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Parametric synthesis of the system of automatic stabilization of a bus movement direction

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Abstract

Vehicle stabilization is one of the components of traffic safety, so research and development in this area are relevant and in demand. In this work, a structural diagram of a closed system of automatic stabilization of the bus movement direction is developed. Parametric synthesis of the systems of a moving electric bus stabilization is made and the weighty coefficients of the additive integral quadratic functional are chosen. An algorithmic method of parametric synthesis of motion stabilization systems of a moving electric bus has been developed. By way of a sensing element it is advised to use a platformless inertial system containing three gyroscopic angular velocity sensors and a computing device. It is also suggested that three sensors of linear acceleration of the housing relative to the same axes are used. The results of the research enable to develop a simple, fast-acting and sensitive to external perturbations system of stabilization of the bus movement direction.

Keywords: clean power technologies, smart cities, energy, intelligent systems, online monitoring, diagnostics, protection, training systems, electric power industry, green energy.

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1. Introduction

Due to the sharp environmental degradation and the loss of natural resources, there is an urgent need to implement energy-efficient and environmentally friendly equipment, devices and systems. This largely applies to transport, which is currently one of the biggest sources of pollution [1–4]. The solution to this problem is replacement of vehicles with an ICE with electrical analogues or hybrid vehicles [5].

The governments of many developed countries encourage in different ways both manufacturers of electric vehicles and their buyers to abandon the motor vehicle with ICE in favor of eco-friendly transport [6–8]. However, there are objective reasons that slow down the introduction of electric vehicles. The first is the underdeveloped charging station infrastructure, and, in some regions, its non-availability. The second is the technical and operational characteristics of electric cars, which are often worse than in conventional cars with ICE of the same class and the same price category.

Scientists and manufacturers around the world are working on these issues.

For example, the authors of [9] suggest using solar panels in the transport infrastructure to charge urban buses.

In [10], a device that generates electrical energy during boarding / disembarking of passengers in an electric bus is studied. This device can also be used as a power-generating platform for public stops. The energy generated is intended for power supply and charging of the electric bus.

An important component of an electric traction vehicle its traction electric motor (EM). The operational properties of the vehicle depend on the correct choice of EM and its quality.

Manufacturers use different types of traction EM in electric buses. But the analysis makes it possible to conclude that by the "price-simplicity-reliability" criterion the use of asynchronous motors (AM) with a short-circuited rotor is the most rational. In addition, various automatic control systems operate quite effectively with these EMs [11, 6, 12].

In [13], a method for the diagnosis of traction AM by vibrodiagnostic characteristics was developed, which gives a complete picture of their technical condition, significantly increases reliability and allows predicting the engine life.

In addition, the improvement of energy efficiency of electric vehicles is achieved through the control system of electric motors. For example, the authors of [14] solve this by reducing the energy consumed by controlling the amplitude of the three-phase voltage of AM.

Probably the most important feature of any vehicle is its safety for both passengers and other road users. Traffic stabilization is one of the components of traffic safety; in addition, it makes the driver's work easier and improve the comfort of passengers, so research and development in this area are relevant and in demand now.

One way to stabilize the vehicle movement is to use automatic control systems (ACS). Developments of the ways to stabilize traffic in various modes of operation of electric vehicles are quite widely presented in the open sources [15–21].

For example, [21] proposes a controller for lateral stabilization of independent-driven electric vehicles without mechanical differential. This paper proposes a new slider mode controller. Its stability is proved by the Lyapunov stability theorem. According to the authors, this sliding mode control structure is faster, more accurate, reliable and has less vibration than the classic slider mode controller.

The authors of article [23] to assess the state of movement of the vehicle developed a virtual longitudinal force sensor.

In [22], the simultaneous path following and lateral stability control method was presented for four-wheel independent drive and four-wheel independent steering autonomous electric vehicles based on Hamilton energy function with the actuator saturation.

The authors of article [24] investigated the system of the yaw moment control for stabilization of movement in electric cars and offered the scheme of yaw moment control with two degrees of freedom. A rear-wheel-drive electric vehicle was used for practical evaluation of the scheme. With its robust control structure, the presented system can overcome model uncertainties, perturbations of crosswinds and problems of parameter changes.

