380. NEW INTELLIGENT REGULATORS FOR MECHATRONIC SYSTEMS

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Abstract. The paper considers new intelligent regulators combining accuracy and speed without overshoot as well as controls providing adaptability at guaranteed stability of controlled system in non-stationary conditions. The developed regulators connect target and actual values of output variables of the controlled system and criteria, enabling variation of properties of the criteria in an accessible form. The proposed adaptive regulators are capable to implement control near the capability limits and consequently provide solutions of known and new control tasks at a qualitatively new level.

Introduction

Currently progress in increasing dynamical and ecological qualities of the machines is directly associated with developments in mechatronics. Dynamic quality of the mechanical systems is defined by built-in control system and materials. Mechatronics - a branch of science and technology devoted to creation and application of machines and systems with computer-aided control of motion, which are based on knowledge in the fields of mechanical engineering, electronics and embedded systems, information technology and control of the machines and aggregates. Typical examples of mechatronic systems (MS) include mobile machines, equipped with active safety systems, automatic gearbox, engine with computer control and others. In design of machines a problem of vibration and noise is of high importance. The fundamentals of these problems are considered in works [1-6] and many others.

The primary goal of MS is maintenance of a minimum of its criteria. Maximization tasks are reduced to minimization. The requirement of minimization of criteria is reduced to minimization of mismatches between the desirable and the actual values of the output variables at each moment in time. For the realization of minimization in non-stationary conditions, an adaptive regulator combining speed and accuracy of control without overshoot is required. Available classical regulators, such as PID regulators, cannot provide perfect quality while solving the tasks of adaptive control. Adaptive regulators, which are used in specific controlled systems, are not universal [12, 13]. There is a need for novel intelligent regulators, which can provide solutions for MS at a qualitatively new level, providing perfect accuracy and fast action. Thus, the problem of design of regulators that combine accuracy and speed without overshoot at guaranteed stability of the controlled system is obvious. To solve this problem, a new concept, a control synthesis technology and adaptive control algorithms were developed.

Criteria

The control criteria are the cornerstone for any system, including MS. Such criteria are completely defined by the end-user of the system. In most cases the requirement to the control system is defined by the quality of the transient. The integral criteria of quality allow evaluating accuracy, speed and some other properties of quality by one number [7-9].

Suppose that the order of the system equals n. Let the state of the controlled system be characterized by an output variable $x(t)$ and its derivatives $\dot{x}(t),...,x^{(n-1)}(t)$. The boundary conditions are given as:

$$t = t_0: \ x(t_0) = x_0,\ \dot{x}(t_0) = \dot{x}_0,\ ..,\ x^{(n-1)}(t_0) = x_0^{(n-1)}; \quad (1)$$

$$t \to \infty: \ x(t) \to \bar{x},\ x^{(\nu)}(t) \to 0, \quad \nu = 1, 2, ..., n-1. \quad (2)$$

The condition (1) reflects an initial state, and the condition (2) - the requirement of asymptotic stability of the system according to the Lyapunov Second law.

Let's for an output variable $x_k(t)$ consider the criteria:

$$J_n = \int_{t_0}^{t_1} \varphi(\varepsilon_k^2, \tau_1^2 \dot{\varepsilon}_k^2, ..., \tau_n^2 \varepsilon_k^{(2n)}) dt \,. \qquad (3)$$

Here $\varphi(.)$ is a given functional; $\varepsilon_k(t) = \bar{x}_k(t) - x_k(t)$ is an error; $\bar{x}_k(t)$ is the target (command) value of $x_k(t)$; $\dot{\varepsilon}_k(t) = \dot{\bar{x}}_k(t) - \dot{x}_k(t)$; $\varepsilon_k^{(n)}(t) = \bar{x}_k^{(n)}(t) - x_k^{(n)}(t)$; for tasks such as stabilization: $\varepsilon_k(t) = \bar{x}_k(t) - x_k(t)$; $\dot{\varepsilon}_k(t) = -\dot{x}_k(t)$; $\varepsilon_k^{(n)}(t) = -x_k^{(n)}(t)$; for tasks of vibration protection: $\varepsilon_k(t) = -x_k(t)$; $\varepsilon_k(t) = -x_k(t)$; $\dot{\varepsilon}_k(t) = -\dot{x}_k(t)$; $\varepsilon_k^{(n)}(t) = -x_k^{(n)}(t)$.

