IOP Conf. Series: Materials Science and Engineering 1151 (2021) 012033 doi:10.1088/1757-899X/1151/1/012033

A method for regulating modes of motion of a wheeled vehicle with installed thermal and reactive energy converters

V A Kim, I S Sazonov, O V Bilyk and E A Moiseev

Vehicle Maintenance Department, Belarusian-Russian University,43, pr. Mira, Mogilev, 212000, Republic of Belarus

E-mail: moisan@inbox.ru

Abstract. Understanding the interaction between an elastic tire and a bearing surface is important not only for studying motion of wheeled vehicles, their controllability and running smoothness, but also necessary for creating systems for car motion automatic control. At the same time, the interaction forces between wheels and the bearing surface attract special attention since they have a decisive effect on vehicle's controllability and stability. Indeed, all effects, including aerodynamic ones, are reflected in forces and moments arising in the wheel/bearing surface contact area, which, in turn, determine car motion parameters. Consequently, in creating a control system for vehicle motion, the primary task is to establish patterns of changes in force factors depending on characteristics of the bearing surface and parameters of the operator's control in order to develop a criterion for controlling signal formation. The analysis of experimental and theoretical studies of wheel rolling showed that all research results are reduced to establishing patterns of change in force factors (indirect parameters) in the wheel/bearing surface contact patch depending on the parameters that indirectly characterize the kinematic parameters. Meanwhile, establishing a regular pattern of changes in force factors in the wheel/bearing surface interface is the most important task in developing a criterion for the formation of control signals for active safety systems based on force analysis. The paper presents a method for increasing vehicle's traction and braking dynamics by partially converting thermal energy of the car into reactive tractive force (air propeller, gas turbine).

1. Introduction

The reactive force applied to a wheeled vehicle during slipping and sliding of the contact area of wheels and obtained by converting part of the thermal energy of the engine will allow maximum realization of the conditions of adhesion between vehicle tires and the bearing surface (road) and will increase the traction and braking dynamics, as well as the fuel efficiency of the machine [1].

Under braking, the reverse reactive force complements the braking force realized by the tire with the bearing surface.

2. Purpose of the research

The purpose of research was to develop a method for controlling the modes of motion of a wheeled vehicle by converting some part of the thermal energy of an internal combustion engine into the air reactive tractive force in order to increase traction and braking dynamics and ensure the stability of vehicle motion.

3. Implementation of the purpose

The results of testing the process of VAZ - 2108 car emergency braking (Figure 1) show that the braking moments realized by the wheels at the contact patch between the tires and the bearing surface decrease after reaching the maximum (points A and B).

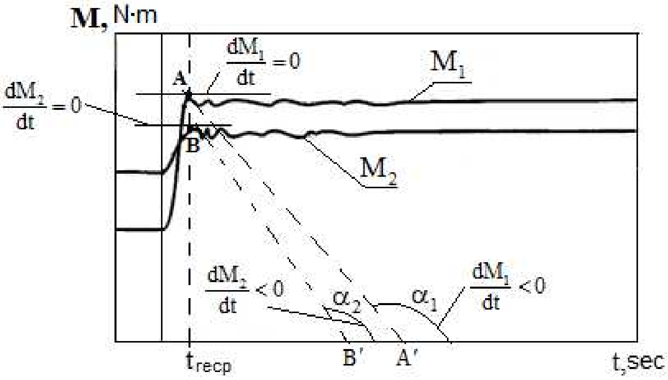

Figure 1. Test results of the process of VAZ-2108 car emergency braking.

The maximum of moments of forces is characterized by their first derivatives being equal to zero $\frac{dM_1}{dt} = 0, \frac{dM_2}{dt} = 0$. The decrease of the moments can be identified by the negative signs of their derivatives $\frac{dM_1}{dt} < 0, \frac{dM_2}{dt} < 0.$

Figure 2 shows the results of the change in the hook force of a wheeled tractor depending on the change in the slip of driving wheels [9]. It should be noted that the hook force of the tractor is proportional to the forces at the contact patch between the tractor driving wheels and the bearing surface.

