PARADIGMS OF DYNAMIC CHAOS

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It is shown that a condition of occurrence of regimes with chaotic behavior of dynamic systems demands more steadfast studying. In particular, it is shown that if we will take into account singular solutions the chaotic behavior will be inherent also in systems with one degree of freedom. It is shown that linear systems can generate chaotic dynamics. The question about necessity of local instability for realization of chaotic regimes is discussed.

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INTRODUCTION

As it is known, for realization of chaotic regimes in considered dynamic system performance of following conditions are necessary: 1. The system should have 1.5 or more degrees of freedom. 2. It should be nonlinear. 3. In phase space local instability should develop. It is possible to name these three conditions as paradigms of dynamic chaos. In this or that forms they are formulated in all books and the reviews devoted to dynamic chaos (see, for example, [1]).

Below we will discuss these conditions. Some words about an essence of these conditions. They, certainly, all are necessary for a certain class of dynamic systems. Necessity for the phase space to have three or more dimension follows from the uniqueness theorem. Really in two-dimensional phase space it is impossible to realize mixing of integrated curves without intersection. Further, for realize mixing phase trajectories in restricted phase area it is necessary that they ran away from each other, i.e. local instability is necessary. And, at last, as the real system is described in restricted phase space, nonlinearity is necessary for returning.

However we know that except usual solutions of the differential equations there are singular solutions. In points of singular solutions the uniqueness theorem is broken. Therefore it is possible to expect that if we will take into account these singular solutions the regimes with chaotic behavior will be inherent also for dynamic systems with one degree of freedom. In the second part we will show that really such dynamics takes place.

Usually at studying of linear systems nobody is oriented on studying of chaotic regimes. Really in linear systems they are absent. However it is very frequent at studying of linear systems that it is convenient to introduce new dependent, and independent variables. At this the linear mathematical model becomes nonlinear. The well known example is the transition from the equations of quantum mechanics to the equations of classical mechanics, and also the transition from the wave equations to the equations of geometrical optics. In all these new nonlinear systems the regimes with dynamic chaos are possible. In the third partition we show that it is enough general situation.

In the conclusion the results and their connection with known results are discussed.

1. CHAOTIC DYNAMICS OF SYSTEMS WITH "ONE" DEGREE OF FREEDOM

Let's look at the first paradigm that regimes with dynamic chaos are possible only in the dynamic systems which number of degrees of freedom is more or equally to 1.5. The cause of occurrence of this paradigm is that fact that for realization of chaotic dynamics the mixing of trajectories in phase space is necessary. The phase space of systems with one degree of freedom represents a plane. Owing the theorem of uniqueness on plane such intersection can not to be. This conclusion, certainly, is true. However it is true only to class of the differential equations which have no singular solutions. As it is known, in the presence of singular solutions on trajectories corresponding to these solutions, the uniqueness theorem is broken. In this case the arguments formulated above about impossibility of chaotic dynamics in systems with one degree of freedom cease to work. Below we will show that in systems with one degree of freedom in the presence of singular solutions chaotic regimes are possible. It is the main result of this part. Clearly that singular solutions are characteristic and for systems with a great number of degrees of freedom. In these systems the regimes with dynamic chaos, which are caused by presence of these singular solutions, also are possible. However in these systems occurrence of such regimes is not surprising. Therefore below we will concentrate our attention on systems with one degree of freedom. It is necessary to notice that, getting on a singular solution, in points where the uniqueness theorem is broken, the system, in the general case, "does not know" the further trajectory. The choice of the further trajectory is defined by any external, even as much as small perturbation. Presence of these perturbations formally transforms system with one degree of freedom into system with one and a half degree of freedom. We will notice that the size of this perturbation can be as much as small, up to what inevitably arise at numerical research of studied model.