The requirement of minimization of the criteria (3) can be reduced to the definition of the desirable properties of the output variable $x_k(t)$ with the help of the differential equation of the order n:

$$x_k^{(n)} = f(\beta_{n-1} x_k^{(n-1)}, \; ... \;, \beta_1 \dot{x}_k, \; \beta_0 x_k, \; \beta_{n-1} \bar{x}_k^{(n-1)}, ..., \beta_1 \dot{\bar{x}}_k, \; \beta_0 \bar{x}_k) \quad (4)$$

with the initial conditions (1). The coefficients $\beta_0, ..., \beta_{n-1}$ are defined through constants $\tau_1, ..., \tau_n$ and included in criteria (3). In other words, the requirement of minimization of criteria in the integral form (3) can be presented in the differential form (4) and vice versa.

Finding the operator $f(.)$ for any function $\varphi(.)$ is not a simple task. However, the solution of this task is not required. It is possible to initially set the properties of the output variables of target transient in the form of the desirable nonlinear differential equations (4).

Task formulation

Given:

- desirable motion properties of the output variables of mechatronic systems as:

$$\dot{x} = f(\bar{x}, x) \,, \qquad (5)$$

with initial conditions (1), where $f(.)$ is the given operator, generally nonlinear;

- limitation on the output variables of the appropriate power drives:

$$q_{pi-} \le q_{pi}(x, u, t) \le q_{pi+}, \;\; i = 1, ..., m, \qquad (6)$$

where q_{pi-}, q_{pi+} are given values;

- limitation on control functions:

$$u_{i-} \le u_i(t) \le u_{i+}, \;\; i = 1, ..., m, \qquad (7)$$

where u_{i-}, u_{i+} are the acceptable values;

- preference functions for the fuzzy set parameters of the mechatronic systems and the quality criterion:

$$\mu_{Ai}(z_i) \,, \quad i = \overline{1, l} \,.$$

Here $\mu_{Ai}(z_i)$ is a preference function of parameter z_i: $0 \le \mu_{Ai}(z_i) \le 1$; A is the set.

It is required to construct a regulator $u_k(x, \dot{x}, \bar{x}, \; f, \; \dot{f}), \; k = 1, ..., m$, such that the conditions of the optimality of motion (5) at each moment of time are provided fulfilling the limitations (6)-(7), and also the initial and boundary conditions (1), (2). The condition (2) ensures an asymptotic stability of the controlled system. It is assumed that the functional $f(.)$ is such that the existence and uniqueness of solution of the formulated task is provided. The obtained formulation of the task corresponds to the inverse tasks of controlled systems dynamics [7-9].

Theoretical premises

Let's consider integral square-law criteria like [7]:

$$J_n = \int_{t_0}^{t_1} (\varepsilon_k^2 + \tau_1^2 \dot{\varepsilon}_k^2 + ... + \tau_n^2 \varepsilon_k^{(2n)}) dt \,. \qquad (8)$$

Using the Euler-Poisson's equation and requiring that at $t \to \infty$ the function $x_k(t)$ approaches specified value $\bar{x}_k$, and its derivatives approach to zero, it is possible to show that the minimum of the integral square-law criteria (8) is reduced to the requirement that the output variable of the controlled system corresponds to the solution of the linear differential equation of the order n:

$$x_k^{(n)} + \beta_{n-1} x_k^{(n-1)} + \; ... \; + \beta_1 \dot{x}_k + \beta_0 x_k = \beta_0 \bar{x}_k \,, \qquad (9)$$

with the initial conditions (1). Constants $\beta_0, ..., \beta_{n-1}$ can be calculated through constants $\tau_1, ..., \tau_n$, which are included in criteria (8). Further on, the equation (9) can be considered as an input equation of the desired motion.

The requirement of a minimum of the integral criteria is reduced to the differential equation of reference motion for an output variable. This principle is basic in the represented theory, and its validity will be shown further on.

Let's consider the criterion:

$$J_n = \int_{t_0}^{t_1} (x^2 + \tau_1^2 \dot{x}^2 + ... + \tau_n^2 x^{(2n)})\ dt\ . \qquad (10)$$

So, we will discover such a function $x(t)$, which corresponds to the boundary conditions (1) and (2) and supplies a minimum to the integral (10). It is a classical task of calculus of variations.