The above methods are intended for use in electric vehicles. Little attention is paid to the stabilization of electric buses. This is probably because the buses operate at a slower speed and have a much longer acceleration time than cars. Nevertheless, the safety and comfort of electric buses is not less important as the consequences of road accidents can be far more serious. Therefore, the purpose of this work is to improve bus safety with the help of the automatic control system using the method of parametric synthesis of systems for stabilizing the bus movement.

To achieve this goal it is necessary:
- to develop a block diagram of a closed system of stabilization of a moving electric bus;
- to perform parametric synthesis of the systems of stabilization of the moving electric bus;
- to choose the weighty coefficients of the additive integral quadratic functional;
- to develop an algorithm for solving the problem of parametric synthesis of a moving bus stabilizer.

2. Automatic control of the traction asynchronous motor of an electric bus

Operating efficiency of an electric bus (EB) is characterized by its stabilization during movement, which is provided by the system of automatic control of traction electric motors (EM) of the electric drive.

Fig. 1 presents a block diagram of a closed system of stabilization of a moving electric bus.

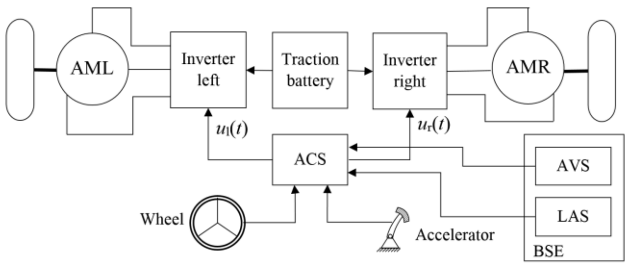

Figure 1. Block diagram of the closed system of stabilization of the moving bus: AML, AMR – AM right and left, respectively; ACS – automatic control system; BSE – block of sensing elements; AVS – angular velocity sensor (gyro); LAS – linear acceleration sensor

The steering wheel, accelerator pedal, and block of sensing elements BSE give signals to the ACS unit.

By way of a sensing element it is advised to use a platformless inertial system containing three gyroscopic angular velocity sensors, whose axis of sensitivity coincides with the main central axes of inertia of the bus body, and a computing device for the calculation of the Rodrigues-Hamilton parameters [25], that determine the angular orientation of the housing relative to the given coordinate system. In addition, it is also suggested that three sensors of linear acceleration of the housing relative to the same axes are used. The alignment of the trajectory of the electric bus is carried out not by turning the wheels, but by changing the speed of rotation of one wheel relative to the other.

The stabilization of the EB during the movement is as follows.

(i) The ACS must ensure that the current speed of motion of the EB center of mass is in conformity with the required speed of movement set by the driver with the accelerator pedal.

(ii) The ACS must provide the direction of movement set by the driver.

As the external conditions are constantly changing during the EB movement, the ACS operates in a continuous transitional mode.

The first requirement for the ACS means that in the transient process, the deviation of the current EB speed $v(t)$ from the desired $v_0(t)$ set by the driver with the accelerator pedal must be minimal. This requirement is satisfied if the ACS delivers a minimum of integral quadratic functional.

$$J_v = \int_0^T \left[\left(v(t) - v_0(t) \right)^2 + \Delta U_r^2(t) + \Delta U_l^2(t) \right] dt = \\ = \int_0^T \left[\Delta U^2(t) + \Delta U_r^2(t) + \Delta U_l^2(t) \right] dt, \tag{1}$$

where $\Delta U_r(t), \Delta U_l(t)$ – are controlling signals at the inputs of invertors on the right and on the left boards of the EB; T – is the regulation time.

During the electric bus movement there is a phenomenon of divergence, consisting in withdrawal of the EB from the trajectory of motion set by the driver. If the electric bus turns evenly Fig. 2, then its current trajectory of motion 1 differs from the required trajectory 2, which is a uniform rotation of the arc of the circle with radius R_0. The degree of deviation of the real motion from the necessary one can be estimated by the value of the integral [26].

$$\int_0^T \left[\Delta\psi^2(t) + \Delta x^2(t) + \Delta y^2(t) \right] dt, \tag{2}$$

$$\Delta\psi(t) = \psi(t) - \psi_0(t);$$
$$\Delta x(t) = x(t) - x_0(t);$$
$$\Delta y(t) = y(t) - y_0(t),$$

where $\Delta\psi_0(t)$, $\Delta x_0(t)$, $\Delta y_0(t)$ – is deviation of current values of turning angle of the EB $\psi(t)$ and coordinates of the center of mass in motionless system x, y from the necessary laws of their change $\psi_0(t)$, $x_0(t)$, $y_0(t)$, which at evenly turn of EB are written down as follows.