As a characteristic example we will consider dynamics of system which is described by following equations:

$$\dot{x}_0 = x_1 ; \quad \dot{x}_1 = \left(\frac{x_1^2}{2x_0} \right) - 0.5 \cdot x_0 . \quad (1)$$

The phase portrait of system (1) is presented on picture 1. Integral curves in this case are circles:

$$\varphi = \left(x_0 - R \right)^2 + x_1^2 - R^2 = 0 \quad (2)$$

and the circle centers settle down on an axis $x_1 = 0$. Radiuses of these circles are equal to distance of these centres to zero point ($x_0 = 0; x_1 = 0$). This point is the common for all circles. Besides, this point is a singular solution of system (1) (see below). The system (1) was analyzed numerically. Results are presented in drawings 1-6. In the second and third drawings characteristic dependences of a variable x_0 on time are presented. Comparing Fig. 1 to Fig. 2 and 3, it is possible to make the conclusion that a representative point, moving on one of circles after crossing the zero point gets on other circle.

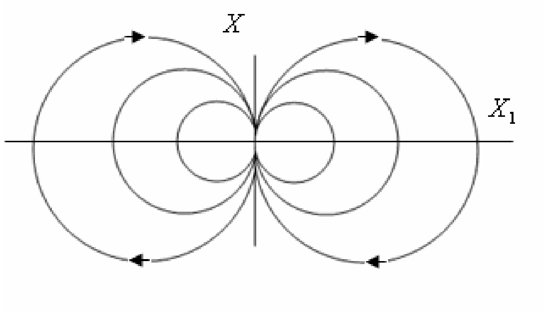

Fig. 1. Phase portrait of system (1)

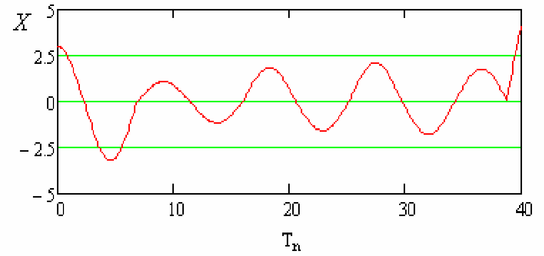

Fig. 2. Time dependence of the variable x_0. Transitions of representative points from one circle on another are visible

