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The Use of Integral Adaptation Principle to Synthesize Robust Control of Electric Vehicle Wheel Slip

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Abstract

The usage of "motor-wheel" systems requires the electric vehicle control system improvement by using the characteristics of the wheel adhesion to the road surface. One of the aspects of such improvement is the enhancement of the algorithms for the functioning of the antilock braking system (ABS). In developing the ABS control algorithms, various approaches and methods of modern control theory are used, including methods based on the estimation of wheel slip, traction force, wheel friction coefficient using linear and nonlinear estimation methods, linear and nonlinear regulators. This work illustrates the application of the principle of high order integral adaptation (PIA) of Synergetic Control Theory (SCT) for constructing a robust control law for an electric vehicle wheel slip. The main features of the SCT contain: firstly, a fundamental change in the goals of the behavior of the synthesized systems; secondly, direct consideration of the natural properties of nonlinear objects; thirdly, the formation of an analytical mechanism for generating feedbacks, i.e. control laws. PIA consists in introducing nonlinear integrators into the control law that compensate for disturbances without their immediate estimation. The obtained in this work control law has a fairly simple structure, is focused on using physically accessible state variables of the braking system, and its implementation does not require immediate estimation of disturbances or building a complex neural network to calculate disturbances. The results of computer simulations of the synthesized robust control law for ABS indicate its effectiveness in functioning under conditions of external environment uncertainty.

Keywords: *electric vehicle, wheel slip, nonlinear control systems, robust control, synergetic control theory, invariant, ADAR method, principle of high order integral adaptation*

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Использование принципа интегральной адаптации для построения робастного управления проскальзыванием колеса электромобиля[1]

Использование систем "мотор-колесо" требует совершенствования системы управления электротранспортным средством, используя характеристики сцепления колеса с поверхностью дороги. Одним из аспектов такого совершенствования является улучшение алгоритмов функционирования антиблокировочной тормозной системы (АБС).

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При разработке алгоритмов управления АБС используются различных подходы и методы современной теории управления, включая методы, базирующиеся на оценивании скольжения колеса, силы сцепления, коэффициента трения колеса посредством линейных и нелинейных методов оценивания, линейных и нелинейных регуляторов. Данная работа иллюстрирует применение принципа интегральной адаптации (ПИА) высокого порядка синергетической теории управления (СТУ) для построения робастного закона управления проскальзыванием колеса электромобиля. Основные особенности СТУ состоят: во-первых, в принципиальном изменении целей поведения синтезируемых систем; во-вторых, в непосредственном учете естественных свойств нелинейных объектов; в-третьих, в формировании аналитического механизма генерации обратных связей, т.е. законов управления. ПИА заключается во введении в закон управления нелинейных интеграторов, компенсирующих возмущения без их оперативной оценки.

Полученный в данной работе закон управления имеет достаточно простую структуру, ориентирован на использование физически доступных переменных состояния тормозной системы и для его реализации не требуется оперативной оценки возмущений или построения сложной нейросети для вычисления возмущений.

Результаты компьютерного моделирования синтезированного робастного закона управления для АБС свидетельствуют о его эффективности при функционировании в условиях неопределенности действия внешней среды.

***Ключевые слова**: электромобиль, проскальзывание колеса, нелинейные системы управления, робастное управление, синергетическая теория управления, инвариант, метод АКАР, принцип интегральной адаптации высокого порядка*

Introduction. The current increase of environmental problems and the gradual expansion of the use of "green" energy have also affected the automobile industry — electric cars are being developed and put into operation, and the transition to cars with a "motor-wheel" system is being carried out everywhere. However, in practice, the usage of "motor-wheel" systems requires the electric vehicle control system improvement by using the characteristics of the wheel adhesion to the road surface. One of the aspects of such improvement is the enhancement of the algorithms for the functioning of the dynamic stabilization system (road holding ability), whose components are the antilock braking system (ABS), the system of distribution of braking forces, anti-slip control, etc. [1]. Thus, in order to increase the driving safety of an ABS, an electric vehicle should control the sliding of each wheel in order to prevent its blocking and ensure the greatest degree of road adherence, i. e. ABS control law should provide robustness in relation to the rapidly changing properties of the roadbed and the characteristics of the tire [1—3].

In developing the ABS control algorithms, various approaches and methods of modern control theory are used, including methods based on the estimation of wheel slip, traction force, wheel friction coefficient using linear methods (LQR, LQRC, Kalman filter, advanced Kalman filter) and nonlinear estimation methods (estimation with sliding mode, nonlinear observers, neural network observers), linear (PID-control) and nonlinear regulators (Lyapunov function method, robust control methods, fuzzy and neural network control), etc. [3—11].

