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Determinaton of mechanical characteristics of high-speed tracked vehicles traction motor with individual drive wheels

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Abstract. The paper describes the study of electromechanical transmission of tracked vehicles with individual drive wheels. The scheme and analytical dependencies for traction calculation of tracked vehicles are considered. A system of equations that describe a plane motion is given. The required traction characteristics have been built to ensure maximum mobility of tracked vehicles. A developed complex of natural-mathematical modeling, made on the basis of a mathematical model that allows operating in a real time mode is presented. It gives an opportunity to collect statistics of the operating modes of the onboard electric motors and analyze the loading modes. To confirm the theoretical studies, a prototype of a tracked vehicle was developed, which allows determining the torques on the drive shafts of the sides, the rotational speeds of the drive wheels, the longitudinal and lateral accelerations of the hull, the machine’s angular velocity around the vertical axis.

Currently, the scheme of electromechanical transmission (EMT) tracked vehicles (TV) with individual drive wheels is the most common and is widely used in mobile robots, as well as on TV of ultra-light category. It can also be one of the operating modes of more complex parallel EMT, for example, in hybrid transmission options. The prospect of this scheme utilization is possibility of its use in the drive of articulated TV for the case of separate movement of sections. In addition, an individual drive wheel unit can be used in the transmission of wheeled vehicles (WV), for example, to improve turning.

The most difficult mode of movement of high-speed TV with this transmission scheme is turning. When moving along a curved trajectory in a TV with an individual electric wheel drive, up to 100% of the total power (required for straight-line movement of the entire machine) through the traction motor (TM) of the same side is used. Besides, a braking force on the electric machine of the lagging side is created by switching to generator mode. To increase the average speeds, it is necessary to ensure that the TV can turn at speeds, close to critical for drift. Thus, it is necessary that TM of the running side has the ability to provide large torques and powers at a wide range of rotational frequencies, which leads to an increase in its size and mass. That is, for rectilinear motion, such a transmission is oversized.

It is possible to determine the required powers at the driving wheels of the lagging and running sides of a TV, when we have to ensure the actual turning radius \( R_f \), if we drive at speed \( V \), and if we use well-known analytic dependencies (Table 1). The calculation scheme is shown at Figure 1.
As can be seen from the presented methodology, to ensure accuracy of the calculation, it is necessary to know value of the proportionality coefficient $k$ between the actual and theoretical turning radius, as well as the current value of the coefficient of resistance to rotation $\mu$. As is known the calculation formula by A.O. Nikitin was experimentally obtained for the existing TV, and at the same time, the coefficient of proportionality $k$, is a function of speed, it becomes clear that existing analytical methods for studying stationary motion and traction calculations do not provide the ability to conduct research when moving at speeds close to critical with the required accuracy. In addition, the presented analytical dependencies do not allow us to estimate stability and controllability of TV. So, to enable analysis of non-stationary modes of motion of TV, it is advisable to use simulation mathematical models that allow computer experiments to be carried out.

In the developed simulation mathematical model [4], dynamics of a TV is considered as motion of a solid body in a horizontal plane of a flat non-deformable bearing surface and is made up of a translational and rotational motion of the centre of mass (Figure 2). The connection of the support rollers (SR) with TV casing in the vertical plane is considered as hard, that is, without taking into account the elastic properties of the suspension. However, the model takes into account the redistribution of normal reactions under the active track sections from the action of air resistance force, moments of resistance to TV rolling accelerating the centre of the masses.
Table 1. Analytical methodology for TV thrust calculation