$$\psi_0(t) = \frac{v_0}{R_0} t; \tag{3}$$

$$x_0(t) = R_0 \cdot \sin \frac{v_0}{R_0} t; \tag{4}$$

$$y_0(t) = -R_0 \cdot \left[1 - \cos \frac{v_0}{R_0} t \right]. \tag{5}$$

Deviation of the current trajectory of EB movement from the necessary trajectory will be minimal if the ACS gives a minimum of integral quadratic functional:

$$J(\psi) = \int_0^T \left[\begin{array}{c} \Delta\psi^2(t) + \Delta x^2(t) + \Delta y^2(t) + \\ + \Delta U_r^2(t) + \Delta U_l^2(t) \end{array} \right] dt. \tag{6}$$

The algorithms for determining the magnitude of the bus deviation from a given direction of rectilinear movement are based on the method of numerical integration of differential equations describing the EB movement relative to the center of mass. To integrate these equations, it is possible to use difference schemes obtained by the first-order Euler method of accuracy [23].

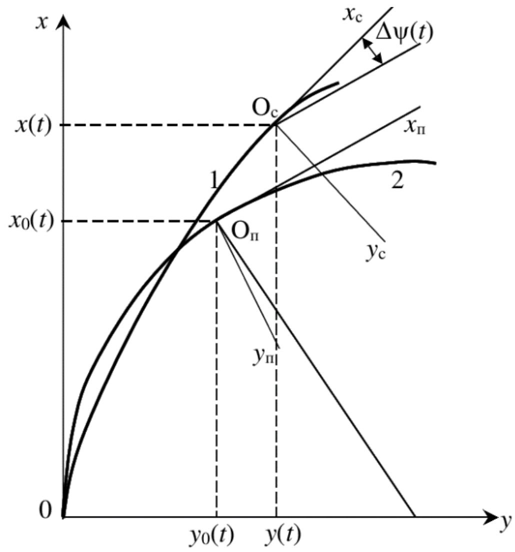

Figure 2. Deviation of the actual movement of the bus from the required: 1 – the current trajectory; 2 – the required trajectory of movement

The accuracy of the Rodrigues-Hamilton parameter calculations can be improved by using the Gauss-Seidel reversal method. In addition, it is proposed to adjust the value of the quaternion norm, which is violated in the process of numerical solution of difference equations.

Improvements in automatic object systems have led to the emergence of the state-of-the-art control theory based on the state space method. Methods of modern control theory are effective in analysis and synthesis of systems of stabilization of complex technical objects in comparison with classical theory of automatic control.

2.1. Parametric synthesis of electric bus stabilization systems during the movement

A schematic representation of the bus movement relative to the predetermined direction specified by the axes of the fixed inertial coordinate system *oxy* is presented in Fig. 3. The moving coordinate system $o_n x_n y_n$ is moved together with the center of mass of the EB, with the directions of the axes $o_n x_n$ and $O_n y_n$ coinciding with the directions of the corresponding axes of the inertial coordinate system, and the point O_n being in the EB center of mass. The axes of associated with the electric bus coordinate system *o'x* 'and *o'y'* coincide with the EB principal central axes of inertia. From the analysis of Fig. 3 we can conclude that the perturbed motion of the EB is characterized by the generalized coordinates $y(t)$ and $\psi(t)$ and the generalized velocities in $\dot{y}(t)$ and $\dot{\psi}(t)$.

The perturbed motion of a closed system of a moving EB stabilization is described by the differential equation of the *n*-th order:

$$\dot{X}(t) = \Phi\left[(t), \alpha\right] + CF(t), \qquad (7)$$

where $\dot{X}(t)$ – is the *n*-dimensional vector of the moving object state; α – is an *s*-dimensional vector of the system varied parameters; $F(t)$ – is an *m*-dimensional vector of random external perturbations, affecting the system; C – is the matrix of external perturbations with the size $n \times m$.