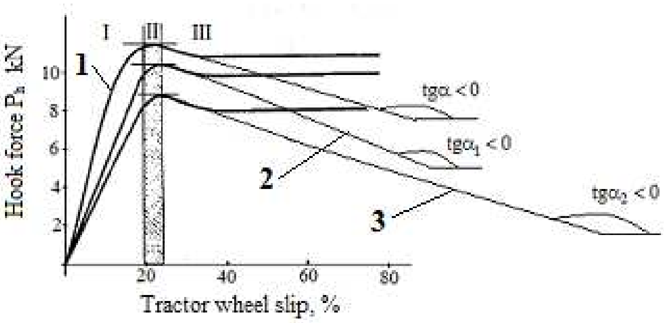

Figure 2. The results of changing the hook force of a wheeled tractor depending on the change in the slip of driving wheels: 1 - stubble field; 2 - light loam; 3 – sandstone.

Reactive tractive force can be obtained by using an air propeller driven by an electric motor powered by an electric generator of the ICE. The magnitude of the tractive force of the propeller can be calculated using the formula:

$$F_{prop} = \alpha \cdot \rho \cdot D_{prop}^4 \cdot \omega_{prop}^2 \quad (1)$$

where α is the coefficient of traction determined experimentally and it depends on the shape and number of blades, as well as on the pitch of the air propeller; ρ is the air density; D_{prop} is the propeller diameter; ω_{prop} is the angular speed of the propeller rotation [1].

The general strategy of the method for controlling the motion of the wheeled machine is schematically shown in Figure 3 and Figure 4.

The wheeled vehicle contains the skeleton of a wheeled vehicle 1, internal combustion engine 2 (ICE), transmission of the wheeled vehicle with the gearbox 3 (TRWV), brake actuator 4 (BA), vehicle's rear axle 5 (RA), rear axle shafts 6, driven wheels of the vehicle 7, driving wheels of the vehicle 8, wheel brakes 9 (WB), brake lines of the front and rear circuits 10, 11, storage battery 12 (SB), electric generator 13 (EG), source for generating a reactive force, for example, an air propeller 14, electric motor for a propeller drive 15 (EM), the unit for information processing and generating control signals by actuating mechanisms 16 (IP & GCSAM unit), sensors for measuring braking torques 17 (SBT), sensors for measuring tractive forces 18 (STF), voltage stabilizer 19 (VS),

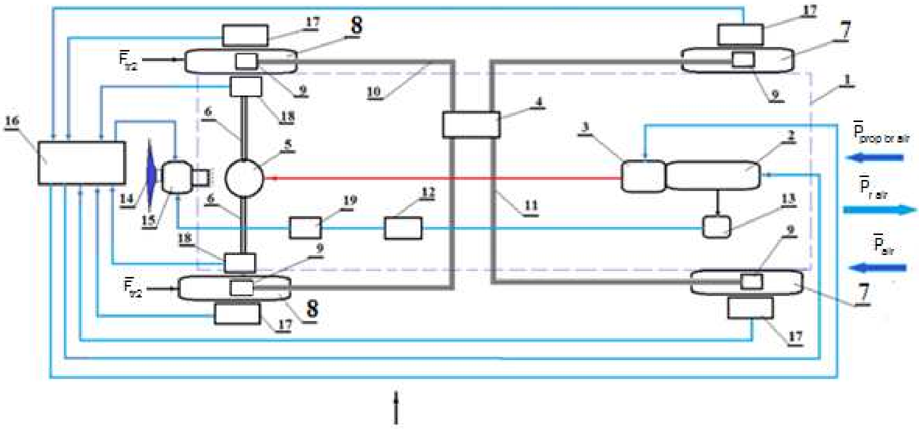

Figure 3. The diagram of the method for controlling the motion of a wheeled machine (top view).

In Figure 3, $\overline{F}_{tr2}$ is the tractive force vector created by the driving wheel; $\overline{P}_{air}$ is the force of air resistance to the vehicle motion; $\overline{P}_{prop\ air}$ is reactive tractive force; l, a are the geometric parameters of the machine; $\overline{P}_{r\ air}$ is the air resistance force, $\overline{P}_{prop\ br\ air}$ is the reactive braking force generated by the propeller during its reverse rotation (Figure 3).