The necessary condition of a minimum of the integral J_n according to the known theory of calculus of variations looks as follows:

$$\frac{\partial \varphi}{\partial x} - \frac{d}{dt}\left(\frac{\partial \varphi}{\partial \dot{x}}\right) + .. + (-1)^n \frac{d^n}{dt^n}\left(\frac{\partial \varphi}{\partial x^{(n)}}\right) = 0\ , \quad (11)$$

where $\varphi(.) = x^2 + \tau_1^2 \dot{x}^2 + ... + \tau_n^2 x^{(2n)}$.

The differential equation (11) is the Euler-Poisson's equation.

Let's insert into (11) the function mentioned $\varphi(x,\ \dot{x}, ...,\ x^{(n)})$:

$$\frac{\partial \varphi}{\partial x} = 2x\ ;$$

$$\frac{\partial \varphi}{\partial x^{(s)}} = 2\tau_s^2 x^{(s)},\ \ s = 1,\ 2, ..., n\ ;$$

$$\frac{d^n}{dt^n}\left(\frac{\partial \varphi}{\partial x^{(n)}}\right) = 2\tau_s^2 x^{2(s)},\ s = 1, 2, ..., n.$$

Therefore, the equation (11) will look like:

$$x - \tau_1^2 \ddot{x} + \tau_2^2 x^{(4)} + ... + (-1)^{n-1} \tau_{n-1}^2 x^{2(n-1)} = 0.$$

Thus, the extremal $x(t)$, at which the integral obtains its minimum, is the solution of the $2(n-1)$ – order differential equation (11), where $x(t)$ should obey to the boundary conditions (1) and (2).

The characteristic equation corresponding (11) is:

$$x - \tau_1^2 p^2 + \tau_2^4 p^4 + ... + (-1)^{n-1} \tau_{n-1}^2 p^{2(n-1)} = 0.$$

It has the property, that its radicals are mutually symmetric about an origin of coordinates of the complex area p, i.e. to the radicals $p_1, ..., p_n$ correspond the radicals $p_{n-1} = -p_1, ...,\ p_{2n} = -p_n$. Based on this, it is possible to write the solution (11) as:

$$x(t) = \sum_{\nu=0}^{n} (c_\nu e^{-p_\nu t} + c_{n+\nu} e^{p_{n+\nu} t}),$$

where the constants c_ν, $c_{n+\nu}$ should be such that the given boundary conditions (1) and (2) are fulfilled.

Let the radicals are such that:

$$\mathrm{Re}(-p_\nu) < 0,\ \ \mathrm{Re}(p_{n+\nu}) > 0,\ \ \nu = 1, ..., n.$$

In this case the values $c_{n+\nu}$ should be equal to zero, because according to (2) at the $t \to \infty$ function $x(t)$ and its derivatives tend to zero.

Thus the expression for the extremal should be:

$$x(t) = c_1 e^{-p_1 t} + ... + c_n e^{-p_n t}. \qquad (12)$$

However it is known that $x(t)$, defined the formula (12), is solution of the equation of the order n:

$$x^{(n)} + \beta_{n-1} x^{(n-1)} + ... + \beta_1 \dot{x} + \beta_0 x = 0. \qquad (13)$$

The initial conditions for the equation (13) are the conditions (1).

The constants $\beta_0, ..., \beta_{n-1}$ of this equation are uniquely expressed through the radicals $-p_\nu$ under the Vieta's formulas. Thus, the Euler-Poisson equations are necessary conditions of a minimum. The sufficient conditions are provided in further by sufficing boundary conditions (1) and (2) for the extremes obtained according to these conditions.

Let's consider the equations (13) in the view of the boundary conditions (1) and (2) for criteria of the first and second orders. We convert to an integral square-law criterion of the first order:

$$J_1 = \int_{t_0}^{t_1} \left[x^2(t) + \tau_1^2 \dot{x}^2(t) \right] dt\ . \qquad (14)$$

Here value τ_1 is assigned according to desirable properties of the transient of the output variable. The square-law integral criterion (14) allows to obtain rapidly damping process, but sufficiently smoothly varying transient.