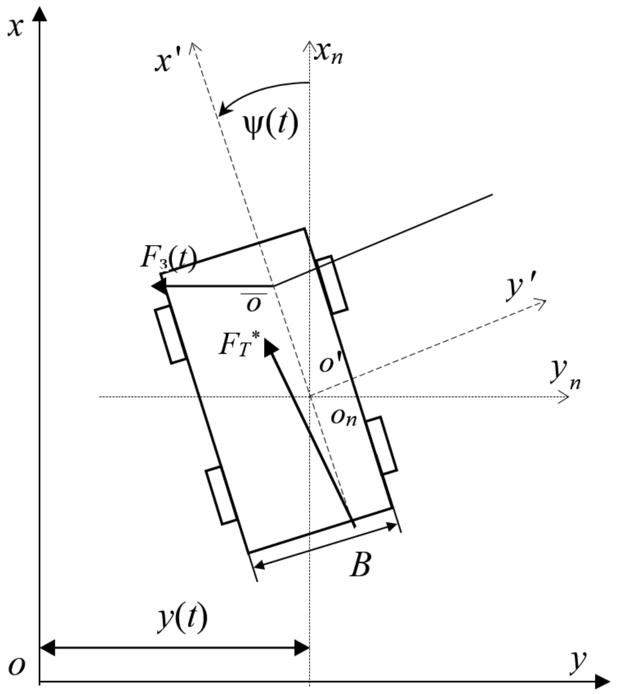

Figure 3. Schematic representation of the electric bus movement relative to a given direction

In the *j*-th implementation of the vector function $F^j(t)$, the *j*-th implementation of the closed-state vector (7) takes place.

The problem of parametric synthesis of system (7) is in the choice of a vector of varied parameters, which, on the solutions of system (7), adds at least an integral quadratic functional:

$$I(\alpha) = \underset{(j=\overline{1,N})}{M} \left\{ \int_0^T \left\langle X^j(t,\alpha), QX^j(t,\alpha) \right\rangle dt \right\}, \qquad (8)$$

where $\underset{j=\overline{1,N}}{M}\{\bullet\}$ – is a symbol of mathematical expectation of a random value $\{\bullet\}$ by implementations of random process $X^j(t,\alpha)$, $(j=\overline{1,N})$; Q – is a quadratic Sylvester matrix.

Functional (8) reflects a system of requirements for a closed system of stabilization, formalized and presented in the form of minimum requirements of a system of integral quadratic functionals.

The formulated problem of parametric synthesis of a stabilization system relates to the nonlinear programming problems, in which the objective function (8) for each of the vectors $\alpha \in G_\alpha$ is calculated by the following rule.

Another equation is added to the system of differential equations (7) of the *n*-th order.

$$\dot{x}_{n+1} = \left\langle X(t), QX^j(t) \right\rangle. \qquad (9)$$

To the system input of (*n* + 1) order (7), (9) *j*-th implementation of random process $F^j(t)$ is fed and solution $X^j(t,\alpha)$ is found, $x^j_{n+1}(t,\alpha)$. For N implementations of random process $F^j(t)$, $(j=\overline{1,N})$ we find N of implementations of random function $x^j_{n+1}(t,\alpha)$, $(j=\overline{1,N})$. From ratios (8) and (9) we obtain:

$$I_j(\alpha) = x^j_{n+1}(T,\alpha). \qquad (10)$$

Thus:

$$I(\alpha) = \underset{(j=\overline{1,N})}{M}\left\{I_j(\alpha)\right\} = \underset{(j=\overline{1,N})}{M} x^j_{n+1}(T,\alpha) = \frac{1}{N}\sum_{j=1}^{N} x^j_{n+1}(T,\alpha). \qquad (11)$$

We evaluate dispersion of a random magnitude (10) [27]:

$$D(\alpha) = \frac{1}{N-1}\sum_{j=1}^{N}\left[x^j_{n+1}(T,\alpha) - I(\alpha)\right]^2. \qquad (12)$$

There is a necessary accuracy of evaluation of functional (8), i.e. magnitudes ε and β, for which $P\left\{\left|I(\alpha) - I_j(\alpha)\right| \le \varepsilon\right\} = \beta$.

According to [27] we find coefficient t_β by the given magnitude β and a necessary quantity of realizations of function $F^j(t)$:

$$\bar{N} = D(\alpha) \cdot t_\beta^2 / \varepsilon^2.$$

Further, we accept $N = \bar{N}$. in function (11).