|   | Analytical methodology for TV thrust calculation                                                                 |
|---|----------------------------------------------------------------------------------------------------------------|
| 1. | Determination of a theoretical radius of turning $R_t$:                                                        |
|    | $R_t = R_f \frac{B}{k \cdot L}$ where $B$ – TV track; $L$ – TV base; $k$ – coefficient of proportionality, separate for each TV; |
| 2. | Determination of the ratio of resistance to turning $\mu$ by means of A.O. Nikitin formula [Ошибка! Источник ссылки не найден.]: |
|    | $\mu = \frac{\mu_{\text{max}}}{0.925 + 0.15 \frac{R_t}{B}}$ Where $\mu_{\text{max}}$ – The maximum coefficient of resistance to turning for a given support base. |
| 3. | Determination of critical velocity of TV skidding $V_{cr}$:                                                    |
|    | $V_{cr} = \sqrt{\mu_{\text{max}} \cdot g \cdot R_f}$ where $g$ – acceleration of gravity |
| 4. | Determination of the required rewinding speed of the tracks of the running $V_2$ and the lagging side $V_1$:     |
|    | $V_2 = V \left(1 + \frac{B}{2R_t}\right)$; $V_1 = V \left(1 - \frac{B}{2R_t}\right)$.                        |
| 5. | Determination of the required forces on the running $P_2$ and lagging $P_1$ board [2]:                         |
|    | $P_2 = \frac{m \cdot g}{2} \left( f_{rp} \left(1 + \frac{2V^2 \cdot H_z}{B \cdot R_f \cdot g}\right) + \frac{\mu \cdot L}{2B} \left(1 - \left(\frac{V}{V_{cr}}\right)^4\right)\right)$ |
|    | $+ \frac{m \cdot V^4 \cdot L}{4 \cdot R_f^3 \cdot \mu \cdot g}$;                                             |
|    | $P_1 = \frac{m \cdot g}{2} \left( f_{rp} \left(1 - \frac{2V^2 \cdot H_z}{B \cdot R_f \cdot g}\right) - \frac{\mu \cdot L}{2B} \left(1 - \left(\frac{V}{V_{cr}}\right)^4\right)\right)$ |
|    | $+ \frac{m \cdot V^4 \cdot L}{4 \cdot R_f^3 \cdot \mu \cdot g}$;                                             |
|    | where $m$ – TV mass; $f_{rp}$ – coefficient of resistance to TV rectilinear motion for a given support base; $H_z$ – height of TV centre of mass |
| 6. | Determination of the efficiency of tracked bypass [3]:                                                        |
|    | $\eta_2 = 0.95 - 0.005 \cdot 3.6 \ V_2$; $\eta_1 = 0.95 - 0.005 \cdot 3.6 \ V_1$;                            |
| 7. | Determination of the required power at the driving wheels of the running and lagging sides.                    |
|    | $N_2 = \frac{P_2 \cdot V_2}{\eta_2}$; $N_1 = \frac{P_1 \cdot V_1 \cdot \eta_1, if P_1 < 0}{\eta_1}$, if $P_1 > 0$ |

In accordance with the presented calculation scheme (Figure 2), the system of equations describing the plane motion of TV has the following view (1). This system allows to calculate current acceleration of the centre of mass of the values of forces and moments acting on TV.
where: $m$ is mass of the TV; $J_z$ is moment of inertia of the TV related to the vertical axis $z$; $a_x$, $a_y$ are projections of TV centre of mass acceleration on the xy axis; $\omega_z$ – projection of the angular velocity vector of TV turning on the vertical axis $z$; $\theta$ – is angle of rotation of TV in a fixed coordinate system; $v_{x'}$, $v_{y'}$ – are coordinates of TV centre of mass in the coordinate system of $x'$ – $y'$; $R_{y_i}$ – lateral reaction acting on the active track under the i-th roller; $P_w$ – projection of the air resistance force vector on the x-axis of the $x$ – $y$; $M_{cn_i}$ – system is moment of resistance to rotation of the active track section under the i-th roller; $n$ – is the number of support rollers. The force of interaction with the soil of the active track section in the plane of the support base is determined using an approach based on the friction ellipse [5, 6, 7, 8, etc.], where the force of interaction between the active track section and the support surface is opposite to the sliding speed.