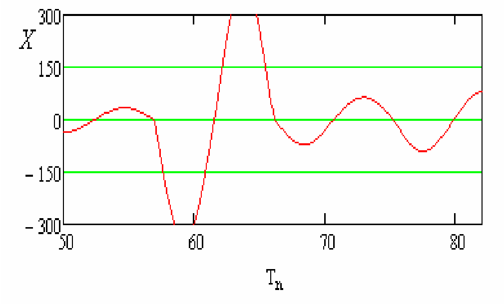

Fig. 3. Time dependence of the variable x_0. $(50 \le t < 85)$

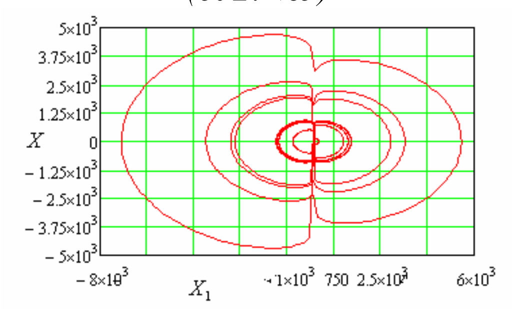

Fig. 4. Phase portrait

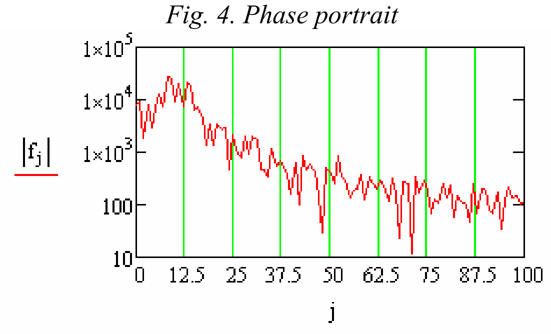

Fig. 5. Spectrum of the variable x_0

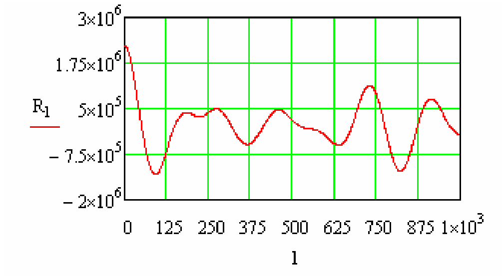

Рис. 6. Correlation function of the variable x_0

Transferring from one circle on another is well visible on a phase plane (Fig. 4). And, transferring from one circle on another circle occur under the casual law. Really, the spectral analysis of dynamics of system (1) shows that spectrums of this dynamics are wide (see Fig. 5), and correlation function enough quickly falls down (Fig. 6).

Let's notice that casual the transitions from one circle to another at crossing zero point depend on accuracy of the computation. Changes, for example, a step of calculations change concrete character of these transitions. However, as a whole statistically, dynamics remains the same.

Let's show now that the zero point is a singular solution of system (1). At that, we will understand as singular solution those solutions on which points the uniqueness theorem is broken. Really, this point belongs to family of circles (2). The Same circles are integral curves of system (1). These integral curves are convenient rewrite in a such kind: $x_1^2 / x_0 + x_0 = R$. From a kind of these integral curves follows that in vicinity of zero point the Lipchitz conditions for system (1) are violated. Really, the Lipchitz conditions for system (1) can be written down in a kind:

$$\left| \frac{\tilde{x}_1^2}{\tilde{x}_0} - \frac{x_1^2}{x_0} \right| \le L\left(\left|\tilde{x}_0 - x_0\right| + \left|\tilde{x}_1 - x_1\right| \right), \qquad (3)$$

where L – positive constant.

In vicinity of zero point the left part of inequality (3) can be estimated by size $\left(\left|\tilde{R} - R\right|\right)$, where $\tilde{R}$ and R radiuses of two arbitrary circles. Generally, differences of these radiuses can be arbitrary size. Thus, in zero point the Lipchitz condition is not carried out, i.e. conditions of the theorem of uniqueness for system (1) are violated. Besides, taking partial derivative of function (2) on R and equating it to zero, we find that really point $(x_0 = 0; x_1 = 0)$ is a singular solution of system (1), and also it is envelope line around integral curves.

The system (1) is not unique. It is possible to show that for example dynamics of system which is described by set of equations

$$\frac{dx_0}{dt} = x_0 \cdot x_1 + \gamma \cdot x_1 \equiv F_1, \; \frac{dx_1}{dt} = x_1^2 - x_0^4 - \gamma \cdot x_0 \equiv F_2 \quad (4)$$

also appears chaotic dynamics. Moreover, sets of such systems can be constructed. We will show how such set can be constructed. Let we have an integral curve which is specified by the equation: $\varphi(x_0, x_1) = 0$. Then the set of equations for which this integrated curve will be as integral, can be presented in a following kind:

$$\frac{dx_0}{dt} = F_1(\varphi, x_0, x_1) - \frac{\partial \varphi}{\partial x_1} M(x_0, x_1);$$

$$\frac{dx_1}{dt} = F_2(\varphi, x_0, x_1) + \frac{\partial \varphi}{\partial x_0} M(x_0, x_1), \quad (5)$$

where $F_s(\varphi, x_0, x_1)$ – arbitrary functions, which has properties: $F_s(0, x_0, x_1) = 0$; $M(x_0, x_1)$ – arbitrary function.