The task of function (11) minimization by $\alpha \in G_\alpha$ is solved with the help of the Optimization Toolbox software of MathLAB package.

The choice of the weighty coefficients of the additive integral quadratic functional

When solving practical problems of parametric synthesis of the systems of moving objects stabilization, matrix Q of functional (8) is chosen as diagonal:

$$Q = \begin{bmatrix} \beta_1^2 & 0 & \dots & 0 \\ 0 & \beta_2^2 & \dots & 0 \\ \dots & \dots & \dots & \dots \\ 0 & 0 & \dots & \beta_n^2 \end{bmatrix}.$$

In this case functional (8) looks like:

$$\begin{aligned} I(\alpha) &= \underset{(j=\overline{1,N})}{M}\left\{\int_0^T \left[\begin{matrix}\beta_1^2 x_1^2(t,\alpha)+\beta_2^2 x_2^2(t,\alpha)+\dots+\\ +\beta_n^2 x_n^2(t,\alpha)\end{matrix}\right]dt\right\} = \\ &= \beta_1^2 \underset{(j=\overline{1,N})}{M}\left\{\int_0^T x_1^2(t,\alpha)dt\right\} + \beta_2^2 \underset{(j=\overline{1,N})}{M} \times \\ &\times\left\{\int_0^T x_2^2(t,\alpha)dt\right\} + \dots + \beta_n^2 \underset{(j=\overline{1,N})}{M}\left\{\int_0^T x_n^2(t,\alpha)dt\right\}. \end{aligned} \quad (13)$$

Let us enter the symbols:

$$I_i(\alpha) = \underset{(j=\overline{1,N})}{M}\left\{\int_0^T x_1^2(t,\alpha)dt\right\}; (j=\overline{1,N}). \quad (14)$$

Then additive functional (13) is put down as follows:

$$I(\alpha) = \sum_{(j=\overline{1,N})}^{n} \beta_i^2 I_i^2(\alpha), \quad (15)$$

Where weighty coefficients β_i, $(i=\overline{1,N})$ are to be chosen.

The components of vector *X (t)* state have different dimensions, so weighty coefficients β_i $(i=\overline{1,N})$ must also have different dimensions, so that the additive functional (15) has a dimension equal to the dimensions of each of the additions. In this connection, we will reduce all partial functionals (14) to a uniform dimension:

$$\overline{I}_i(\alpha) = \frac{1}{x_{i\max}^2} I_i(\alpha);\ i=\overline{1,N}, \quad (16)$$

where $x_{i\max}^2$ – is a maximum value that component $x_i(t,\alpha)$ can reach in the stabilized process. In this case, all normalized of partial function (16) have the same dimensions.

The normalized weighty dimensionless coefficients are also input:

$$\overline{\beta}_i = x_{i\max}\beta_i;\ (i=\overline{1,n}). \quad (17)$$

Then the additive functional (15) has the dimension of each of the normalized partial functionals (16) and is equal to:

$$I(\alpha) = \sum_{i=1}^{n} \overline{\beta}_i^2 \overline{I}_i\ (\alpha). \quad (18)$$

When the weighty coefficients $\overline{\beta}_i, (i=\overline{1,n})$ are fixed, the minimal value of functional (18) is:

$$I^* = \sum_{i=1}^{n} \overline{\beta}_i^2 \overline{I}_{ii}^*(\alpha), \quad (19)$$

where $\overline{I}_{ii}^*(\alpha)$ – is the minimum values of partial functionals (14) obtained by minimizing each of these functionals.

Let us set the problem of choosing weighty coefficients $\overline{\beta}_i, (i=\overline{1,n})$ such that the additive functional reaches the minimum (19). If no restrictions are imposed on value $\overline{\beta}_i, (i=\overline{1,n})$, then the formulated problem has a trivial solution $\overline{\beta}_i = 0, (i=\overline{1,n})$ in which the functional (19) has zero value. However, this decision is not practical, so coefficients $\overline{\beta}_i, (i=\overline{1,n})$ need to be constrained that would not allow these coefficients to be zero. Let us write this restriction in the form:

$$\sum_{i=1}^{n} \overline{\beta}_i = 1. \quad (20)$$

Let us put the task of minimizing function (19) when constraining (20).