Synergetic Control Theory (SCT), which has found extensive application in various fields of modern science and technology, is considered to be a fundamentally different direction of nonlinear control of technical systems [12—19]. The main features of the SCT, related to the problem of synthesizing the nonlinear technique of controlling complex technical objects, consist of: firstly, a fundamental change in the goals of the behavior of the synthesized systems; secondly, direct consideration of the natural properties of nonlinear objects; thirdly, the formation of an analytical mechanism for generating feedbacks, i.e. control laws.

Earlier it was noted that in the SCT there are two ways to ensure the adaptability of the nonlinear system to external and parametric disturbances. The first way is to use the principle of integral adaptation of the SCT [15—17], which consists in introducing nonlinear integrators into the control law that compensate for disturbances without their immediate estimation. At the same time, minimal information about the disturbances is necessary — its class (piecewise constant, polynomial, harmonic, etc.), which can be represented by a dynamic model in the form of a system of differential equations. The second method is to construct nonlinear observers of parametric and/or external disturbances [18, 19]. In this case, the synthesized nonlinear control laws are complemented by the observation subsystem, which dynamically estimates unmeasured disturbances and compensates them. Both methods are fairly formalized and are based on the main SCT method — method of analytical design of aggregated regulators (ADAR) [12].

This paper illustrates the first method as applied to the problem of adaptive control of an electric vehicle wheel slip. A detailed description of the principle of integral adaptation is omitted, because the given problem can be found in the references works [15—17].

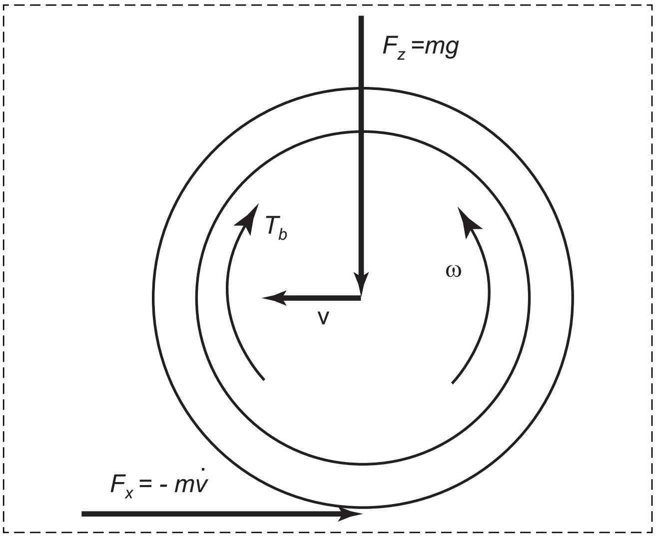

Fig. 1. Forces and torques of the braking system

1. Control problem. Fig. 1 shows a diagram of the interaction forces of the braking system of a wheel attached to a mass *m*. When the wheel rotates in the direction of the longitudinal (horizontal) velocity *v*, the traction force (resistance) of the tire F_x is created by friction between the tire surface and the road surface. This force will create a moment that generates a rotating movement of the wheel, creating an angular velocity ω. The braking torque applied to the wheel will act against the rotation of the wheel, creating a negative angular acceleration.

The equations of motion of the braking system wheels in the braking mode have the form [2, 3, 10]

$$\begin{aligned} m\dot{v}(t) &= -F_x; \\ J\dot{\omega}(t) &= rF_x - T_b \mathrm{sign}(\omega), \end{aligned} \tag{1}$$

where $F_x = F_z\mu(\lambda, \mu_H, \alpha)$; $F_z = mg$ — vertical force; μ — friction coefficient, which is a nonlinear function of the following arguments: λ — longitudinal slip of the tire; μ_H — coefficient of adhesion between the tire and the road; α — wheel slip angle; T_b — braking torque (control); *r* — wheel radius; *J* — wheel inertia.

Longitudinal slip is determined by the equation:

$$\lambda = \frac{v - r\omega}{v}. \tag{2}$$

The coefficient λ (2) describes the normalized difference between the horizontal velocity of the car *v* and the velocity of rotation of the wheel *r*ω. The value of this coefficient λ = 0 corresponds to the free movement of the wheel, when the adhesion force F_x has no effect. If a slip reaches a value λ = 1, the wheel is blocked, which means it stops [3].

There are different approaches for calculating the adhesion force, so in [2], [11] the following relations are considered:

$$F_x = F_z\mu(\lambda,\omega) = F_z \mathrm{sign}(\lambda)\frac{\frac{\sigma_0}{L_0} g(\omega,\lambda,\theta)\frac{\lambda}{1-\lambda}}{\frac{\sigma_0}{L_0}\frac{\lambda}{1-\lambda} + g(\omega,\lambda,\theta)};$$
$$g(\omega,\lambda,\theta) = \theta\left(\mu_c + (\mu_s - \mu_c)\mathbf{e}^{-\frac{|r\omega\lambda|}{|1-\lambda|v_s}}\right), \tag{3}$$

where μ_c, μ_s are the coefficients of static and Coulomb friction; v_s — Stribek velocity; σ_0 — normalized longitudinal stiffness; L_0 — the length of the contact surface of the tire; θ — parameter characterizing the properties of the surface.

