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Robust Stabilization by Additional Equilibrium

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1. Introduction

There is huge number of developed methods of design of robust control and some of them even become classical. Commonly all of them are dedicated to defining the ranges of parameters (if uncertainty of parameters takes place) within which the system will function with desirable properties, first of all, will be stable. Thus there are many researches which successfully attenuate the uncertain changes of parameters in small (regarding to magnitudes of their own nominal values) ranges. But no one existing method can guarantee the stability of designed control system at arbitrarily large ranges of uncertainly changing parameters of plant. The offered approach has the origins from the study of the results of catastrophe theory where nonlinear structurally stable functions are named as 'catastrophe'. It is known that the catastrophe theory deals with several functions which are characterized by their stable structure. Today there are many classifications of these functions but originally they are discovered as seven basic nonlinearities named as 'catastrophes':

$x^3 + k_1 x$ (fold);

$x^4 + k_2 x^2 + k_1 x$ (cusp);

$x^5 + k_3 x^3 + k_2 x^2 + k_1 x$ (swallowtail);

$x^6 + k_4 x^4 + k_3 x^3 + k_2 x^2 + k_1 x$ (butterfly);

$x_2^3 + x_1^3 + k_1 x_2 x_1 - k_2 x_2 + k_3 x_1$ (hyperbolic umbilic);

$x_2^3 - 3x_2 x_1^2 + k_1\left(x_1^2 + x_2^2\right) - k_2 x_2 - k_3 x_1$ (elliptic umbilic);

$x_2^2 x_1 + x_1^4 + k_1 x_2^2 + k_2 x_1^2 - k_3 x_2 - k_4 x_1$ (parabolic umbilic).

Studying the dynamical properties of these catastrophes has urged to develope a method of design of nonlinear controller, continuously differentiable function, bringing to the new dynamical system the following properties:

1. new (one or several) equilibrium point appears so there are at least two equilibrium point in new designed system,
2. these equilibrium points are stable but not simultaneous, i.e. if one exists (is stable) then another does not exist (is unstable),

3. stability of the equilibrium points are determined by values or relations of values of parameters of the system,
4. what value(s) or what relation(s) of values of parameters would not be, every time there will be one and only one stable equilibrium point to which the system will attend and thus be stable.

Basing on these conditions the given approach is focused on generation of the euilibria where the system will tend in the case if perturbed parameter has value from unstable ranges for original system. In contrast to classical methods of control theory, instead of zero –poles addition, the approach offers to add the equilibria to increase stability and sometimes to increase performance of the control system.

Another benefit of the method is that in some cases of nonlinearity of the plant we do not need to linearize but can use the nonlinear term to generate desired equilibria. An efficiency of the method can be prooved analytically for simple mathematical models, like in the section 2 below, and by simulation when the dynamics of the plant is quite complecated.

Nowadays there are many researches in the directions of cooperation of control systems and catastrophe theory that are very close to the offered approach or have similar ideas to stabilize the uncertain dynamical plant. Main distinctions of the offered approach are the follow:

- the approach does not suppress the presence of the catastrophe function in the model but tries to use it for stabilization;
- the approach is not restricted by using of the catastrophe themselves only but is open to use another similar functions with final goal to generate additional equilibria that will stabilize the dynamical plant.

Further, in section 2 we consider second-order systems as the justification of presented method of additional equilibria. In section 3 we consider different applications taken from well-known examples to show the technique of design of control. As classic academic example we consider stabilization of mass-damper-spring system at unknown stiffness coefficient. As the SISO systems of high order we consider positioning of center of oscillations of ACC Benchmark. As alternative opportunity we consider stabilization of submarine's angle of attack.

2. SISO systems with control plant of second order

Let us consider cases of two integrator blocks in series, canonical controllable form and Jordan form. In first case we use one of the catastrophe functions, and in other two cases we offer our own two nonlinear functions as the controller.

2.1 Two integrator blocks in series

Let us suppose that control plant is presented by two integrator blocks in series (Fig. 1) and described by equations (2.1)

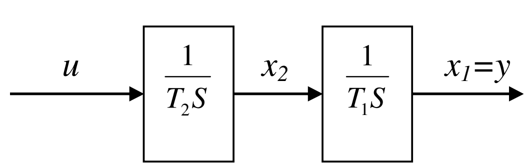

Fig. 1.

$$\begin{cases} \dfrac{dx_1}{dt} = \dfrac{1}{T_1} x_2, \\ \dfrac{dx_2}{dt} = \dfrac{1}{T_2} u. \end{cases} \tag{2.1}$$