Using system (5), it is possible to construct the big diversity of the dynamic systems possessing the necessary properties. As an example we will consider a case when integrated curves is the family of circles with radius R.

$$\varphi = (x_0 - R)^2 + x_1^2 - R^2 = 0. \quad (6)$$

Set of integral curves (6) are presented in Fig. 1. By choosing of functions F_s and M it is possible to achieve an elimination of parameter R from set of equations (5). Really, let us choose these functions in a kind:

$$F_1 = 0;\ F_2 = \varphi \cdot f(x_0, x_1);\ M = -x_0 \cdot f(x_0 x_1)$$

here $f(x_0 x_1)$ – an arbitrary function. Substituting these expressions in system (5), we will get set of equations in which the parameter R is already excluded:

$$\frac{dx_0}{dt} = 2x_0 \cdot x_1 \cdot f(x_0 x_1);\ \frac{dx_0}{dt} = (x_1^2 - x_0^2) \cdot f(x_0 x_1). \quad (7)$$

Choosing function $f(x_0 x_1)$ in a kind $f(x_0 x_1) = 1/2x_0$, we will get set of equations (1). Dynamics of this system is chaotic. It is presented in Fig. 1-6.

Let's point out in one another possibility of construction of systems of the differential equations with one degree of freedom which dynamics can display chaotic character. Let we have two families of integral curves $\varphi_1(x_0, x_1) = 0$ and $\varphi_2(x_0, x_1) = 0$. Using set of equations (5), it is easy to find system of the differential equations which solutions are these integral curves:

$$\frac{dx_0}{dt} = \frac{\partial \varphi_2}{\partial x_1} F_1(\varphi_1, x_0, x_1, t) - \frac{\partial \varphi_1}{\partial x_1} F_2(\varphi_2, x_0, x_1, t),$$

$$\frac{dx_1}{dt} = -\frac{\partial \varphi_2}{\partial x_0} F_1(\varphi_1, x_0, x_1, t) + \frac{\partial \varphi_1}{\partial x_0} F_2(\varphi_2, x_0, x_1, t), \quad (8)$$

here $F_s(\varphi_s, x_0, x_1, t)$ – the arbitrary functions possessing property $F_s(0, x_0, x_1, t) = 0$. Imposing on integral curves and on function F_s necessary conditions it is possible to construct extensive enough set of the dynamic systems possessing chaotic dynamics.

2. THE DYNAMIC CHAOS GENERATED BY LINEAR SYSTEMS

In works [2-5] examples when linear dynamic systems generate chaotic dynamics of studied systems are in detail enough considered. Below we will shortly describe the key moments of such consideration. Let for us is available three linear connected oscillators. Two of them are identical. Frequency of the third slightly differs from frequency of two others. Set of equations which describe this dynamic system, it is possible to present in a kind:

$$\begin{aligned} \ddot{q}_0 + q_0 &= -\mu_1 q_1 - \mu_2 q_2 \\ \ddot{q}_1 + q_1 &= -\mu_1 q_0 \\ \ddot{q}_2 + (1+\delta) q_2 &= -\mu_2 q_0 \end{aligned}, \quad (9)$$

where $\dot{q} \equiv \frac{dq}{d\tau}$, $\delta \ll 1$, $\mu_i \ll 1$ connection coefficients.

As coefficients of coupling are small, (9) it is convenient to search the solution of these equations in a form:

$$q_i = A_i(\tau) \exp(i\omega_i t). \quad (10)$$

In the solution (10) dependence of complex amplitudes $A_i(\tau)$ on time is caused by connection presence between oscillators. In that case when this connection is small, it is possible to consider that these amplitudes are slowly changing functions. For a finding of these amplitudes it is possible to use averaging method. As a result we will get the following system of the linear truncated equations for these amplitudes:

$$2i\dot{A}_0 = -\mu_1 A_1 - \mu_2 A_2 \exp(i\delta\tau)$$

$$2i\dot{A}_1 = -\mu_1 A_0 \qquad 2i\dot{A}_2 = -\mu_2 A_0 \exp(-i\delta\tau). \quad (11)$$

For the further analysis of dynamics of complex amplitudes $A_i(\tau)$ we will present them in a kind:

$$A_i(\tau) = a_i(\tau) \exp(i\varphi_i(\tau)), \quad (12)$$

here a_i, φ_i – real amplitudes and real phases.

