Methods of information systems synthesis

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PARAMETRIC SYNTHESIS OF THE INVARIANT SYSTEM OF CAR COURSE STABILITY

Abstract. The problem of constructing the invariant stabilizer of the ESP (Electronic Stability Program) car course stability system is considered by implementing two control principles by the electronic brake force distribution unit EBD (Electronic Brakeforce Distribution) – the principle of control by deviation and the principle of control by external disturbance. The values of the variable parameters of the stabilization algorithm are selected from the conditions for minimizing both the static and dynamic errors of the system. Two brake fluid pressure sensors are introduced into the EBD structural-functional scheme in the brake lines of the right and left sides of the car. It is proven that the pressure difference of the brake fluid, which is measured by pressure sensors, is proportional to the external disturbance acting on the car body from the side of the road surface. Therefore, in order to give the ESP system the property of invariance to external disturbances, the control signal generated by the EBD electronic unit contains current information not only about the parameters of the disturbed movement of the car, namely, about the angle of deviation of the longitudinal axis of the car relative to the given direction of movement, about the angular velocity of rotation of the body relative to its vertical axis and about lateral displacement of the center of mass of the body, but also the current information about the external disturbance acting on the car body. Recommendations for choosing the values of variable parameters of the ESP system stabilizer are given, which ensure the minimization of both static and dynamic errors of the closed system in the emergency braking mode.

Keywords: car course stability system; invariant stabilizer; static error of system; dynamic error of system; variable parameters of stabilizer.

Introduction

Problem statement. The main task of the ESP (Electronic Stability Program) car course stability system is to help the driver in critical situations, namely, to maintain the course stability and the given trajectory of the car under the influence of random external disturbances [1-3].

For the first time, the idea of creating ESP arose in 1959 and was patented by the Daimler-Benz company. In its modified form, it first appeared in 1995 on the Mercedes 600 serial car. Currently, most modern cars of various manufacturers are equipped with the ESP system. Since November 2011, ESP, together with the anti-lock braking system ABS, has become one of the active safety systems that all new models of cars and trucks registered in the European Union must be equipped with. Since November 2014, this law applies to all new cars without exception.

The conventional ESP system contains sensors of the angular speed of rotation of the wheels of the car, which are integrated with the anti-lock braking system ABS and the ASR traction control, a sensor of the position of the steering wheel, sensors of pressure of brake fluid in the brake lines of the right and left sides of the car, a sensor of the angular speed of rotation of the body relative to the main central vertical axis inertia of the body, a sensor of linear accelerations of the body relative to the main central transverse axis and a sensor of the current speed of the car. Information from the listed sensors enters the digital electronic brake force distribution unit EBD (Electronic Brakeforce Distribution), which, in the event of a critical situation, helps to restore the position of the car body by generating an electrical control signal that is fed to the input of the executive body of the ESP system.

The ESP executive body changes the brake fluid pressure in the brake lines of the right and left sides of the car [4, 5].

Most often, a critical situation related to the loss of stability and controllability of the car occurs in emergency acceleration and braking modes. If the driver sharply presses the fuel pedal during urgent acceleration, the driving wheels of the car may slip, which leads to a loss of stability during acceleration. In this case, the ASR system reacts to the processes of skidding by reducing the active moments transmitted from the engine to the driving wheels of the car.

If the driver presses the brake pedal sharply during emergency braking, some of the car's wheels may lock, which may also lead to a loss of stability. In this case, the ABS system comes into play, reducing the braking force on the locked wheels.

In cases where the anti-lock braking system (ABS) or the anti-skid system (ASR) is unable to ensure stable movement of the car, the ESP system comes in action. Most often, this situation occurs in the mode of emergency braking. It should be noted that the capabilities of ESP to correct skidding and stabilize the car body in a critical situation are not unlimited. And if the speed at which a skid occurs is excessively high, or the grip between the wheels and the road surface is excessively low, then even the ESP system can be helpless. The ESP system significantly reduces the risks of skidding and an emergency situation on the road, but does not eliminate them [6].