Let us use one of the catastrophe function as controller:

$$u = -x_2^3 + 3x_2 x_1^2 - k_1\left(x_1^2 + x_2^2\right) + k_2 x_2 + k_3 x_1, \tag{2.2}$$

and in order to study stability of the system let us suppose that there is no input signal in the system (equal to zero). Hence, the system with proposed controller can be presented as:

$$\begin{cases} \dfrac{dx_1}{dt} = \dfrac{1}{T_1} x_2, \\ \dfrac{dx_2}{dt} = \dfrac{1}{T_2}\left(-x_2^3 + 3x_2 x_1^2 - k_1\left(x_1^2 + x_2^2\right) + k_2 x_2 + k_3 x_1\right). \end{cases}$$

$$y = x_1 . \tag{2.3}$$

The system (2.3) has following equilibrium points

$$x_{1s}^1 = 0 \, , x_{2s}^1 = 0 \, ; \tag{2.4}$$

$$x_{1s}^2 = \frac{k_3}{k_1}, \; x_{2s}^2 = 0 \, . \tag{2.5}$$

Equilibrium (2.4) is origin, typical for all linear systems. Equilibrium (2.5) is additional, generated by nonlinear controller and provides stable motion of the system (2.3) to it.
Stability conditions for equilibrium point (2.4) obtained via linearization are

$$\begin{cases} -\dfrac{k_2}{T_2} > 0, \\ \dfrac{k_3}{T_1 T_2} < 0. \end{cases} \tag{2.6}$$

Stability conditions of the equilibrium point (2.6) are

$$\begin{cases} -\dfrac{3k_3^2 + k_2 k_1^2}{k_1^2 T_2} > 0, \\ \dfrac{k_3}{T_1 T_2} > 0. \end{cases} \tag{2.7}$$

By comparing the stability conditions given by (2.6) and (2.7) we find that the signs of the expressions in the second inequalities are opposite. Also we can see that the signs of expressions in the first inequalities can be opposite due to squares of the parameters k_1 and k_3 if we properly set their values.

Let us suppose that parameter T_1 can be perturbed but remains positive. If we set k_2 and k_3 both negative and $|k_2| < 3\frac{k_3^2}{k_1^2}$ then the value of parameter T_2 is irrelevant. It can assume any values both positive and negative (except zero), and the system given by (2.3) remains stable. If T_2 is positive then the system converges to the equilibrium point (2.4) (becomes stable). Likewise, if T_2 is negative then the system converges to the equilibrium point (2.5) which appears (becomes stable). At this moment the equilibrium point (2.4) becomes unstable (disappears).

Let us suppose that T_2 is positive, or can be perturbed staying positive. So if we can set the k_2 and k_3 both negative and $|k_2| > 3\frac{k_3^2}{k_1^2}$ then it does not matter what value (negative or positive) the parameter T_1 would be (except zero), in any case the system (2) will be stable. If T_1 is positive then equilibrium point (2.4) appears (becomes stable) and equilibrium point (2.5) becomes unstable (disappears) and vice versa, if T_1 is negative then equilibrium point (2.5) appears (become stable) and equilibrium point (2.4) becomes unstable (disappears).

Results of MatLab simulation for the first and second cases are presented in Fig. 2 and 3 respectively. In both cases we see how phase trajectories converge to equilibrium points $(0,0)$ and $\left(\frac{k_3}{k_1};0\right)$

In Fig.2 the phase portrait of the system (2.3) at constant k_1*=1*, k_2*=-5*, k_3*=-2*, T_1*=100* and various (perturbed) T_2 (from *-4500* to *4500* with step *1000*) with initial condition *x=(-1;0)* is shown. In Fig.3 the phase portrait of the system (2.3) at constant k_1*=2*, k_2*=-3*, k_3*=-1*, T_2*=1000* and various (perturbed) T_1 (from *-450* to *450* with step *100*) with initial condition *x=(-0.25;0)* is shown.