For an integrand:

$$\varphi(.) = x^2 + \tau_1^2 \dot{x}^2$$

the Euler-Poisson's equation looks like:

$$\frac{\partial \varphi}{\partial x} - \frac{d}{dt}\left(\frac{\partial \varphi}{\partial \dot{x}}\right) = 0\ .$$

Putting the expression for $\varphi(.)$ in this equation and fulfilling the necessary conversions, we receive the differential equation:

$$x(t) - \tau_1^2 \ddot{x}(t) = 0,$$

which solution is extremes, supplying a minimum to an integral J_1.

Characteristic equation:

$$1-\tau_1^2 p^2 = 0, \qquad (15)$$

responding to the requirement of a minimum (11), has the radicals:

$$p_1 = -1/\tau_1,\ p_2 = 1/\tau_1.$$

Therefore, according to the (15) the required solution will look like:

$$x(t) = C_1 e^{-t/\tau_1} + C_2 e^{t/\tau_1}. \qquad (16)$$

Substitution of initial conditions (1) into expression (16) yields the constants:

$$C_1 = \frac{x_0}{1+e^{-2t_0/\tau_1}};\ \ C_2 = \frac{x_0}{1+e^{2t_0/\tau_1}}.$$

As the extremal should fulfill the boundary conditions (1) and (2), it is necessary to accept $C_2 = 0$. The expression (16) will look as follows:

$$x(t) = C_1 e^{-t/\tau_1},\ C_1 = x_0. \qquad (17)$$

The extremes (17) is a solution of the differential equation of the first order:

$$\begin{aligned} &\tau_1 \dot{x} + x = 0, \\ &t \ge t_0:\ \ x(t_0) = x_0. \end{aligned} \qquad (18)$$

Thus, at tendency to minimize the value of the criteria J_1 the transient curve comes closer to the exponent (17) with a desirable time constant τ_1. The equation of reference motion is the linear differential equation of the first order (18).

The equation of reference motion (18) can be obtained without usage of the Euler's equation. Let's perform the following conversions:

$$J_1 = \int_{t_0}^{t_1}\left[x^2(t)+\tau_1^2\dot{x}^2(t)\right]dt = \int_{t_0}^{t_1}\left[x(t)+\tau_1\dot{x}(t)\right]^2 dt + \int_{t_0}^{t_1} 2\tau_1\, x\dot{x}dt =$$
$$\int_{t_0}^{t_1}\left[x(t)+\tau_1\dot{x}(t)\right]^2 dt + \tau_1 x_0^2. \qquad (19)$$

The least value J_1 will be under condition of:

$$\tau_1 \dot{x} + x = 0. \qquad (20)$$

The solution of the equation (20) is:

$$x(t) = x_0 e^{-t/\tau_1}.$$

and it represents that exponential curve, to which the extremes curve approaches at tendency to minimize value J_1.

At nonzero target value $\bar{x}(t)$ instead of the equation (20) we obtain:

$$\begin{aligned} &\tau_1 \dot{x} + x = \bar{x}, \\ &t \ge t_0:\ \ x(t_0) = x_0. \end{aligned}$$

Let's consider the square-law criteria of the second order:

$$J_2 = \int_{t_0}^{t_1}\left[x^2(t)+\tau_1^2\dot{x}^2(t)+\tau_2^2\ddot{x}^2(t)\right]dt. \qquad (21)$$

Let's designate the integrand:

$$\varphi(.) = x^2 + \tau_1^2\dot{x}^2 + \tau_2^2\ddot{x}^2. \qquad (22)$$

Following the presented technology for minimization of criteria J_2, we shall substitute the function $\varphi(.)$ in the Euler-Poisson equation and perform necessary conversions. Necessary conditions of a minimum will be obtained as the equation of the fourth order. Taking into account boundary conditions (2), a linear differential equation of the second order will correspond to the reference motion as shown:

$$\ddot{x} + 2\psi\omega_0\dot{x} + \omega_0^2 x = 0. \qquad (23)$$

The definition of motion properties of the controlled system by the equation (23) is equivalent to the requirement of a minimum of the integral square-law criteria (21).