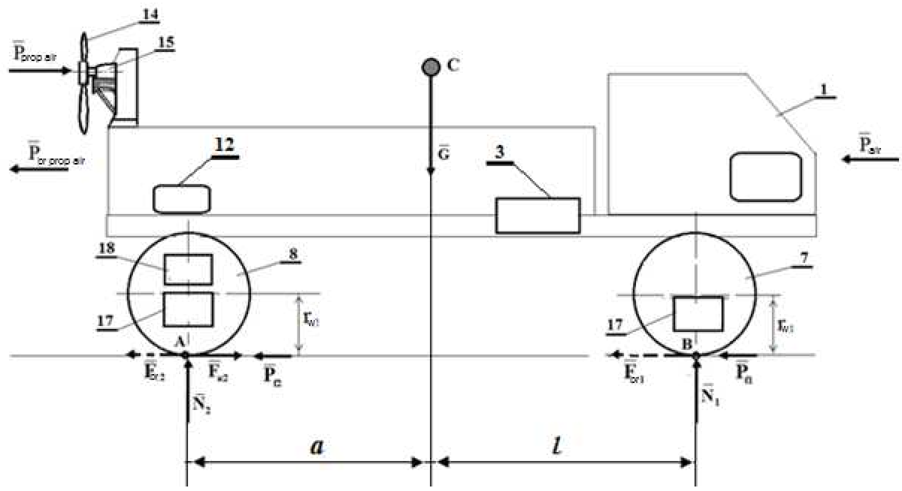

Figure 4. The diagram of the method for controlling wheeled car motion (side view).

Figure 4 presents the diagram showing the arrangement of elements which make it possible to implement the proposed method of controlling the motion of the wheeled vehicle and the forces acting on it: $\overline{P}_{r\ air}$ is the force of air resistance to the machine motion; $\overline{P}_{prop\ br\ air}$ is the propeller's reactive force which slows the vehicle down; $\overline{F}_{tr_2}$ is the tangential tractive force at the contact area between the driving wheels and the road; $\overline{P}_{f_2}$, $\overline{P}_{f_1}$ are the forces of resistance to wheels' rolling; $\overline{N}_1$, $\overline{N}_2$ are normal reactions of the bearing surface of the wheels of car axles; $\overline{F}_{br1}$, $\overline{F}_{br2}$ are braking forces at the contact patches of the wheels; l, a are the geometric parameters of the car.

When a wheeled car accelerates, the sensors for measuring tractive forces (STF) 18 continuously generate electrical signals proportional to the torques M_r realized by the driving wheels 8 with the bearing surface A. The electrical signals proportional to M_r are fed to IP & GCSAM unit 16. The IP unit differentiates signals M_r and identifies negative signs of time derivatives of M_r. When identifying negative signs of derivatives of torques $\frac{M_r}{dt} < 0$, the GCSAM unit generates a signal to turn on the EM 15. As a result of the rotation of the propeller screw 14, the reactive tractive force P_{prop} is created, which "pushes" the vehicle.

When identifying $\frac{M_r}{dt} = 0$, which means that there is no increase in the acceleration in the vehicle's motion, i.e. $\frac{d\ddot{x}}{dt} = 0$, the control operation ends. Besides, with the equality $\frac{M_r}{dt} = 0$, the IP unit 16 fixes the current value of the measured torque M_{rbr}, which characterizes the maximum torques.

Tracking the sliding of the contact patches of car driving wheels 8 will allow reducing fuel consumption of the ICE 2 by limiting the wheel slip at large torques transmitted by the ICE 2 through the transmission (TRWV) 3 to the driving wheels 8, which reduce the coefficient of adhesion at the driving wheel-bearing surface interface.