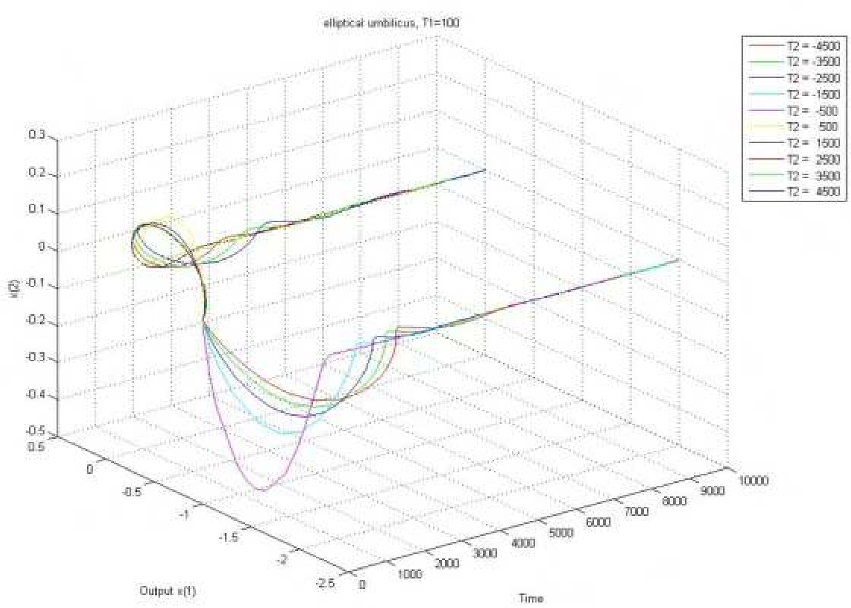

Fig. 2. Behavior of designed control system in the case of integrators in series at various T_2.

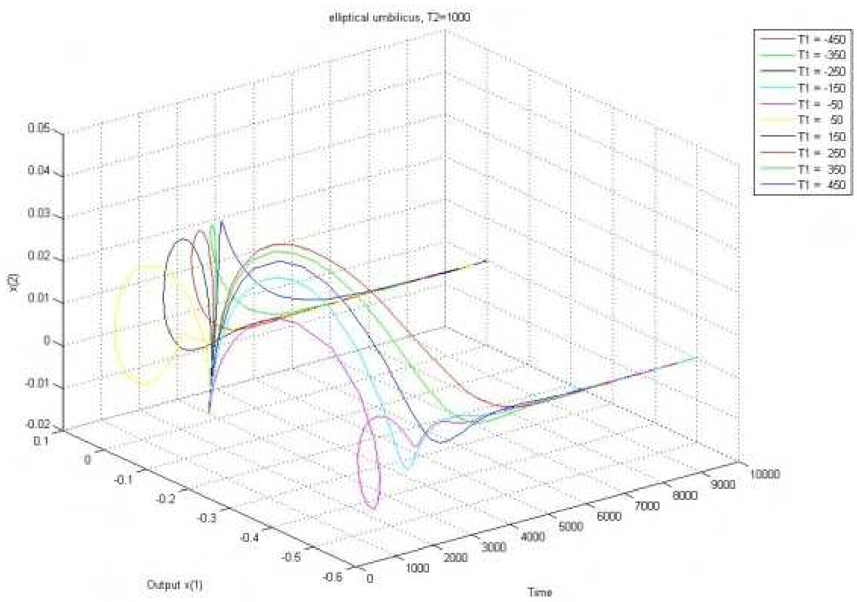

Fig. 3. Behavior of designed control system in the case of integrators in series at various T_1.

2.2 Canonical controllable form

Let us suppose that control plant is presented (or reduced) by canonical controllable form:

$$\begin{cases} \dfrac{dx_1}{dt} = x_2, \\ \dfrac{dx_2}{dt} = -a_2 x_1 - a_1 x_2 + u. \end{cases}$$

$$y = x_1 \tag{2.8}$$

Let us choose the controller in following parabolic form:

$$u = -k_1 x_1^2 + k_2 x_1 \tag{2.9}$$

Thus, new control system becomes nonlinear:

$$\begin{cases} \dfrac{dx_1}{dt} = x_2, \\ \dfrac{dx_2}{dt} = -a_2 x_1 - a_1 x_2 - k_1 x_1^2 + k_2 x_1. \end{cases}$$

$$y = x_1 \,. \tag{2.10}$$

and has two following equilibrium points:

$$x_{1s}^1 = 0\,,\;\; x_{2s}^1 = 0\,; \tag{2.11}$$

$$x_{1s}^2 = \frac{k_2 - a_2}{k_1}\,,\;\; x_{2s}^2 = 0\,; \tag{2.12}$$

Stability conditions for equilibrium points (2.11) and (2.12) respectively are

$$\begin{cases} a_1 > 0, \\ a_2 > k_2. \end{cases}$$

$$\begin{cases} a_1 > 0, \\ a_2 < k_2. \end{cases}$$

Here equlibrium (2.12) is additional and provides stability to the system (2.10) in the case when k_2 is negative.