Instead of the equation (23), the following equation is considered for the given command value $\bar{x}(t)$:

$$\ddot{x} + 2\psi\omega_0\dot{x} + \omega_0^2 x = \omega_0^2\bar{x}. \qquad (24)$$

It is necessary to pay attention to the important circumstance: the equations (23) or (24), considered further as initial equations of reference motion for a controlled variable, are obtained with respect to boundary conditions (1) and (2). It means that the conditions of an asymptotic stability of the system are fulfilled, if the controlled variable corresponds to these equations. An important conclusion follows: if we manage to synthesize a control, which provides the course of the output processes according to the given reference equations, the stability of the system is ensured.

Let the desirable motion properties of the system for the controlled coordinates $x = (x_1, ..., x_m)^T$ be given as a diversity:

$$\Omega:\ w_\mu(x,t) = C_\mu, \quad \mu = 1, ..., m, \qquad (25)$$

where $w_\mu(.)$ are given operators; C_μ are constants: $C_\mu > 0$; and t is time.

The type of representation of the desirable motion properties of the system (25) is not a uniquely possible. The motion properties, as it was already mentioned, can be given differentially by equations of the reference motion:

$$\dot{x} = f(\bar{x}, x) \qquad (26)$$

with boundary conditions (1) and (2). Here $f = (f_1, ..., f_m)^T$; $f_i(.)-$are given operators, generally nonlinear, defined by fuzzy sets; $x = (x_1, ..., x_m)^T$ is a vector of phase coordinates; $\dot{x} = (\dot{x}_1, ..., \dot{x}_m)^T$ is a vector of phase velocities; $\bar{x} = (\bar{x}_1, ..., \bar{x}_m)^T$ is a vector of target (command) values.

According to the conditions (1) or (2) the equation of motion of the controlled system can be constructed. However, in widely used statements of the tasks of control the equation of the system are assumed to be known with accuracy to a control vector $u = (u_1, ..., u_m)^T$:

$$\dot{x} = F(x, u), \qquad t \ge t_o:\ x(t_o) = x_o, \qquad (27)$$

Here $F = (F_1, ..., F_n)^T$ is a vector of the right-hand parts.

Generally, the desirable motion properties of the controlled system are set by the nonlinear differential equations for the controlled variables:

$$x_k^{(n)} = f_k(x_k^{(n-1)}, ..., x_k, \bar{x}_k), \quad k = 1, ..., m \qquad (28)$$

with boundary conditions (1) and (2). Here $f_k(.)$ are nonlinear operators; $\bar{x}_k$ are given target values.

5. Intelligent regulators

The basic control algorithms, corresponding to the shown statement of the task, look like [13, 14]:

$$u_k(\bar{x}_k, x_k, \dot{x}_k, \ddot{x}_k, \dddot{x}_k, x_k^{(4)},\ f_k, \dot{f}_k, \ddot{f}_k,\ z_k, \dot{z}_k, \ddot{z}_k) = \Phi_0(k_0 z_k + \sum_j \Phi_j(.)), \quad j = 1...3 \qquad (29)$$

where:

$$\Phi_1(.) = \Phi_1(f_k, \dot{f}_k, \ddot{f}_k),$$

$$\Phi_2(.) = \Phi_2(\bar{x}_k, x_k, \dot{x}_k, \ddot{x}_k, \dddot{x}_k, x_k^{(4)}),$$

$$\Phi_3(.) = \Phi_3(z_k, \dot{z}_k, \ddot{z}_k).$$

Here $\Phi_j(.)$ are known functions, which variation enables to obtain a wide spectrum of adaptive regulators; k_0 is a constant describing the efficiency of negative feedback on an output variable z_k of the actuator, $k_0 \ge 0$. The functions f_k, describing the desirable motion properties of the output variables x_k are, as a rule, defined analytically. In such case, the derivatives $\dot{f}_k$ and $\ddot{f}_k$ can also be obtained analytically. The parameters of regulator (29) can be calculated precisely without application of numerical methods. As it is visible from expression (29), regulators consist of several components, each of which fulfils their specific functions. The role of the functional Φ_1 in the regulator (29) consists in giving desirable motion properties to the controlled system. The functional Φ_2 reflects the actual dynamic status of the system, functional Φ_3 - status of an operating mechanism. The role of the functional Φ_0 is only to limit the control signal, if required. The component $k_0 z_k$ compensates the weakening of the control signal when adding a priori negative feedback of an output variable of an operating mechanism. If the feedback mentioned is not used then $k_0 = 0$.