The transformation (12) is key transformation for us. It transforms linear set of equations (11) into the nonlinear. We will notice that such transformation is widely used in the physics, especially in the radiophysics. Substituting (12) in (11) for a finding of the real amplitudes and phases, we will get the following set of equations:

$$\dot{a}_0 = -(\mu_1/2) a_1 \cdot \sin(\Phi) - (\mu_2/2) \cdot a_2 \cdot \sin(\Phi_1),$$

$$\dot{a}_1 = (\mu_1/2) a_0 \cdot \sin(\Phi) \qquad \dot{a}_2 = (\mu_2/2) a_0 \cdot \sin(\Phi_1),$$

$$\dot{\Phi} = (\mu_1/2)\left(\frac{a_0}{a_1} - \frac{a_1}{a_0}\right)\cos(\Phi) - (\mu_2/2)\left(\frac{a_2}{a_0}\right)\cos(\Phi_1), \quad (13)$$

$$\dot{\Phi}_1 = (\mu_2/2)\left(\frac{a_0}{a_2} - \frac{a_2}{a_0}\right)\cos(\Phi_1) - (\mu_1/2)\left(\frac{a_1}{a_0}\right)\cos(\Phi) + \delta,$$

where $\Phi \equiv \varphi_1 - \varphi_0$, $\Phi_1 \equiv \varphi_2 - \varphi_0 + \delta\tau$.

The set of equations (13) is the simplified system in comparison with initial system (9). However this system is nonlinear. Generally, dynamics of such system can be chaotic. It is possible to show that its dynamics is similar to dynamics of two nonlinear connected oscillators. The condition of a overlapping of these nonlinear resonances is condition for regimes with chaotic dynamics occurrence. This condition is simple and looks like: $(\mu_1 + \mu_2) > \delta$. Here δ – is distance between nonlinear resonances. More detailed results of investigation of system (13), the analytical estimations of conditions of dynamic chaos occurrence, and also results of numerical researches are represented in [2-4].

2.1. QUANTUM SYSTEMS

The appearing the regimes with chaotic motion in quantum systems are special interest. Below we will see that such regimes are quite inherent to quantum systems. At this the key model is three-level systems, but not two-level systems. Really set of equations (11) is equivalent to system which is used for description of quantum three-level system under influence on it the perturbation. We will show it. We will consider quantum system which is described by such Hamiltonian:

$$\hat{H} = \hat{H}_0 + \hat{H}_1(t). \quad (14)$$

The second summand in the right part describes perturbation. Wave function of system (14) is subject to Schrödinger equation. The solution of the Schrödinger we will search in the form of a series on own functions of unperturbed system:

$$\psi(t) = \sum_n A_n(t) \cdot \varphi_n \cdot \exp(i\omega_n t), \quad (15)$$

where $\omega_n = E_n / \hbar$; $i\hbar \frac{\partial \varphi_n}{\partial t} = \hat{H}_0 \varphi_n = E_n \cdot \varphi_n$.

Let's substitute (15) in Schrödinger equation and by usual way we can get system of equations for complex amplitudes A_n:

$$i\hbar \cdot \dot{A}_n = \sum_m U_{nm}(t) \cdot A_m, \quad (16)$$

where $U_{nm} = \int \varphi_m^* \cdot \hat{H}_1(t) \cdot \varphi_n \cdot \exp[i \cdot t \cdot (E_n - E_m)/\hbar] \cdot dq$.

Let's consider the more simple case - the case of harmonic perturbation: $\hat{H}_1(t) = \hat{U} \cdot \exp(i\Omega t)$. Then the matrix elements of interaction will get following expression:

$$U_{nm} = V_{nm} \exp\{i \cdot t \cdot [(E_n - E_m)/\hbar + \Omega]\},$$

$$V_{nm} = \int \varphi_n^* \cdot \hat{U} \cdot \varphi_m dq. \quad (17)$$

Let's consider dynamics of three-level systems ($|0\rangle, |1\rangle, |2\rangle$).