In the attached to references paper [3] it is noted that the adhesion force can also be determined as

$$F_x(\lambda) = D\sin(C\arctan(B\lambda - E(B\lambda - \arctan(B\lambda))))$$

or

$$F_x = F_z\mu(\lambda,\omega) = (C_1(1 - \mathbf{e}^{-C_2\lambda}) - C_3\lambda)\mathbf{e}^{-C_4\lambda v},$$

where *B*, *C*, *D*, *E* — empirical coefficients; C_1, C_2, C_3 — constant tire adhesion coefficients depending on the condition (circumstances) of the road; C_4 = 0,2÷0,04 — a constant coefficient reflecting the relationship of the horizontal wheel speed and tire grip to the road surface.

From equations (2), (3) it can be seen that, when $v \to 0$, the dynamics of an open-loop system becomes infinitely fast with an infinite boost factor. This leads to a loss of controllability, and the slip regulator at low *v* must be turned off.

According to [10], the control task is to control the value of the longitudinal slip λ in a given value. The slip regulator must be robust with respect to uncertainties in tire performance and changes in road surface conditions.

So, the purpose of controlling the system (1) is to brake the wheel at the required value of the slip coefficient $\lambda = \lambda^0$ = const. In this case, the value λ^0 is either a constant or is determined by a top-level control system, for example, from a system of road-holding ability.

Thus, according to (2) we have the synergetic technological invariant

$$\lambda - \lambda^0 = v - r\omega - v\lambda^0 = 0. \tag{4}$$

When constructing the law of robust control in model (1) the uncertainty due to force F_x, will be considered as a parametric perturbation, for which, according to the principle of integral adaptation of the SCT, it is necessary to construct a dynamic model. As such a model, we consider a dynamic model in the form of three successively included integrators [15—17]:

$$\begin{aligned} &\dot{z}_1(t) = z_2; \\ &\dot{z}_2(t) = z_3; \\ &\dot{z}_3(t) = \eta(v - r\omega - v\lambda^0), \end{aligned} \quad (5)$$

where z_i — dynamic variables of the perturbation model; $z_1 = \widehat{F}_x$ — a dynamic variable that performs the role of evaluator of an external *non-measurable perturbation* F_x, acting on system (1); η — some constant coefficient. In the right side of the last equation of model (5) the input technological invariant (4) is reflected.

2. Synthesis of the control law and modeling of closed-loop system. Then, in accordance with this goal and the principle of high-order integral adaptation [15—17], from (1) we can compile an extended model of synergistic synthesis with $\omega > 0$:

$$\begin{aligned} &\dot{v}(t) = -\frac{1}{m} z_1; \\ &\dot{\omega}(t) = -\frac{T_b}{J} + \frac{r}{J} z_1; \\ &\dot{z}_1(t) = z_2; \\ &\dot{z}_2(t) = z_3; \\ &\dot{z}_3(t) = \eta(v - r\omega - v\lambda^0). \end{aligned} \quad (6)$$

For the extended synthesis model (6) we introduce the synergetic macrovariable

$$\psi = v - r\omega - v\lambda^0 + \gamma_1 z_1 + \gamma_2 z_2 + \gamma_3 z_3. \quad (7)$$

Following the procedure of synthesis of the method of ADAR [12—19], from the joint solution (7), the functional equation of SCT

$$\dot{\psi}(t) + \beta\psi = 0 \quad (8)$$

and the extended model (6) we find the expression for the control law:

$$\begin{aligned} T_b = &\left(\frac{J}{rm}(1 - \lambda^0) + r\right) z_1 - \\ &- \frac{J}{r}\gamma_1 z_2 - \frac{J}{r}\gamma_2 z_3 - \frac{J}{r}\gamma_3 \eta(v - r\omega - v\lambda^0) - \\ &- \frac{J\beta}{r}(v - r\omega - v\lambda^0 + \gamma_1 z_1 + \gamma_2 z_2 + \gamma_3 z_3). \end{aligned} \quad (9)$$

The control law (9) is dynamic, since its structure includes dynamic variables of the system (5). We also note that the condition for asymptotic stability (8) is the condition $\beta > 0$. When diversity $\psi = 0$ is achieved, the dynamics of system (6) is described by the following linear decomposed system:

$$\begin{aligned} &\dot{z}_1(t) = z_2; \\ &\dot{z}_2(t) = z_3; \\ &\dot{z}_3(t) = \eta\left(-\gamma_1 z_1 - \gamma_2 z_2 - \gamma_3 z_3\right). \end{aligned} \quad (10)$$