Due to the harmonious cooperation of all the components ("team members"), included into the regulator (29), at each instant of time, a fast action and accuracy without overshoot are combined, when using nonlinear assigned motion properties $f(.)$.

The regulator (29) is adequate to hardware possibilities of modern digital engineering and also guarantees an asymptotic stability of the controlled system. Thus it is not required to fulfill a parameter optimization to define the parameters of regulator: their values are calculated precisely without using numerical methods.

The regulator (29) still has a number of advantages. Using nonlinear built-in desirable motion properties, outstanding accuracy and speed without overshoot are combined. Besides, at a guaranteed stability, the adaptive control and quality of operation close to the capabilities of the used drives, is provided. Thus, we can improve known existing controlled systems and create new systems, ensuring:

- precise control,

- fast response time,
- transients with desirable properties without overshoot,
- adaptive control,
- unification of all modules of the minimization of mismatches,
- the possibility of the linear and nonlinear quality criteria, when it is easy to vary parameters of control criteria of each module of system.

In simple cases, the following regulator can be used:

$$\dot{u}(\bar{x},\ x,\ \dot{x},\ \ddot{x},\ f) = k\left[f(x,\ \dot{x},\ \bar{x}) - \ddot{x}\right]. \qquad (30)$$

Here $f(.)$ is a given function, generally nonlinear; k is the amplification factor.

Integrating (30) and considering feedback of an output variable of the actuating mechanism, it is possible to write:

$$u(x,\ \dot{x},\ \bar{x},\ z,\ f) = k_0 z + k\int f(x,\ \dot{x},\ \bar{x})dt - k(\dot{x} - \dot{x}_0), \qquad (31)$$

where k_0 is a priori selected feedback factor; $\dot{x}_0$ is the initial value of the output variable.

At the zero initial conditions the regulator (31) will look like:

$$u(x,\ \dot{x},\ \bar{x},\ z,\ f) = k_0 z + k\int f(x,\ \dot{x},\ \bar{x})dt - k\dot{x} \qquad (32)$$

Thus, for implementation of the regulator (32) the output variable $x(t)$, speed of change $\dot{x}(t)$, the target value $\bar{x}$ and also output variable z are required.

In the linear case it is possible to accept:

$$f(.) = \omega_0^2(\bar{x} - x) - 2\psi\omega_0\dot{x}. \qquad (33)$$

Here ψ is the desirable coefficient of an aperiodicity in the transient of the output variable at realization of a constant target signal $\bar{x}$; ω_0 is the desirable frequency in the transient of the output variable: $\omega_0 = 3/t_x$, 1/s; t_x is the transition time of the output variable realization of a constant target signal $\bar{x}$.

Using (33) regulator (32) will be accepted:

$$u(x,\ \dot{x},\ \bar{x},\ z) = = k_0 z + k\omega_0^2\int(\bar{x} - x)dt - 2k\psi\omega_0(x - x_0) - k(\dot{x} - \dot{x}_0). \qquad (34)$$

In the tasks, where the initial values x_0 and $\dot{x}_0$ are equal to zero, the regulator (34) will be as follows:

$$u(x,\ \dot{x},\ \bar{x},\ z) = k_0 z + k\omega_0^2\int(\bar{x} - x)dt - 2k\psi\omega_0 x - k\dot{x}. \qquad (35)$$

6. Applications

Despite exclusive achievements in the theory and practice of active traffic safety of vehicles, methods, algorithms, software and hardware of a traffic control (ABS, ASR, ESP, etc.) are continuously improved. The use of the described intelligent regulators represents an important direction of improvement of the quality of operation of the mentioned systems.

Other example of mechatronic systems are an active vibration protection/stabilization systems and Intelligent Vehicle Safety Systems [17-30]. Application of the considered concept allows realization of the following functions:

- an adaptive vibration protection of the chassis (cabins, armchairs of the person-operator, special cargo transporters) at continuous motion sprockets/skating rinks;
- stabilization in space of the set position of the body of the vehicle;
- minimization of effects on a road cloth etc.

Let's consider the task of active vibration protection with electro-hydraulic drives. The generalized scheme of the system is shown in Fig. 1. The system includes sensors of acceleration and relative movement, regulator and actuator with a drive mechanism, which can function based on different physical principles. The signals from sensors are transmitted into the controller. The reference signal is sent to the input from the electro-hydraulic amplifier.