In the article [7], the authors solve the problem of parametric synthesis of the ESP system, which is optimal in terms of dynamic accuracy, of a car-refueling vehicle.

Experimental studies of the developed system proved the presence of a static error in the ESP system.

Therefore, the goal of this work is to reduce the static error while maintaining high dynamic accuracy of the system, that is, to develop an ESP system that is invariant to the action of external disturbances acting on the object of stabilization.

Main material

Mathematical model of disturbed car movement during emergency braking mode. In work [7], a mathematical model of the disturbed movement of a car during emergency braking mode was developed, which has the following form:

$$\dot{v}_x(t) = -\frac{2k_b}{M} p_0 - gf(t); \quad (1)$$

$$\ddot{\psi}(t) = -\frac{Bk_b}{I}\Delta p(t) - \frac{2H_m M}{I} v_x(t)\dot{\psi}(t) f(t); \quad (2)$$

$$\Delta\ddot{p}(t) = -\frac{f_r}{I_r}\Delta\dot{p}(t) - \frac{c_r}{I_r}\Delta p(t) + \bar{k}_u u(t); \quad (3)$$

$$\dot{y}(t) = -v_x(t)\psi(t), \quad (4)$$

where the following values are taken (Fig. 1):

$v_x(t)$ – the current speed of the car;

$\psi(t)$ – angle of deviation of the main longitudinal central axis of inertia of the car ox relative to the given direction of movement OX;

$\Delta p(t)$ – brake fluid pressure difference in the brake lines of the right and left sides of the car

$$\Delta p(t) = p_r(t) - p_l(t);$$

$y(t)$ – lateral shift of the center of mass of the car body relative to the given direction of movement;

$u(t)$ – control signal generated by the EBD electronic unit;

M – mass of the car;

g – acceleration of gravity;

I – the moment of inertia of the car body relative to its own central vertical axis of inertia;

B – track width;

H_m – the distance from surface of movement of the car to its center of mass;

$f(t)$ – the car's movement resistance coefficient, which depends on the properties of the road surface and the tread of the car's wheels;

p_0 – brake fluid pressure in the main brake cylinder;

k_b – the proportionality factor between the braking force on one of the sides of the car and the pressure of the brake fluid in the line of the corresponding side;

I_r – the moment of inertia of the rocker arm of the EM electromagnet of the executive body of the ESP system (Fig. 2);

f_r – coefficient of liquid friction in the axis of rotation of the rocker arm;

c_r – stiffness coefficient of the fixing spring of the rocker arm;

$\bar{k}_u$ is the reduced value of the gain coefficient of the executive body.

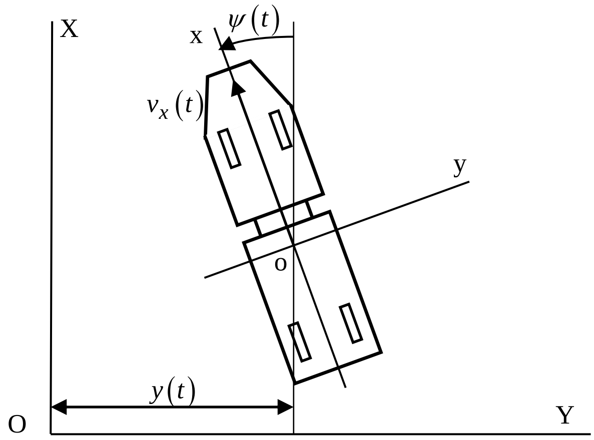

Fig. 1. For determination the current parameters of disturbed car movement

In works [7, 9], the control signal $u(t)$ was formed in the form

$$u(t) = k_\psi \psi(t) + k_{\dot{\psi}}\dot{\psi}(t) + k_y y(t), \quad (5)$$

where k_ψ, $k_{\dot{\psi}}$, k_y are varied EBD parameters, for the determination of which a combined algorithmic method of parametric synthesis is proposed in [10], which is a sequential combination of the Sobol grid method [10] and the Nelder-Mead method [11], implemented in the "Optimization Toolbox" extensions software package MATLAB and "Minimize" software package MATHCAD. Such a combination of two optimization methods allows, at the first stage of parametric synthesis, to bring the working point of the ESP system into the zone of the global minimum, and at the second stage to bring the working point to the point of the global minimum of the integral additive quadratic functional

