate system \( x' - y' \); \( R_{x_i}, R_{y_i} \) are the longitudinal and lateral components of the reaction acting at the contact patch of the \( i \)-th wheel; \( P_e \) is the projection of the air resistance force onto the \( x \)-axis; \( M_{cpi} \) is the moment of resistance to rotation of the contact patch of the \( i \)-th wheel around a vertical axis passing through the patch center; \( n \) is the number of the vehicle wheels.

The force of interaction between the wheels and the ground in the base plane is determined by an approach based on the concept of "friction ellipse", according to which the force of interaction with the support surface is directed opposite to the sliding velocity [12, 13, 14].

The connection of the steering angle with the steering angles of the driven wheels is carried out "according to Ackerman" [15], taking into account the gear ratio of the steering mechanism.

The following system of equations describes the connection of the drive motor torque of each wheel with the value of the control parameter and the rotor speed:

\[
M_d(\omega_{ed}, h) = \begin{cases} 
M_{ed}^{max} \cdot h, & \text{если } \omega_{ed} < N_{ed}^{max} / M_{ed}^{max} \text{ и } \omega_{ed} \geq 0 \\
N_{ed}^{max} / M_{ed}^{max} \cdot \omega_{ed}, & \text{если } \omega_{ed} \geq N_{ed}^{max} / M_{ed}^{max} \text{ и } \omega_{ed} < \omega_{ed}^{max} \\
0, & \text{если } \omega_{ed} \geq \omega_{ed}^{max} 
\end{cases}
\]

(2)

where \( M_{ed}^{max} \) is the maximum traction/braking torque generated by the motor; \( N_{ed}^{max} \) is the maximum traction/braking power of the motor; \( \omega_{ed}^{max} \) is the limit rotation frequency of the rotor; \( \omega_{ed} \) is the current rotation frequency of the rotor; \( h \) is the the value of the control parameter (\( h \in [-1, 1] \)).

Figures 2 and 3 show the driving simulator layout and its graphical interface.

In order to get statistical data on the drive motor operation in conditions of long and short duration a lot of numerical experiments with the use of the driving simulator must be carried out. These experiments consist of simulation runs of the wheeled vehicle model for stochastically generated roads in typical operation conditions performed by an operator or by a group of operators.

The roads are generated by means of the mathematical statistics methods with the use of the known stochastic characteristics (correlation functions) of the model inputs affecting the dynamical behavior of the wheeled vehicle. Based on the stochastic data on the road curvature \( k, \) maximum road friction \( \mu_{s,max}, \) coefficient \( \psi \) of the total motion resistance these parameters are distributed along the road by the non-canonical decomposition [16, 17, 18, 19]. Figure 4 shows an example of the driving route generated from the realization of the random function of the road curvature \( k, (s) \).
Figure 2. Driving simulator layout:
1,2 — controls; 3 — graphic information output station

Figure 3. Graphical output of the driving simulator
3. Selection of the required mechanical characteristics of the electric motors

The driving simulator provides statistical data on the operation modes of the electric motors. This data can be used for selection of the mechanical characteristics of the electric motors of the combat vehicles with individual wheel drive.

A wheeled vehicle with gross mass of 25 t (figure 5) is used as an example. Technical specification of the vehicle is shown in table 1.

| Parameter                                    | Value          |
|----------------------------------------------|----------------|
| Gross mass, kg                               | 25000          |
| Wheelbase, mm                                | 4625           |
| Track width, mm                              | 2500           |
| Height of the center of mass, mm             | 1400           |
| Inertia moment about the central vertical axis, kg m² | 57580          |
| Loaded tire radius, mm                       | 630            |
| Steering system configuration                | 12-00          |
| Wheel width, mm                              | 500            |
| Powertrain type                              | Individual electrically driven wheels |
| Total number of electric motors              | 8              |
| Maximum speed, km/h                          | 120            |
| Air drag coefficient                         | 0.7            |
| Frontal projection area, m²                  | 5.3            |
| Height of the center of pressure, mm         | 1700           |
The speed — torque characteristic of the electric drive providing the pre-defined mobility is selected from the results of the simulation of the vehicle operation on typical roads.