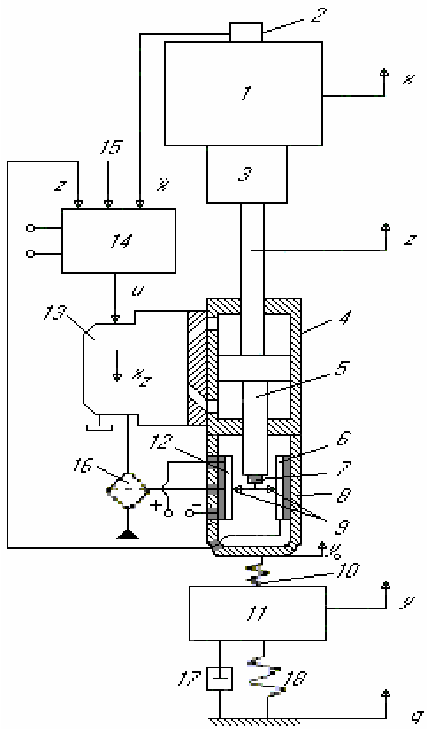

Fig 1. The scheme of the electro-hydraulic vibration protection system

Let's consider a controlled object with the following motion equations:

$$
\begin{aligned}
&\dot{q}_1 = q_2, \\
&\dot{q}_2 = -\sum\nolimits_1 / m_1, \\
&\dot{q}_3 = q_4, \\
&\dot{q}_4 = (\sum\nolimits_1 - \sum\nolimits_2) / m_2, \qquad (36) \\
&\dot{q}_5 = (-q_5 + k_x(u - k_{oz} q_6)) / T_x, \\
&\dot{q}_6 = (-q_6 + k_z q_5 - k_z k_e q_2) / T_z, \\
&\dot{q}_7 = q_8, \\
&\dot{q}_8 = F_s(q_8, \dot{q}_2, k_s, T_s), \\
&t \geq t_0: \; q_i(t_0) = q_{i0}, \; i = 1, ..., 8.
\end{aligned}
$$

Here k_x, T_x accordingly are a factor of amplification and a time constant of the electro-hydraulic converter; k_z, T_z are a factor of amplification and a time constant of the power executive mechanism; k_s, T_s are a factor of amplification and a time constant of the measuring device (the acceleration of the amortized weight); k_e is the parameter describing the leakage of a working body in a hydraulic engine; k_{oz} is a factor of a feedback by plunger position the actuating mechanism; $\sum_1, \sum_2 -$ "sheaf" of the forces influencing weights m_1 and m_2 accordingly:

$$
\begin{aligned}
&\sum\nolimits_1 = P_{11} + P_{21} + P_{31}, \\
&\sum\nolimits_2 = P_{12} + P_{22} + P_{32}, \\
&P_{11} = P_{11}(\Delta_1), \;\; P_{21} = P_{21}(\dot{\Delta}_1), \;\; P_{31} = \bar{P}_{31} \operatorname{sgn} \dot{\Delta}_1; \\
&P_{12} = P_{12}(\delta_2), \;\; P_{22} = P_{22}(\dot{\delta}_2), \;\; P_{32} = \bar{P}_{32} \operatorname{sgn} \dot{\delta}_2; \\
&\Delta_1 = q_3 - q_1 + q_6 : \; \dot{\Delta}_1 = \dot{q}_3 - \dot{q}_1; \\
&\delta_2 = Q(t) - q_3; \; \dot{\delta}_2 = \dot{Q}(t) - q_4,
\end{aligned}
$$

where $P_{ji}(.)$ are known functions, generally nonlinear; $\bar{P}_{31}$, $\bar{P}_{32}$ are dry friction in a static condition in an elastic element and the trunk accordingly; $Q(t)$ is a kinematic perturbation; $\dot{Q}(t) = dQ(t)/dt$.

The control, entering into the fifth equation of system (36), is calculated according to algorithm (29). Apparently, moving of the actuating mechanism piston q_6 adjusts the deformation Δ_1 of an elastic element.