2.3 Jordan form

Let us suppose that dynamical system is presented in Jordan form and described by following equations:

$$\begin{cases} \dfrac{dx_1}{dt} = \rho_1 x_1, \\ \dfrac{dx_2}{dt} = \rho_2 x_2. \end{cases} \tag{2.13}$$

Here we can use the fact that states are not coincided to each other and add three equilibrium points. Hence, the control law is chosen in following form:

$$u_1 = -k_a x_1^2 + k_b x_1,\ u_2 = -k_a x_2^2 + k_c x_2 \tag{2.14}$$

Hence, the system (2.13) with set control (2.14) is:

$$\begin{cases} \dfrac{dx_1}{dt} = \rho_1 x_1 - k_a x_1^2 + k_b x_1, \\ \dfrac{dx_2}{dt} = \rho_2 x_2 - k_a x_2^2 + k_c x_2. \end{cases} \tag{2.15}$$

Totaly, due to designed control (2.14) we have four equilibria:

$$x_{1s}^1 = 0,\ x_{2s}^1 = 0; \tag{2.16}$$

$$x_{1s}^2 = 0,\ x_{2s}^2 = \frac{\rho_2 + k_c}{k_a}; \tag{2.17}$$

$$x_{1s}^3 = \frac{\rho_1 + k_b}{k_a},\ x_{2s}^3 = 0; \tag{2.18}$$

$$x_{1s}^4 = \frac{\rho_1 + k_b}{k_a},\ x_{2s}^4 = \frac{\rho_2 + k_c}{k_a}; \tag{2.19}$$

Stability conditions for the equilibrium point (2.16) are:

$$\begin{cases} \rho_1 + k_b > 0, \\ \rho_2 + k_c > 0. \end{cases}$$

Stability conditions for the equilibrium point (2.17) are:

$$\begin{cases} \rho_1 + k_b > 0, \\ \rho_2 + k_c < 0. \end{cases}$$

Stability conditions for the equilibrium point (2.18) are:

$$\begin{cases} \rho_1 + k_b < 0, \\ \rho_2 + k_c > 0. \end{cases}$$

Stability conditions for the equilibrium point (2.19) are:

$$\begin{cases} \rho_1 + k_b < 0, \\ \rho_2 + k_c < 0. \end{cases}$$

These four equilibria provide stable motion of the system (2.15) at any values of unknown parameters ρ_1 and ρ_2 positive or negative. By parameters k_a, k_b, k_c we can set the coordinates of added equilibria, hence the trajectory of system's motion will be globally bound within a rectangle, corners of which are the equilibria coordinates (2.16), (2.17), (2.18), (2.19) themselves.

3. Applications

3.1 Unknown stiffness in mass-damper-spring system

Let us apply our approach in a widely used academic example such as mass-damper-spring system (Fig. 4).

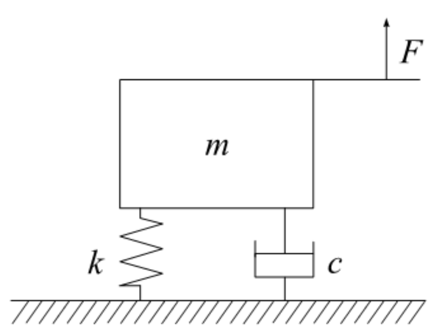

Fig. 4.

The dynamics of such system is described by the following 2nd-order deferential equation, by Newton's Second Law

$$m\ddot{x} + c\dot{x} + kx = u \ , \tag{3.1}$$

where x is the displacement of the mass block from the equilibrium position and F = u is the force acting on the mass, with m the mass, c the damper constant and k the spring constant.

We consider a case when k is unknown parameter. Positivity or negativity of this parameter defines compression or decompression of the spring. In realistic system it can be unknown if the spring was exposed by thermal or moisture actions for a long time. Let us represent the system (3.1) by following equations:

$$\begin{cases} \dot{x}_1 = x_2, \\ \dot{x}_2 = \dfrac{1}{m}\left(-kx_1 - cx_2\right) + \dfrac{1}{m}u. \end{cases} \tag{3.2}$$

that correspond to structural diagram shown in Fig. 5.

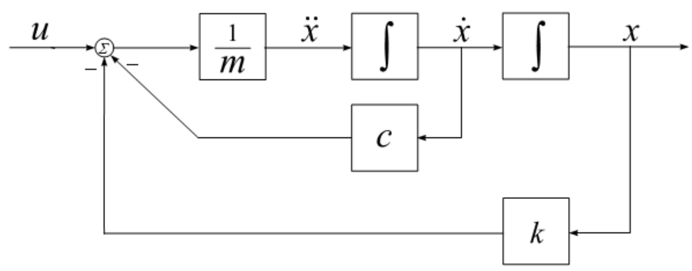

Fig. 5.