To solve the formulated task for the constrained extremum the Lagrange function is made:

$$F(\overline{\beta}_1,\overline{\beta}_2,\dots,\overline{\beta}_n) = \sum_{i=1}^{n} \overline{\beta}_i^2 \overline{I}_i^* + \lambda\left(1-\sum_{i=1}^{n}\overline{\beta}_i\right). \quad (21)$$

where λ – is the Lagrange multiplier.

Let us write down the conditions of the function extremum (21):

$$\frac{\partial F(\overline{\beta}_1,\overline{\beta}_2,\dots,\overline{\beta}_n)}{\partial \overline{\beta}_i} = 2\overline{\beta}_i\,\overline{I}_i^* - \lambda = 0;\ \ (i=\overline{1,n}). \quad (22)$$

From ratios (22) we have:

$$\overline{\beta}_i = \frac{\lambda}{2\overline{I}_i^*};\ \ (i=\overline{1,n}). \quad (23)$$

Let us put ratios (23) in formula (20):

$$\frac{\lambda}{2}\sum_{i=1}^{n}\frac{1}{I_i^*}=1 \Rightarrow \lambda = 2/\sum_{i=1}^{n}\frac{1}{I_i^*}. \qquad (24)$$

With condition (24) ratios (23) look like:

$$\bar{\beta}_i = \frac{1}{\bar{I}_i^* \sum_{i=1}^{n}\frac{1}{\bar{I}_i^*}}; \; (i=\overline{1,n}). \qquad (25)$$

In formula (25) we put ratios (16) and (17):

$$\beta_i = \frac{x_{i\max}}{\bar{I}_i^* \sum_{i=1}^{n}\frac{x_{i\max}^2}{\bar{I}_i^*}}; \; (i=\overline{1,n}). \qquad (26)$$

Thus, in order to find the weighty coefficients of an additive functional (13), it is necessary to consistently solve n problems of parametric synthesis of a dynamic system (7) for each of the partial functionals (14) and to find their minimum values I_i^*; $(i=\overline{1,n})$.

An algorithm for solving the problem of parametric synthesis of the stabilizer of a moving electric bus

The algorithm is a set of four consecutive computing blocks, Fig. 4.

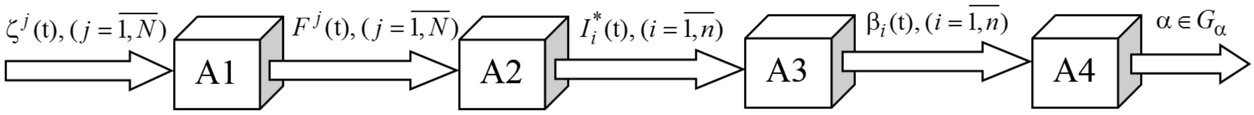

Figure 4. Structural and logical scheme of the algorithm for solving the problem of parametric synthesis

Block A1 is the generator of a random vector function $F^j(t), (j=\overline{1,N})$. A vector m-dimensional white noise $\zeta^j(t)$ is fed to the input of block A1. The function generator $F^J(t), (j=\overline{1,N})$ is a set of m-forming dynamic units, each of which converts the "white noise" $\zeta_i^j(t), (j=\overline{1,N}; i=\overline{1,m})$ into the j-th implementation of the corresponding component of the vector function $F^j(t), (j=\overline{1,N})$, which we denote like $F_i^j(t), (j=\overline{1,N}; i=\overline{1,m})$.

From the output of block A1, realizations of $j=\overline{1,N}$ of the external perturbation $F(t)$ are fed to the input of block A2, which implements the mathematical model of a closed stabilization system (7), as well as the Optimization Toolbox procedure of the MathLAB software package with respect to partial functionals (14). As a result, output A2 has minimal values of partial functionals.

From the output of the block A2 values $I_i^*, (i=\overline{1,n})$ are fed to input A3. Unit A3 implements formulas (26) for finding weighty coefficients $\beta_i, (i=\overline{1,n})$ of the additive functional (13) and forms the additive functional (13). Block A4, like A2, implements the mathematical model (7), as well as the above minimization procedures with respect to additive functional (13). As a result, at the output of block A4 we have the value of the variable parameters of the movable object stabilizer $\alpha \in G_\alpha$, which provide a minimum of additive functional (13). As a set of acceptable values of the varied parameters Gα, it is recommended to choose the stability region of a closed stabilization system in the space of the variable parameters of the stabilization algorithm.