$$I\left(k_\psi, k_{\dot{\psi}}, k_y\right) = \int_0^\tau \left[\beta_1^2\psi^2(t) + \beta_2^2\dot{\psi}^2(t) + \beta_3^2 y^2(t)\right]dt, \quad (6)$$

where β_1, β_2, β_3 are weighting coefficients of the functional (6), the values of which are calculated using a special algorithm implemented in the above-mentioned combined method of parametric synthesis.

In Fig. 2 shows the structural and functional scheme of the ESP executive body, where the following designations are adopted:

EM – electromagnet;
W1, W2 – electromagnet windings;
R – rocker arm;
Sp - fixing spring;
N1, N2 – locking needles;
MBC – main brake cylinder;
WBC – working brake cylinder;
HP – hydraulic pump;
BP – brake pedal;
PSL, PSR – brake fluid pressure sensors in the brake lines of the right and left sides, respectively.

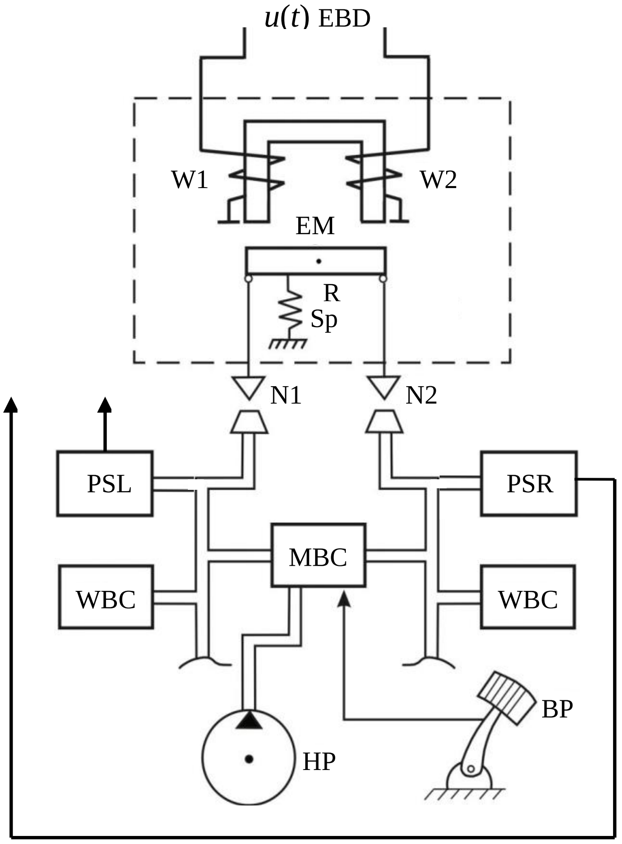

Fig. 2. Structural and functional scheme of the ESP executive body

From the EBD output, the control signal $u(t)$ is applied to one of the windings W1 or W2 of the EM.

If $u(t)>0$, then the control signal module $|u(t)|$ is supplied to the winding W2, which leads to the rotation of the rocker arm R in the positive direction (counter-clockwise).

If $u(t)<0$, then the control signal module $|u(t)|$ is supplied to the winding W1, which leads to the rotation of the rocker arm R in the negative direction (clockwise).

The rotation of R leads to the movement of the needles N1 and N2 in the corresponding direction.

When turning R counter-clockwise, the pressure of the brake fluid $p_l(t)$ in the left line increases, that is, the left side is braked at the same time, which causes the car to turn to the left.

When turning R clockwise, the right side of the car is braked, which causes it to turn to the right.

