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 $n \times m$.

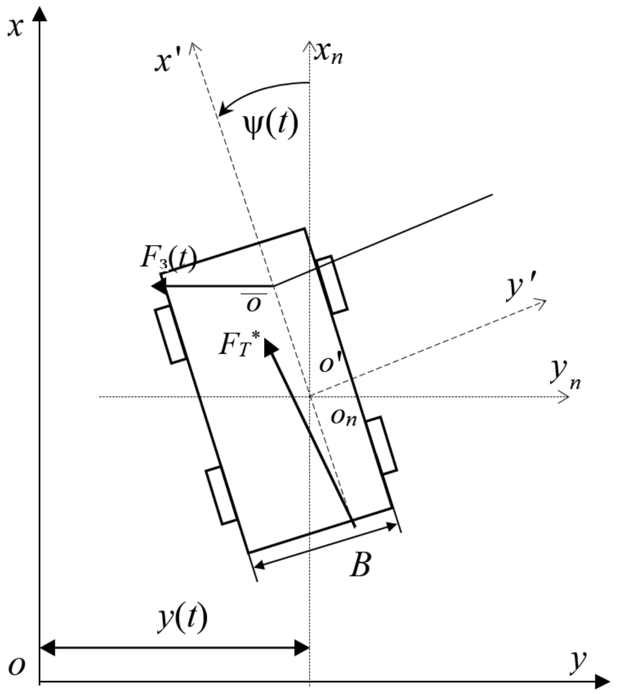

Figure 3. Schematic representation of the electric bus movement relative to a given direction

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:

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

where $\underset{j=1,N}{M}\{\bullet\}$ – 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, $x_{n+1}^j(t,\alpha)$. For *N* implementations of random process $F^j(t)$, $(j=\overline{1,N})$ we find *N* of implementations of random function $x_{n+1}^j(t,\alpha)$, $(j=\overline{1,N})$. From ratios (8) and (9) we obtain:

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

Thus:

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

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

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

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:

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

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.

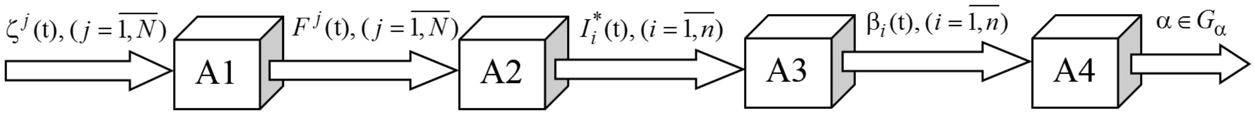

Figure 4. Structural and logical scheme of the algorithm for solving the problem of parametric synthesis

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:

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

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:

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

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).

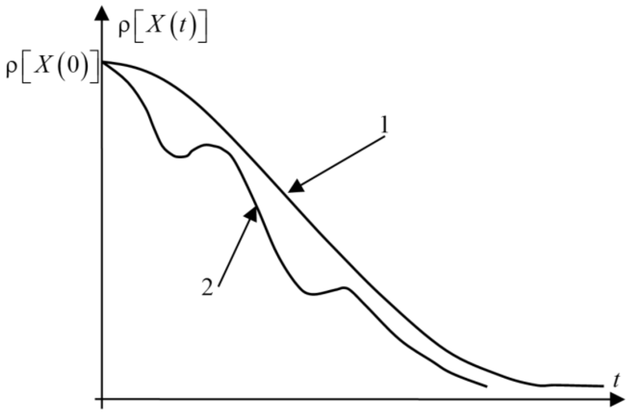

Figure 5. Norm of the vector of state *X*(*t*) ρ[*X*(*t*)]: 1 – solution of the tasks of parametric synthesis; 2 – at several local minimums (8)

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.

Acknowledgements.

This work was conducted under the Scientific research "Development of the system of energy saving and electric energy generation for vehicles", 0219U100696, funded by the Ministry of Education and Science of Ukraine.

Conflict of interests.

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

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