The uniqueness of solution to the problem of parametric synthesis of a moving bus stabilizer

Let us look at the system of first approximation in relation to the system (7):

$$\dot{X}(t) = A(\alpha)X(t) + CF(t), \qquad (27)$$

Where the quadratic matrix $A(\alpha)$ equals:

$$A(\alpha)=\begin{bmatrix} \left(\frac{\partial\varphi_1 X(t),\alpha}{\partial x_1(t)}\right)_0 & \left(\frac{\partial\varphi_1 X(t),\alpha}{\partial x_2(t)}\right)_0 & \dots & \left(\frac{\partial\varphi_1 X(t),\alpha}{\partial x_n(t)}\right)_0 \\ \left(\frac{\partial\varphi_2 X(t),\alpha}{\partial x_1(t)}\right)_0 & \left(\frac{\partial\varphi_2 X(t),\alpha}{\partial x_2(t)}\right)_0 & \dots & \left(\frac{\partial\varphi_2 X(t),\alpha}{\partial x_n(t)}\right)_0 \\ \dots & \dots & \dots & \dots \\ \left(\frac{\partial\varphi_n X(t),\alpha}{\partial x_1(t)}\right)_0 & \left(\frac{\partial\varphi_n X(t),\alpha}{\partial x_2(t)}\right)_0 & \dots & \left(\frac{\partial\varphi_n X(t),\alpha}{\partial x_n(t)}\right)_0 \end{bmatrix},$$

and through $\varphi_i[X(t),\alpha],(i=\overline{1,n})$ the components of vector-function $\Phi[X(t),\alpha]$ are indicated. The elements of matrix *A (α)* are derivatives of the component of the vector function $\Phi[X(t),\alpha]$ at point X = 0. In accordance with the O.M. Lyapunov theorems on stability at first approximation, system (7) is stable if the first approximation system (27) is stable.
The value of system (27) is:

$$I(\alpha)=X(0),\ K(\alpha)X(0)+...+T\cdot S_p\left[Q_f K(\alpha)\right] \quad (28)$$

where Q_f – is a matrix of intensity of external perturbation $F(t)$; $S_p\{\bullet\}$ – is a hole or a matrix spur $\{\bullet\}$; $K(\alpha)$ – is a quadratic symmetrical Sylvester *V* matrix, which meets the matrix algebraic equation:

$$K(\alpha)A(\alpha)+A^T(\alpha)K(\alpha)+Q=0 \quad (29)$$

where *T* – is the time of analysis of a random process *X*(*t*).

The solution of the parametric synthesis problem formulated above is carried out to find the minimum by $\alpha\in G_\alpha$ in relation (28). Any of the many known numerical methods of the extremum of the function of many variables, including the most common Nelder-Mead method implemented in MATLAB's Optimization Toolbox software, allows you to find the local minimum of function (28). Finding the global minimum of function (28) significantly complicates the problem of parametric synthesis.

As the set Gα, we choose the stability region of system (27), whose characteristic equation is written in the form:

$$\det\left[A(\alpha)-E_s\right]=0. \quad (30)$$

When $\alpha\in G_\alpha$ all the roots of the characteristic equation (30) are to the left of the imaginary axis of the complex plane of the roots, and the hypersurface Gα, which limits the set Gα, is the reflection of the imaginary axis of the plane of the roots of the characteristic equation (30) to the *s*-dimensional space of the variable parameters R^S.

In the plane of the roots of characteristic equation (30), we consider the line:

$$s=\beta+j\omega, \quad (31)$$

that is parallel to the imaginary axis of the plane of the roots and spaced from the imaginary axis by value β <0. The mapping of this line to the *s*-dimensional space of the variable parameters of the R^S system determines the hypersurface of equal degree of stability and limits domain Gα (β). If $\alpha\in G_\alpha(\beta)$, then the degree of stability of such a system is not less than β. This means that when $\alpha\in G_\alpha(\beta)$ the nearest root to the imaginary axis is a real root, or a pair of complex conjugated roots of equation (30) are to the left of the imaginary axis not less than distance |β|. Choosing $|\beta_1|<|\beta_2|<...<|\beta_k|$, we obtain the sets $G_\alpha(\beta_1),G_\alpha(\beta_2),...,G_\alpha(\beta_k)$, that are limited by hypersurfaces $\Gamma_\alpha(\beta_1)$, $\Gamma_\alpha(\beta_2)$, ... $\Gamma_\alpha(\beta_k)$ respectively, which are put into each other: $G_\alpha(\beta_k)\in G_\alpha(\beta_{k-1})\in...\in G_\alpha(\beta_1)$.