When the vehicle slows down, the sensors SBT 17 which measure braking torques, actually realized by the wheels (Figure 3, 4), continuously generate electrical signals proportional to the actually realized braking forces F_{br1} and F_{br2} (proportional to the torques $M_{br1} = F_{br1} \cdot r_{w1}$, $M_{br2} = F_{br2} \cdot r_{w2}$) realized at the braking wheels/bearing surface interface. Electrical signals proportional to the braking forces are fed to the IP and GCSAM unit 16 and brake actuators BA of the wheel brakes WB 9. The IP unit 16 also performs differentiation of signals F_{br1} and F_{br2} and identification of their negative signs of time derivatives. When the negative sign of the derivative $\frac{dF_{br1}}{dt} < 0$, $\frac{dF_{br2}}{dt} < 0$ is identified, the IP unit generates a signal to turn on the EM 15 of the propeller drive to create a reactive reverse braking force $\overline{P}_{prop\ br\ air}$. The force $\overline{P}_{prop\ br\ air}$ is independent of the conditions of wheel adhesion. When the force $\overline{P}_{prop\ br\ air}$ arises, the total braking force of the wheeled machine increases. Besides, with $\frac{dF_{br1}}{dt} < 0$, $\frac{dF_{br2}}{dt} < 0$, the current magnitude of the braking forces $F_{br1} = \frac{M_{br1}}{r_{w1}}$, $F_{br2} = \frac{M_{br1}}{r_{w2}}$ is stored in the controller, which is residently installed in the IP & GCSAM unit for subsequent assessment of the adhesion conditions of braking wheels. Based on the current magnitudes of the braking torques F_{br1}, F_{br2}, the GCSAM unit generates a control signal for the BA

4, which brings the pressure in the brake drive of the wheel brakes WB 9 in accordance with adhesion conditions of the vehicle's braking wheels in such a way that $F_{br1} = N_1 \cdot \varphi_{adh1}$; $F_{br2} = N_2 \cdot \varphi_{adh2}$.

There were repeated attempts to install an air propeller on cars in different periods of the development of road transport [6, 7, 8, 9]. The peculiarity of using the propeller in the design of automobiles is associated with energy recuperation, setting the vehicle into motion, its acting as an additional mover aimed at increasing fuel efficiency and speed of car travel.

In the science laboratory of the Vehicle Maintenance Department of the Belarusian-Russian University, the system incorporating the VV-1200-6 screw propeller and the FF 37 D90S4 cylindrical geared motor is manufactured and installed on the Daewoo Matiz II car. The technical characteristics of the geared motor with an installed electric motor are as follows: power N=1.1 kW, rotational speed of the output shaft n = 98 min^{-1}, the force developed on the output shaft F = 3,680 N, the torque on the output shaft of the geared motor M=108 Nm, 12 V consumed voltage). The installed electric motor uses a standard generator and a car battery, since in terms of power consumption it is comparable with an electric starter.

Figure 5. The vehicle equipped with an air propeller: 1– vehicle; 2 - air propeller.

The technical characteristics of the VV-1200-6 screw propeller are presented in Table 1 [10]

Table 1. The technical characteristics of the VV-1200-6 screw propeller.

Parameter	Magnitude
Diameter, mm	1,200
Hub diameter, mm	244
Number of blades	6
Permissible power, hp	150
Allowable number of revolutions, min^{-1}	2,400
Mass, kg	14.0±0.3
Guaranteed service life, h	1,000
Temperature range, degrees	-40/+40
Direction of rotation	left, right
Material	aluminium alloy

The method developed for controlling the modes of motion of the vehicle equipped with thermal and reactive energy converters can be used when accelerating a car at the moment of slipping, thereby creating an additional force spent on overcoming the resistance forces acting on the car during acceleration, which shortens engine run time in the acceleration mode, thus reducing the amount of fuel consumed for the transition to the specified driving mode [7].

In the process of braking with the help of a screw propeller driven by the electric motor, tractive force is directed opposite to the movement of the car. Hence, additional air resistance arises, which contributes to reducing the braking distance.