For this purpose the maximum power of the electric drive is changed iteratively (for instance by the bisection method) until the power providing the required average speed of the vehicle is found.

As the initial approximation for simulation, the drive motor reference torque — speed curve (figure 6) providing the pre-defined tractive effort of the vehicle was analytically found, and the gear ratios of the transmission in driving and technological gear ranges were selected 11.88 and 18.81 respectively. The vehicle was assumed to be equipped with a two-range transmission. The purpose of the driving gear range is to provide the maximum speed and the purpose of the technological gear range is to provide the maximum tractive effort on the wheels [20].

Figure 7 shows the tractive effort to weight ratio — speed curve of the 8x8 vehicle (for the case of the drive motor with the torque — speed curve shown in figure 6). The mechanical efficiency the transmission was assumed to be 0.95.

Next, in order to calculate the maximum power and torque — speed curve of the drive motor providing the pre-defined mobility criterion during the vehicle operation the driving simulator is used.

![Figure 6. Drive motor theoretical torque — speed curve providing tractive effort of the 8x8 vehicle.](image)

![Figure 7. Tractive effort to weight ratio — speed curve of the 8x8 vehicle.](image)
At the first stage, the electric motor maximum power variation range is selected based on the reference torque — speed curve of the motor: from the minimal value (initial power $N_e^{rd}$) providing given maximum speed to the maximum attainable value $N_e^{\text{MAX}}$ defined by the limitations on the maximum torque of the motor and maximum rotational speed of its rotor (figure 8).

![Figure 8. Electric motor maximum power variation range.](image)

In the resulting range, several power levels are selected, for each of which the virtual tests are carried out in different road conditions.

To illustrate this, let us consider the results of the simulation runs for the 8x8 vehicle obtained on the macadam road. The dependence of the average speed of the vehicle on this road on the utilized portion of the maximum power of the electric drive is shown in figure 9.

![Figure 9. The dependence of the average speed of the vehicle on the utilized portion of the maximum power of the electric drive on the macadam road](image)
The distribution of the electric drive operation modes, as well as the distribution functions of power, torque and angular velocity of the rotor of the electric motor in the traction mode, for one of the performed simulation runs are shown in figure 10, where:

a) distribution of the electric drive operation modes (the modes with relative duration lower than 5% of the simulation time are discarded);

b) electric drive traction power distribution function;

c) distribution function of the electric drive torque;

d) distribution function of the angular velocity of the rotor.

These results show that with the growth of the maximum power of the electric drive, the probability that the vehicle would use the external speed — torque curve of the electric motor during its motion decreases. When the probability of using the external speed — torque curve of the electric motor is reduced to ~50-60%, the increase in the average speed becomes insignificant. Thus, when the 8x8 vehicle drives on a macadam road there is no reason to make the electric drive motor power higher than 96 kW (power-weight ratio is 30.6 kW/t).

The distribution functions of torque and rotor angular velocity for the selected maximum power level determine the torque — speed characteristic of the electrical motor and the distribution of the electric drive operation modes in the traction mode define the region of the motor high efficiency (figure 11).
The max torque in operating conditions of long duration is lower than the torque having the probability of 90% (in our example this torque equals 448 Nm). The maximum power in both cases is limited by the calculated value of 95.6 kW. The maximum continuous output of the drive motor during operation with the maximum rotor speed $\omega_{ed}^{\max}$ corresponds to the calculated power $N_{emax}^{rd} = 45.6$ kW providing the maximum speed of the straight-line motion of the vehicle. The rotor speed after which the motor output power can be lowered corresponds to the maximum rotor speed having probability of 90% (in our example 304 rad/s).

The dependence of the average speed of the vehicle on different roads on the utilized portion of the maximum power of the electric drive is shown in figure 12.
Figure 12. Dependancy of the average speed of the 8x8 vehicle on the utilized portion of the maximum output power of its drive motors for different types of terrain

This data show that when the 8x8 vehicle moves on these types of terrain there is no reason selecting the output power of its drive motors higher than 95.6 kW.