The developed simulation model allows to clarify the analytical dependencies for the study of stationary TV rotation when moving at speeds close to critical. To do this, coefficient of resistance to rotation by A.O. Nikitin formula [1] and the proportionality coefficient were replaced by a neural network that approximates TV simulation data with different L / B ratios, during cornering at different radii and at different speeds. A comparison of the results obtained using the refined analytical dependencies with the simulation data is presented in Figure 3. Calculations were carried out for TV-569.

\[
a_x = -\frac{\omega_z v_y}{m} = \frac{1}{m} \left( \sum_{i=1}^{n} R_{x_i} - P_w \right) \\
a_y = \frac{dv_x}{dt} + \omega_z v_x = \frac{1}{m} \left( \sum_{i=1}^{n} R_{y_i} \right) \\
J_z \frac{d\omega_z}{dt} = \sum_{i=1}^{n} M_{cn_i} - \sum_{i=1}^{n} M_{R_{x_i}} - \sum_{i=1}^{n} M_{R_{y_i}} \\
v_{x'} = \frac{dx'}{dt} = v_x \cos(\theta) - v_y \sin(\theta) \\
v_{y'} = \frac{dy'}{dt} = v_x \sin(\theta) + v_y \cos(\theta) \\
\omega_x = \frac{d\theta}{dt}
\]
Calculation of the coefficient of resistance to rotation when using a simulation mathematical model was carried out according to the formula:

\[
\mu = \frac{4}{mgL\left(1 - \left(\frac{v}{v_{cr}}\right)^4\right)} \left(\sum_{i=1}^{n} M(R_{xi}) + \sum_{i=1}^{n} M(R_{zi}) + \frac{mV^2H_{z}}{R_f} f_{gr}\right)
\]

where \(R_{zi}\)–normal reaction acting on the track active area under the i-th track roller.

The obtained results allow to estimate the maximum required moments and powers on the driving wheels of TV (Figure 4), according to which it is possible to build the required traction characteristics for maximum mobility (movement of TV in turns with a speed of 0.8\(V_{cr}\)) (Figure 5).

**Figure 4.** Results of the evaluation of the required power and traction / braking forces on the sides of TV
Figure 5. Required characteristics of TV drive side to provide possibility of movement while turning with a speed of $0.8V_{kp}$

The approach used does not allow obtaining statistical information about short-term and long-term operation modes of the TM in the process of movement, nor allows us to investigate the features of TV control with an individual drive of the sides.

To solve the set tasks, a complex of natural-mathematical modelling was created, made on the basis of an imitational mathematical model. The developed complex is able to operate in real time and allows to investigate the reaction of the machine to the control action of a person when driving on the track “played out” based on statistical data about curvature of the trajectory, coefficient of adhesion to the supporting surface (SS) and coefficient of resistance to the linear motion of TV.

To ensure the possibility of sustainable movement of TV, a regulator was developed that allows the driver to control the action (degree of accelerator / brake pedal depression and the steering wheel angle) with the parameters of TV control.

Figure 6. General view of mathematical modelling complex
The obtained statistics on the operating modes of the on-board electric motors allows to consider the loading modes taking into account short-term overloads, estimate the required high efficiency zone, determine its limiting characteristics to ensure the required average speed, and form requirements for the cooling system.

In N.E. Bauman Moscow State Technical University (BMSTU), a prototype model of TV was created, aimed at experimental research (Figure 7). The design feature is diagonal arrangement of the driving wheels, which allows to set the EMT of various kinematic schemes. The developed prototype model is equipped with a measuring complex, for recording:

- torques on the side drive shafts;
- rotational speeds of the driving wheels;
- longitudinal and transverse accelerations of TV case;
- angular velocity of TV around the vertical axis.

Results of one of the experimental trials are presented at Figure 8.

Figure 7. General view of TV prototype ($m=3000$ kg; $L/B=1.78$)

Figure 8. Results of the experimental arrival of the prototype model (turn around the stopped track)
To "eliminate" the well-known shortcomings of TV electric transmission with an individual drive of the driving wheels, BMSTU is currently carrying out EMT studies of various kinematic circuits (Figure 9).

![Figure 9. Various transmission schemes: a) electric transmission scheme with onboard electric machines; b)scheme of double-current electric transmission; c)scheme of three-way electric transmission; d)scheme of electric transmission with AC mechanism.](image)

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