We will consider that the frequency of harmonic perturbation and own energy of these levels satisfy to such conditions:

$$m = 1, n = 0, \quad \hbar\Omega = E_1 - E_0; \quad m = 2, n = 0$$

$$\hbar(\Omega + \delta) = E_2 - E_0 \quad |\delta| << \Omega. \quad (18)$$

These relations specify in that fact that frequency of external perturbation is resonant for transitions between zero and the first levels, and energy of the third level is slightly differs from energy of the second level. Using these relations in system (16) it is possible to leave only three equations:

$$i \cdot \hbar \cdot \dot{A}_0 = V_{01} A_1 + V_{02} A_2 \cdot \exp(i \cdot \delta \cdot t);$$

$$i \cdot \hbar \cdot \dot{A}_1 = V_{10} A_0; \; i \cdot \hbar \cdot \dot{A}_2 = V_{20} A_0 \cdot \exp(-i \cdot \delta \cdot t). \quad (19)$$

Let matrix elements of interaction of the direct and the backward transitions are equal ($V_{i0} = V_{0i}$, $(i = 1; 2)$). Then from (19) we can find the following connection between squares of complex amplitudes A_n:

$$\frac{d}{d\tau}\left[A_0^2 - A_1^2 - A_2^2 \right] = 2 \cdot \mu_2 \cdot A_0 A_2 \sin(\delta\tau). \quad (20)$$

From this relation follows that if the third level coincides with the second (two-level system, $\delta = 0$) the system (19) has only one degree of freedom. Development of dynamic chaos in such system is impossible. Above we saw that the size δ defines distance between nonlinear resonances. For the further analysis of dynamics of the complex amplitudes $A_i(\tau)$ we will present them in a kind:

$$A_i(\tau) = a_i(\tau) \exp(i\varphi(\tau)). \quad (21)$$

It's clearly that dynamics of such quantum system will be similar to dynamics of system (13), i.e. in it the regimes with dynamic chaos are possible. It is necessary to notice that these regimes can correspond to essentially quantum values of the parameters (not quasi-classical). Results of more detailed studying of dynamics of such quantum system are contained in [5].

2.2. MORE COMPLICATED SYSTEMS

The examples considered above are simple enough. We knew (in second part) an analytical kind of integral curve these systems. This fact has allowed us to define solutions and areas of phase space in which the uniqueness theorem is not carried out. We have only three linear oscillators in third part. In more complex cases such possibility arises seldom enough, therefore it would be desirable to find more simple and general criteria which will allow to define areas of phase space in which exhibiting of elements of unpredictability is possible.

One of possibilities consists in measure use. Really, let we will introduce of the measure of «an interval» $\Delta\vec{x}$: $\Delta\mu = p(\vec{x}_i) \cdot \Delta\vec{x}$. Here $p(\vec{x}_i)-$ is density of probability that this representative point is inside this interval. Let, as a result of time dynamics of considered system, the point $\vec{x}_i$ passes in a point $\vec{z}$. Thus, we have $\vec{z} = f(\vec{x}_i)-$ a image of a point $\vec{x}_i$; and the point $\vec{x}_i$ is preimage of $\vec{z}$. The number of prototypes (preimages) can be many. We will consider now certain "piece" $\Delta\vec{z}$: $[\vec{z} - \Delta\vec{z}/2; \; \vec{z} + \Delta\vec{z}/2]$. The measure of this piece will be defined now by the formula:

$$\Delta\mu_z = g(\vec{z}) \cdot \Delta\vec{z} = \sum_i p(\vec{x}_i) \cdot \Delta\vec{x}_i. \quad (22)$$

Here $g(\vec{z})$ – density of probability to find of a representative point in phase volume $\Delta\vec{z}$. From this formula we find expression for density $g(\vec{z})$:

$$g(\vec{z}) = \sum_i p(\vec{x}_i) \frac{\Delta\vec{x}_i}{\Delta\vec{z}} = \sum_i \frac{p(\vec{x}_i)}{|J_i|}. \quad (23)$$

Here J_i – Jacobean transformations of new variables through old variables.