The simulation provided the required torque — speed curves of the drive motor for each type of the terrain. For convenience, the curves are schematically shown in figure 13 and in table 2.

Figure 13. Schematic torque — speed curves of the drive motor for operating conditions of long and short duration

The figure uses the following nomenclature:

- \( N_{e\text{max}}^{\text{short}} \), \( N_{e\text{max}}^{\text{long}} \) is maximum output power of the drive motor in conditions of short and long duration respectively;
- \( M_{e\text{max}}^{\text{short}} \), \( M_{e\text{max}}^{\text{long}} \) is maximum output torque of the drive motor in conditions of short and long duration respectively;
- \( \omega_{ed}^{\text{max}} \) is the maximum rotor speed of the drive motor;
\( \omega_{ed}^{c} \) is the drive motor rotor speed after which the maximum output power of the motor can be lowered. \( N_{e}^\max \) is the motor power providing the maximum velocity on a rigid road.

**Table 2.** Parameters of the torque — speed curves of the 8x8 vehicle motors on different roads

| Terrain index | \( N_{e_{\text{max}}}^\text{short} = N_{e_{\text{max}}}^\text{long} \) kW | \( M_{e_{\text{max}}}^\text{short} \) Nm | \( M_{e_{\text{max}}}^\text{long} \) Nm | \( \omega_{\text{ed}}^\max \) rad/s | \( \omega_{\text{ed}}^c \) rad/s | \( N_{e_{\text{max}}}^\max \) kW |
|---------------|-------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 1             | 95.6              | 448             | 484             | 304             | 259             | 45.6            |
| 2             | 95.6              | 796.1           | 484             | 628             | 285             | 45.6            |
| 3             | 95.6              | 484             | 547             | 230             |                 |                 |
| 4             | 95.6              |                 |                 |                 |                 |                 |

1 — macadam road  
2 — dry smooth soil road  
3 — bumpy soil road  
4 — wet soil road

Thus the resulting torque — speed curve in conditions of long and short duration for the 8x8 vehicle is the sum of the torque — speed curves for every road taken with weighting factor depending on the probability of operation on the road.

The resulting torque — speed curve of the drive motor is shown in figure 14 and in table 3 (power to weight ratio 30.6 kW/t).

![Figure 14. Resulting torque — speed of the 8x8 vehicle drive motor.](image)

**Table 3.** Parameters of the resulting torque — speed of the 8x8 vehicle drive motor in conditions of long and short duration

| \( N_{e_{\text{max}}}^\text{short} \) kW | \( M_{e_{\text{max}}}^\text{short} \) Nm | \( M_{e_{\text{max}}}^\text{long} \) Nm | \( \omega_{\text{ed}^\text{max}} \) rad/s | \( \omega_{\text{ed}^c} \) rad/s | \( N_{e_{\text{max}}}^\max \) kW |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 95.6            | 796.1           | 473.8           | 628             | 278.5           | 45.6            |
4. Conclusions

The simulation has shown that the average speed of the vehicle saturates at a certain level of the maximum output power of the drive motor and then remains constant or rises insignificantly. This result allows selecting maximum reasonable output power of the drive motor for a vehicle designed to operate on a pre-defined road or a group of roads.

During the simulation, the 8x8 vehicle operated in the running-down mode during considerable time and almost never braked using its drive motor in the generator mode or with its mechanical brakes. This can be explained by the fact that the maximum speed was limited by the vehicle stability condition. Further rise of the average speed can be provided by more frequent braking, which implies a higher qualification of the driver, or by using a dynamic stability control system to prevent skidding, anti-lock braking system and traction control system.

The stochastic data obtained during the simulation was used for selection of the torque — speed curve of the electric motor operating in conditions of long and short duration. In conditions of long duration the maximum required output power of the electric motor can be selected lower in the region of the torques and rotor speeds the probability of which is not less than 90 %. Maximum output power of the electric motor can be selected such that the probability of the motor to be operating on the external torque — speed curve when the vehicle moves on a pre-defined road or on a group of roads is 50–60 %.

The analysis has also shown that the electric motor operates in the region of average speeds at the maximum output power, which requires the motor to have a high efficiency in this region of the torque — speed curve.

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