Let us suppose that at β = βk, the set Gα (βk) and the hypersurface Gα (βk) are contracted to a point in the *s*-dimensional space R^S, which is the point of the maximum degree of stability.

It is known that any stable system:

$$\dot{X}(t) = A(\alpha)X(t) \quad (32)$$

corresponds to Lyapunov function:

$$V\left[X(t),\alpha\right] = \left\langle X(t),K(\alpha)X(t)\right\rangle, \quad (33)$$

where matrix K (α) satisfies the linear algebraic equation (29) obtained by the Lyapunov equation:

$$\frac{\partial V\left\lfloor X(t),\alpha\right\rfloor}{\partial t} = -\left\langle X(t),QX(t)\right\rangle. \quad (34)$$

Lyapunov function (33) is a positive-definite quadratic form that can be interpreted as the norm of the state vector *X*(*t*) ρ[*X*(*t*)],, which is zero at *X*(*t*)=0, and for all *X*(*t*)≠0 is a positive value. The complete derivative of the Lyapunov function in time, in accordance with equation (34), is a negative-definite form, that is, at any moment of time, the norm of the state vector ρ[*X*(*t*)] decreases and approaches zero indefinitely (Fig. 5, curve 1).

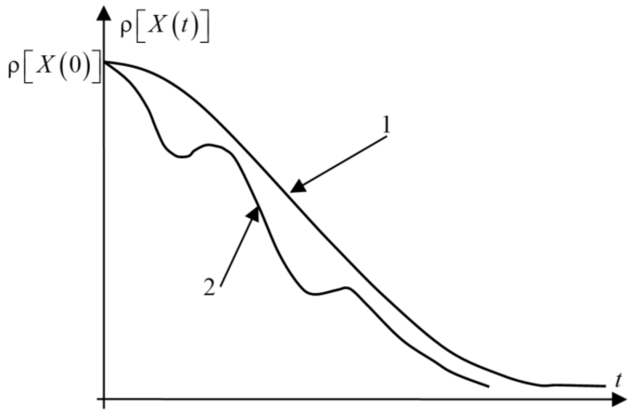

Figure 5. Norm of the vector of state *X*(*t*) ρ[*X*(*t*)]:
1 – solution of the tasks of parametric synthesis;
2 – at several local minimums (8)

If functional (8) had several local minimums, then such minimums would be affected by the trajectory of the curve ρ[*X*(*t*)] (Fig. 5, curve 2). Thus, functional (8) calculated on the solutions of the dynamic system (32) has a single minimum, which is global and determines the solution to the problem of parametric synthesis.

Bottom line, it should be said that one of the most important trends in the development of modern control theory is the method of parametric synthesis of the systems of moving objects stabilization. The algorithmic method of parametric synthesis of stabilizing systems is designed to automate the process of parametric synthesis of the system.

6. Conclusions

In this work a structural diagram of a closed system of stabilization of a moving electric bus has been developed. Parametric synthesis of the systems of stabilization of the electric bus during movement is made and the weighty coefficients of the additive integral quadratic functional are chosen.

An algorithmic method of parametric synthesis of motion stabilization systems of a moving electric bus has been developed. This method is based on the direct calculation of the purpose function on the solutions of the mathematical model of the perturbed motion of the electric bus with the further minimization of this function with the purposeful choice of weighty coefficients and enables to almost completely automate the process of parametric synthesis of the system.

It is proposed to use as a sensible element a platformless inertial system containing three gyroscopic angular velocity sensors, whose axes of sensitivity coincide with the main central axes of inertia of the bus body, and a computing device for calculating the Rodrigues-Hamilton parameters that determine the angular orientation of the housing relative to the given coordinate system. Using three sensors for linear acceleration of the housing relative to the same axes is also suggested.

The alignment of the trajectory of the electric bus movement is made not by turning the wheels, but by changing the speed of rotation of one wheel relative to the other.

The results of the research make possible to develop a simple, high-speed and sensitive to external disturbances system of stabilization of a bus movement direction.

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Conflict of interests.

The authors declare that there is no conflict of interests regarding the publication of this paper.

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