In system (36) the first two equations describe the movement of the amortized weight m_1; the third and fourth equations – movement of the non-amortized weight m_2; the fifth – converter-amplifier; the sixth – executive mechanism (hydraulic cylinder); the seventh and eighth – measuring device (the gauge of acceleration). Apparently, from the eighth equation of the system, the second derivative of a controlled system is observable. Other variables used in the regulator can be identified.

For passive and active vibration protection systems in Fig. 2 and Fig. 3, the spectral density of the accelerations of the amortized weight at movement on soil road 300 m long with a speed of 36 km/h (Fig. 2) and 54 km/h (Fig. 3) is obtained. The accepted step of numerical integration by Runge-Kutta method of the equations (36) is equal to 0.0005 s and the amount of points at calculation of the spectral density of accelerations equals 32768.

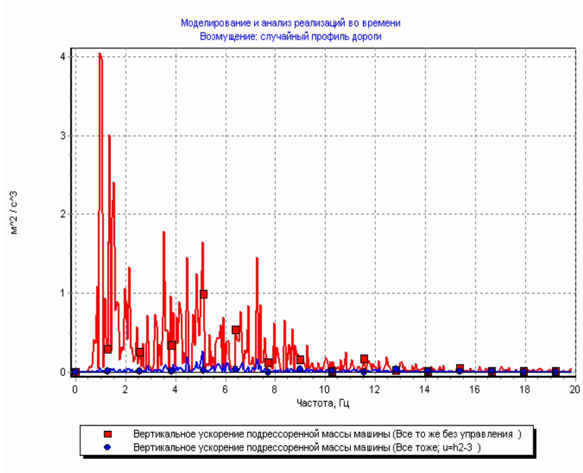

Fig. 2. Spectral density of accelerations of the amortized weight. Speed is 36 km/h

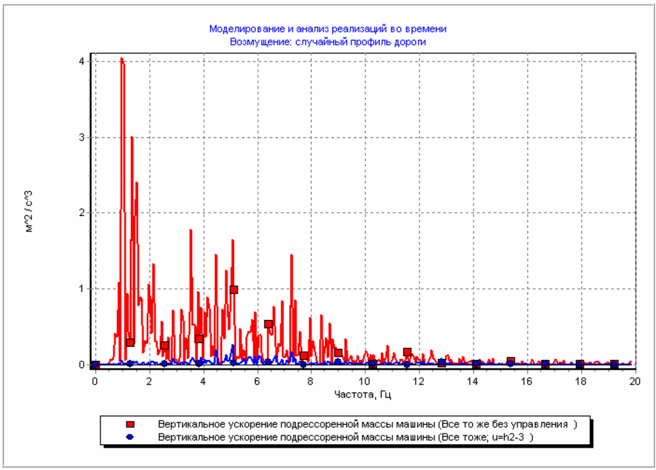

Fig. 3. Spectral density of accelerations of the amortized weight. Speed is 54 km/h

Comparing spectra at active and passive vibration protection system it can be noticed that using adaptive regulators, high quality of vibration protection is achieved. Thus, there are possibilities for increasing the mobility of vehicles.

Conclusions

In the class of linear criteria it is impossible to increase the speed of the system without loss of accuracy, as well as to increase accuracy of the system without loss of speed.

This main principle is valid for all systems operating according to the requirement of minimization of integral square-law criteria of quality, reduced to appropriate linear reference motion equations of an output variable. Thus, the inconsistency between accuracy and speed is solved by compromising.

The preferable controlled process is provided by using nonlinear motion properties of output variables, which can be implemented using the proposed adaptive regulators.
Actual design of adaptive regulators for mechatronic systems operating in non-stationary conditions is demonstrated. The efficiency of integral square-law criteria which can be reduced to the reference motion equations is shown. The nonlinear reference motion equations constitute the path to realization of the best control. In our report the concept, regulator design technology and new adaptive regulators are obtained.

For the modeling and analysis of the efficiency of regulators, the original visual software was developed [16]. This software reduces both terms and cost as well as increases quality of the analysis and design of controlled systems according to the proposed concept. The results of computer modeling demonstrated high efficiency of the systems that are controlled with the new regulators.

The originality of the new regulators is confirmed by patents. The suggested intelligent regulators can be embedded on any systems using, for example, software CoDeSys (Controller Design System), created by 3S-Smart Software Solutions [31].

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