The formula (23) practically is the Perron-Frobenius formula. From this formula it is visible that in those areas where Jacobean transformations will have any singularity (for example, to go to infinity or to zero), is possible to expect that relations between initial density of probabilities and transformed – become uncertain. These areas can be sources of chaotic motion.

CONCLUSIONS

Thus, abandoning from the theorem of uniqueness essentially increase quantity of the dynamic systems having regimes with chaotic behavior. However it is necessary to remember that the chaotic behavior in this case by their nature differs from dynamic chaos. This chaos in dynamic systems is generated by not considered casual forces. These forces can be as much as small, but they define a trajectory of integral curves when they pass through ambiguity area. For this cause we in the title of the second part used inverted commas when we spoke about one degree of freedom. Actually the behavior of such dynamic system with one degree of freedom is defined by as much as small numerical fluctuations. The real systems constructed on such model, also will chaotically behave. It's absolutely clearly that the considered mechanism of occurrence of chaotic dynamics will be inherent also for systems with a great number of degrees of freedom. In particular, dynamics of system (13) can chaotically behave as a result of such mechanism. Really, for values of the amplitudes which are going to zero ($a_i \to 0$), there is an infringement of the theorem of uniqueness. Therefore, generally, the chaotic behavior of system (13) can be caused as occurrence gomoclinic structures (when nonlinear resonances overlapped), and as a result of infringement of the theorem of uniqueness.

To distinguish these two mechanisms of occurrence of chaotic dynamics, in general cases, difficultly. However it can be made thus (by such way). At the chaotic dynamics caused by dynamic processes, the combination of some functions for example, such as $a_i(\tau)\cos(\varphi_i(\tau))$ or $a_i(\tau)\sin(\varphi_i(\tau))$, will behave regularly, despite fact that each of multipliers of this function behaves chaotically. Really, each of these combinations, according to the formula (12) represents simply real and imaginary part of the function which dynamics is regular. This fact is similar to known result that the combination of the functions representing integral, is conserved, despite chaotic behaviors of everyone the components, which are entering into this integral. If chaotic dynamics is caused by infringement of the theorem of uniqueness any such combination of functions will remain chaotic because their dynamics it is defined by fluctuations (though as much as small).

It is necessary to tell some words about local instability which are necessary for appearing of dynamic chaos. If the chaotic behavior in system is caused by infringement of the theorem of uniqueness, in general cases, presence of such instability is not necessarily. Really, let's look at system (1). Its trajectories after crossing the zero point are going away from each other. However after it they again direct to the zero point and the distance between them contracts.

Lyapunov's index calculated, for example, under the Benetin schema (see, for example, [1]) will be equal to zero.

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ПАРАДИГМЫ ДИНАМИЧЕСКОГО ХАОСА

В.А. Буц

Показано, что условия возникновения режимов с хаотическим поведением динамических систем требуют более пристального изучения. В частности, показано, что если принять в качестве решений особые решения, то хаотическое поведение будет присуще и системам с одной степенью свободы. Показано, что линейные системы могут порождать хаотическую динамику. Обсуждается вопрос о необходимости локальной неустойчивости для реализации хаотических режимов.

ПАРАДИГМИ ДИНАМІЧНОГО ХАОСУ

В.О. Буц

Показано, що умови виникнення режимів з хаотичною поведінкою динамічних систем вимагають більш пильного вивчення. Зокрема, показано, що якщо прийняти в якості рішень особливі рішення , то хаотична поведінка буде притаманна й системам з одним ступенем свободи. Показано, що лінійні системи можуть породжувати хаотичну динаміку. Обговорюється питання про необхідність локальної нестійкості для реалізації хаотичних режимів.