The differential equations which describe the braking process of the automobile either excluding the air reverse reactive force of braking or taking it into account, take the form:

$$\begin{cases} \ddot{x}_{1br} = -\dfrac{1}{M}\left(F_{br1} + F_{br2} + G\cdot(f_1 + f_2) + F_w\right); \\ \ddot{x}_{2br} = -\dfrac{1}{M}\left(F_{br1} + F_{br2} + G\cdot(f_1 + f_2) + F_w + P_{prop\ br}\right), \end{cases} \tag{2}$$

where $\ddot{x}_{1br}$ is the acceleration of deceleration of the wheeled vehicle without taking into account reactive force of the air propeller;

$\ddot{x}_{2br}$ is the acceleration of deceleration of the wheeled vehicle taking into account the reactive force of the air propeller;

M is the car mass (mass of the Daewoo Matiz II car during testing was 890 kg);

G is the car weight (weight of the Daewoo Matiz II car during testing was G=8730 N);

$\overline{F}_{br1}$, $\overline{F}_{br2}$ are the braking forces at the contact patches of the wheels;

P_{propbr} is the braking force arising from reverse rotation of the propeller;

F_w is the air resistance to car motion;

g is the acceleration of gravity;

f_1, f_2 are the coefficients of resistance to the rolling of car wheels based on the characteristics of the road and tires;

$\ddot{x} = -\dfrac{d^2x}{dt^2}$ is the acceleration of deceleration of the wheeled vehicle.

The maximum braking force at contact patches of the car wheels with the road $F_{br\,max}$ at full use of the coefficient of adhesion between the wheel and the bearing surface is equal to:

$$F_{br\ max} = G\cdot\varphi_{adh} \tag{3}$$

where φ_{adh} is the coefficient of adhesion between the car wheels and the bearing surface, and it depends on the characteristics of the road surface (in what follows, assuming that the coefficients of adhesion for the wheels-road interface are the same $\varphi_{adh1} = \varphi_{adh2}$).

Taking into account (2), the system of equations can be rewritten as follows:

$$\begin{cases} \ddot{x}_{1br} = -\left(g\cdot(\varphi_{adh} + f_1 + f_2) + \dfrac{1}{M}\cdot F_w\right); \\ \ddot{x}_{2br} = -\left(g\cdot(\varphi_{adh} + f_1 + f_2) + \dfrac{1}{M}\cdot(F_w + P_{prop\ br})\right). \end{cases} \tag{4}$$

From the system (4), let us find the value of the increase in deceleration with the propeller operating in the reverse mode:

$$\Delta\ddot{x} = \frac{1}{M}\cdot P_{br\ air}\,. \tag{5 }$$

By integrating the system of equations (4), the laws of speed change during braking of the wheeled car can be obtained:

$$\begin{cases} \dot{x}_{1br} = -\left(g \cdot (\varphi_{adh} + f_1 + f_2) + \frac{1}{M} \cdot F_w \right) \cdot t + V_0; \\ \dot{x}_{2br} = -\left(g \cdot (\varphi_{adh} + f_1 + f_2) + \frac{1}{M} \cdot (F_w + P_{prop\ br}) \right) \cdot t + V_0, \end{cases} \quad (6)$$

where V_0 is the speed before braking;

t is the point of time.

The braking time is determined from the condition that at the end of braking, the speed of the wheeled vehicle is zero taking into account the force $P_{prop\ br}$ and excluding the reverse force of the propeller.

Consequently, when the air reactive reverse force generated by the propeller is applied, the time of car braking decreases by the value:

$$\Delta t_{br} = \frac{M \cdot V_0}{P_{prop\ br}}, \text{ s.} \quad (7)$$

$$\begin{cases} t_{1br} = \dfrac{V_0}{\left(g \cdot (\varphi_{adh} + f_1 + f_2) + \frac{1}{M} \cdot F_w \right)}; \\ t_{2br} = \dfrac{V_0}{\left(g \cdot (\varphi_{adh} + f_1 + f_2) + \frac{1}{M} \cdot (F_w + P_{prop\ br}) \right)}. \end{cases} \quad (8)$$