The structural and functional scheme of the ESP executive body shown in Fig. 2, is slightly different from the scheme given in [7]. In order to reduce the static error of the ESP system, that is, to give the system the property of invariance to external disturbances, it is necessary to implement two control principles in the ESP system, namely, the principle of deviation control and the control principle of external disturbance [14]. For this purpose, in the scheme of the ESP executive body, shown in Fig. 2, PSL and PSR sensors are used, the output signals of which are fed to the EBD inputs, and the control algorithm formed by the EBD electronic unit has the form

$$u(t)=k_\psi \psi(t)+k_{\dot\psi}\dot\psi(t)+k_y y(t)+k_p\Delta p(t), \quad (7)$$

moreover, the variable parameter should be chosen under the condition of minimizing the static error of the ESP.

Differential equations (1)–(4) together with relation (7) make up the mathematical model of the disturbed motion of the ESP closed system. This model is nonlinear because the right parts of the differential equations (2) and (4) have nonlinear terms.

Parametric synthesis of the invariant system of car course stability. In the emergency braking mode, the pressure of the brake fluid in the working cylinders reaches its maximum value p_0, and the car begins to move with constant maximum acceleration a. The current speed of the car is

$$v_x(t)=v_0-a\cdot t, \quad (8)$$

where v_0 is the initial speed at the beginning of the emergency braking mode. As a result, the disturbed motion of the car in the angular stabilization channel is described by differential equations

$$\ddot\psi(t)=-\frac{Bk_b}{I}\Delta p(t)-\\ -\frac{2H_m M}{I}(v_0-a\cdot t)\dot\psi(t)f(t); \quad (9)$$

$$\Delta\ddot p(t)=-\frac{f_r}{I_r}\Delta\dot p(t)-\frac{c_r}{I_r}\Delta p(t)+\bar k_u u(t); \quad (10)$$

$$u(t)=k_\psi\psi(t)+k_{\dot\psi}\dot\psi(t)+k_p\Delta p(t). \quad (11)$$

Let's enter the notation

$$a_{\psi p}=\frac{Bk_b}{I};$$

$$a'_{\psi\psi}(t)=\frac{2H_m M}{I}v_x(t)f(t);$$

$$a'_{pp}=\frac{f_r}{I_r};$$

$$a_{pp}=\frac{c_r}{I_r}.$$

Then the transfer function of the stabilization object is written as

$$W_0(s,t) = -\frac{a_{\psi p}}{s\left[s + a'_{\psi\psi}(t)\right]}. \qquad (12)$$

Substitute relation (11) into the right part of the differential equation (10).

As a result, the differential equation (10) will be written as

$$\begin{gathered}\Delta\ddot{p}(t) + a'_{pp}\Delta\dot{p}(t) + \left(a_{pp} - \bar{k}_u k_p\right)\Delta p(t) = \\ = \bar{k}_u\left[k_\psi \psi(t) + k_{\dot{\psi}}\dot{\psi}(t)\right],\end{gathered} \qquad (13)$$

and the transfer function of the stabilizer of the ESP system, which contains the EBD electronic unit and the executive body, is equal to

$$W_c(s) = \frac{\bar{k}_u\left(k_\psi + s\cdot k_{\dot{\psi}}\right)}{s^2 + a'_{pp}s + \left(a_{pp} - \bar{k}_u k_p\right)}. \qquad (14)$$

Let's write down the transfer function of the open circuit ESP in the angle stabilization channel

$$\begin{gathered}W_{oESP}(s,t) = W_0(s,t)W_c(s) = \\ = -\frac{\bar{k}_u a_{\psi p}\left(k_\psi + s\cdot k_{\dot{\psi}}\right)}{s\left[s + a'_{\psi\psi}(t)\right]\left[s^2 + a'_{pp}s + \left(a_{pp} - \bar{k}_u k_p\right)\right]}.\end{gathered} \qquad (15)$$