To find the unknown coefficients that ensure the stability of system (10), we use the modal control method. We write the state matrix of the system (10) and find its characteristic equation:

$$A(s) = \det(s\mathbf{E} - \mathbf{A}) = s^3 + \eta\gamma_3 s^2 + \eta\gamma_2 s + \eta\gamma_1 = 0.$$

The desired characteristic equation with a given location of the roots is represented as

$$A_0(s) = (s - s_0)^3 = s^3 - 3s_0 s^2 + 3s_0^2 s - s_0^3 = 0,$$

in which $s_0 < 0$ is the desired root. Equating the coefficients of these equations with equal powers of s, we find

$$\gamma_1 = -p_0^3 / \eta, \gamma_2 = 3p_0^2 / \eta, \gamma_3 = -3p_0 / \eta. \quad (11)$$

Thus, the choice of the coefficient $\beta > 0$ and the definition γ_i according to (11) will ensure the asymptotic stability of the system (6) with the synthesized control law (9).

Let's perform simulation of the system (1), in which the force F_x is given by expression (3), with the synthesized control law (9). The following object parameters are set [11]: $\sigma_0 = 200$; $L_0 = 0{,}25$; $\mu_c = 0{,}5$; $\mu_s = 0{,}9$; $v_s = 12{,}5$; $r = 0{,}3$; $m = 200$; $J = 0{,}23$; and regulator parameters $\lambda^0 = 0{,}1$; $\eta = 100$; $\beta = 100$; $p_0 = -500$. The simulation results are presented in Fig. 2—5. In the simulation, it was assumed that the coefficient of adhesion with the

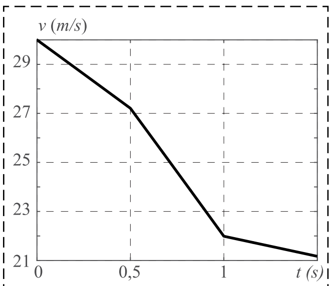

Fig. 2. Linear velocity variance graph

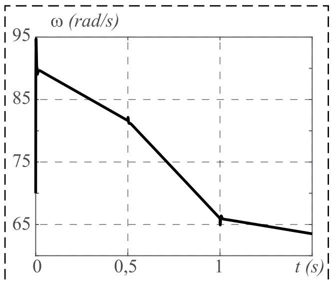

Fig. 3. Angular velocity variance graph

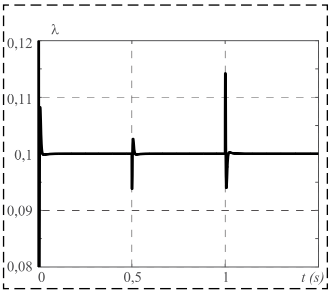

Fig. 4. Slip variance graph

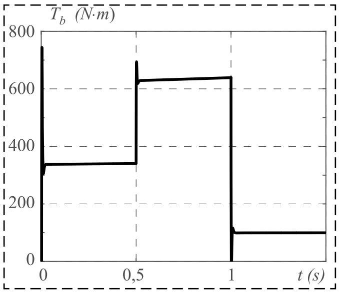

Fig. 5. Control variance graph

surface θ varies with time in accordance with the dependence:

$$\theta(t)=\begin{cases}0.7 & for \;\; t<0.5;\\ 1.3 & for \;\; 0.5\leqslant t<1;\\ 0.2 & for \;\; t\geqslant 1.\end{cases} \qquad (12)$$

It is seen from Fig. 4 that at different values of the coefficient of adhesion with the surface θ, the technological invariant (4) is satisfied. Thus, the results of computer simulations of the synthesized robust control law for ABS indicate its effectiveness in functioning under conditions of external environment uncertainty.

Conclusion. In [11] an adaptive ABS control law was proposed, including in its structure a function $F_x(F_z, v, \omega, \theta)$, defined according to (3). It is assumed that on the basis of this function it is possible with the help of an observer to evaluate the characteristics of the roadway, in particular the parameter θ. Such an assumption seems practically ineffective, since in real conditions, the characteristics of the roadbed can vary significantly. Of course, in specialized ideal conditions, when much is known in advance about a function $F_x(F_z, v, \omega, \theta)$ and its parameters, and almost no current physical measurements are required, this approach may be quite justified. Such conditions arise, for example, when conducting computer experiments, etc.

The robust control law (9), synthesized by the ADAR method, providing the required properties of an ABS in conditions of considerable uncertainty, is much simpler than the adaptive control law synthesized in [11]: indeed, the control law (9) is linear in structure to the state variables of the system (6), and its implementation does not require both an immediate estimation of the parameters of a function $F_x(F_z, v, \omega, \theta)$, and a complex neural network for its calculation.

The results obtained in this paper will be distributed to all-wheel drive electric vehicle and electric vehicle with two-wheel drive.

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