To obtain the braking distance of the machine, let us integrate the system of equations (6):

$$\begin{cases} x_{1br} = -\frac{1}{2} \cdot \left(g \cdot (\varphi_{adh} + f_1 + f_2) + \frac{1}{M} \cdot F_w \right) \cdot t^2 + V_0 \cdot t; \\ x_{2br} = -\frac{1}{2} \cdot \left(g \cdot (\varphi_{adh} + f_1 + f_2) + \frac{1}{M} \cdot (F_w + P_{prop\ br}) \right) \cdot t^2 + V_0 \cdot t. \end{cases} \quad (9)$$

Whence, when the reversing air force of the propeller is applied, the braking distance of the machine will be reduced by the value:

$$\Delta x_{br} = \frac{P_{prop\ br}}{2 \cdot M} \cdot t^2, \text{ m.} \quad (10)$$

Therefore, the braking performance of the wheeled vehicle is increased by using the reversing force of the air propeller.

The traction force of the VV-1200-6 screw propeller is calculated by the formula (1):

$$P_{propbr} = 0.17 \cdot 1.225 \cdot 1.2^4 \cdot 10.26^2 = 45.46\ N.$$

When substituting the magnitude of the air reverse force of the propeller into the expression (10), we can determine the magnitude by which the braking distance of the machine will be reduced by using the screw propeller. The Daewoo Matiz II car was bench-tested using a roller brake tester at the testing ground of the *Vehicle Maintenance* Department. These tests determined the braking forces developed at the contact patches of the wheels (for wheels of the front axle F_{br1}=1.85 kN, for wheels of the rear axle F_{br2}=1.44 kN). Also, the *EFFECT-02* device made it possible to obtain the following—

the acceleration of deceleration, the magnitude of braking distance, the time of braking (the initial speed of travel V_0=25 km/h, the braking time t=3.2 s), then the use of the VV-1200-6 screw propeller reduces the braking distance by:

$$\Delta x_{br} = \frac{45.46}{2 \cdot 890} \cdot 3.2^2 = 0.26\ m.$$

With the measured braking distance being x_{1t} = 14.0 m, a 1.9% reduction of the braking distance occurred.

4. Conclusions

The proposed method for controlling the process of wheeled vehicle acceleration makes it possible to increase:

- Traction dynamics of the wheeled vehicle due to the additional propeller-generated traction force, which is independent of the adhesion conditions of the driving wheels.
- Fuel efficiency in the traction mode of wheeled vehicle motion due to the reduction of acceleration time provided by an additional reactive force generated by the air propeller, which is independent of the conditions of adhesion between the driving wheels of the vehicle and the bearing surface.
- Stability of the traction mode of wheeled vehicle motion by limiting the sliding of contact patches of the driving wheels in the longitudinal direction, which ensures that the adhesion coefficients of the driving wheels are preserved in the lateral direction.

References

[1] Electronic Stability Control System ESP 1998 *J. Autom. Ind. Abroad* ***11*** 16-17
[2] Yablonsky A A 1977 *Theoretical Mechanics Course Part II Dynamics* (Moscow: Vysshaya Shkola)
[3] Kim V A et al. 2003 *Methodology for Creating Active Safety Systems for Vehicles Based on Force Analysis* (Mogilev: Belarusian-Russian University)
[4] Kim V A 1998 Control Method for Vehicle’s Anti-Lock Brake System Bulletin WO 98/01332, MKI6 B *60* T 8/52
[5] Guskov V V 1982 *Tractor Theory* (Moscow: Mashinostroyeniye)
[6] Propeller Driven Cars 2020 Available at: https://www.drive2.ru/b/1427221/
[7] Gordon Murray finally launches his wildly innovative T.50 masterpiece Available at: https://newatlas.com/automotive/gordon-murray-t-50-launch/
[8] Nenashko E F 1992 *Automobile* Patent RU 2 048 358 C1 MKP B62D
[9] Medvedev V P 2000 *Automobile* Patent RU 2 189 922 C2 MKP B62D
[10] VV-1200-6 screw propeller Available at: http://vint-nn.ru/vozdushnye-vinty-i-ventilyatory/vinto-ventilyator-vv-1200-6.html
[11] Onishchenko G B 2015 *Electric Drive Theory* (Moscow: INFRA-M)