The analysis of relation (15) allows us to conclude that the analyzed ESP in the angular stabilization channel is characterized by astatism of the first order, that is, the first coefficient of static error of the system is zero. If you put

$$a_{pp} - \bar{k}_u k_p = 0, \qquad (16)$$

then the transfer function of the open ESP can be presented in the form

$$W_{oESP}(s,t) = -\frac{\bar{k}_u a_{\psi p}\left(k_\psi + s\cdot k_{\dot{\psi}}\right)}{s^2\left[s + a'_{\psi\psi}(t)\right]\left(s + a'_{pp}\right)}. \qquad (17)$$

When condition (16) is fulfilled, the ESP system is characterized by astatism of the second order, that is, the first two coefficients of the static error of such a system are equal to zero.

The degree of invariance of such a system to external disturbances is much higher than that of systems with a transfer function in an open state (15). Therefore, the value of the variable parameter k_p of the stabilization algorithm (7) should be chosen from the condition (16)

$$k_p = \frac{a_{pp}}{\bar{k}_u}. \qquad (18)$$

It is known [14, 15] that a decrease in the static error leads to a decrease in the degree of stability of the closed system, that is, to an increase in the dynamic error.

Therefore, the choice of variable parameters of algorithm (7), namely k_ψ, $k_{\dot{\psi}}$ and k_y, should be aimed at minimizing the dynamic error of the closed ESP. It is advisable to select the values of these parameters using the combined algorithmic method of parametric synthesis, which is described in the article [7].

Conclusions

To reduce the static error of the car course stability system, it is advisable to combine two control principles, namely, the principle of control by deviation and the principle of control by external disturbance;

The ESP system control algorithm, which is formed by the EBD electronic unit, contains information about the current values of the parameters of disturbed car movement $\psi(t)$, $\dot{\psi}(t)$ and $y(t)$, as well as indirect information about the current value of the external disturbance acting on the car body, which is obtained by measuring the brake fluid pressure in the brake lines of the right and left sides of the car $p_r(t)$ and $p_l(t)$ and the formation of the difference in these pressures $\Delta p(t)$;

The value of the variable parameter k_p is chosen from the condition of increasing the degree of astatism of the ESP system, which leads to a decrease in the static error of the system, and the value of the variable parameters k_ψ, $k_{\dot{\psi}}$ and k_y – from the condition of the minimum of its dynamic error, which is estimated by functional (6).

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Параметричний синтез інваріантної системи курсової стійкості автомобіля

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Анотація. Розглядається задача побудови інваріантного стабілізатора системи курсової стійкості автомобіля ESP (Electronic Stability Program) шляхом реалізації електронним блоком розподілення гальмівних зусиль EBD (Electronic Brakeforce Distribution) двох принципів керування – принципу керування за відхиленням і принципу керування за зовнішнім збуренням. Значення варійованих параметрів алгоритму стабілізації обираються з умов мінімізації як статичної, так і динамічної похибок системи. В структурно-функціональну схему EBD вводяться два датчики тиску гальмівної рідини в гальмівних магістралях правого і лівого бортів автомобіля. Доводиться, що різниця тисків гальмівної рідини, яка вимірюється датчиками тиску, пропорційна зовнішньому збуренню, що діє на корпус автомобіля з боку дорожнього покриття. Тому, для надання системі ESP властивості інваріантності до дії зовнішніх збурень сигнал керування, що формується електронним блоком EBD, містить поточну інформацію не тільки про параметри збуреного руху автомобіля, а саме, про кут відхилення поздовжньої осі автомобіля відносно заданого напрямку руху, кутову швидкість повороту корпусу відносно його вертикальної осі та бічний зсув центру мас корпусу, але й поточну інформацію про зовнішнє збурення, що діє на корпус автомобіля. Додаються рекомендації про вибір значень варійованих параметрів стабілізатора системи ESP, які забезпечують мінімізацію як статичної, так і динамічної похибок замкнутої системи в режимі термінового гальмування.

Ключові слова: система курсової стійкості автомобіля; інваріантний стабілізатор; статична похибка системи; динамічна похибка системи; варійовані параметри стабілізатора.