Let us set the controller in the form:

$$u = k_u x_1^2, \tag{3.3}$$

Hence, system (3.2) is transformed to:

$$\begin{cases} \dot{x}_1 = x_2, \\ \dot{x}_2 = \dfrac{1}{m}\left(-kx_1 - cx_2\right) + \dfrac{1}{m}k_u x_1^2. \end{cases} \tag{3.4}$$

Designed control system (3.4) has two equilibira:

$$x_1 = 0,\ x_2 = 0; \tag{3.5}$$

that is original, and

$$x_1 = \frac{k}{k_u},\ x_2 = 0. \tag{3.6}$$

that is additional. Origin is stable when following conditions are satisfaied:

$$\frac{c}{m} > 0,\ \frac{k}{m} > 0 \tag{3.7}$$

This means that if parameter k is positive then system tends to the stable origin and displacement of x is equal or very close to zero. Additional equilibrium is stable when

$$\frac{c}{m} > 0,\ \frac{k}{m} < 0 \tag{3.8}$$

Thus, when k is negative the system is also stable but tends to the (3.6). That means that displacement x is equal to $\frac{k}{k_u}$ and we can adjust this value by setting the control parameter k_u.
In Fig. 5 and Fig. 6 are presented results of MATLAB simulation of behavior of the system (3.4) at negative and positive values of parameter k.

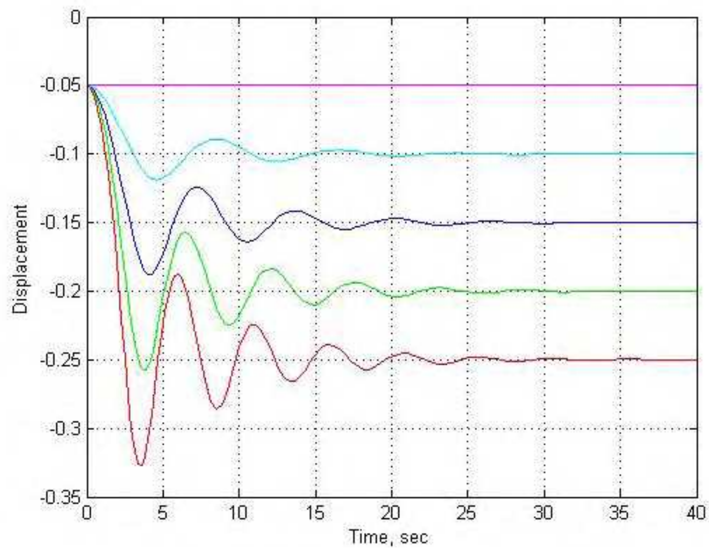

Fig. 6.

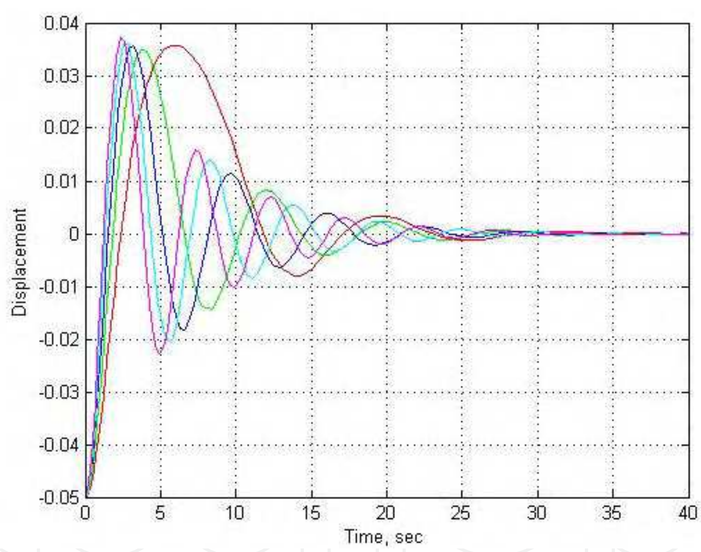

Fig. 7.

In Fig. 6 changing of the displacement of the system at initial conditions x=[-0.05, 0] is shown. Here the red line corresponds to case when k = -5, green line corresponds to k = -4, blue line corresponds to k = -3, cyan line corresponds to k = -2, magenta line corresponds to k = -1. Everywhere the system is stable and tends to additional equilibria (3.6) which has different values due to the ratio $\frac{k}{k_u}$.
In Fig. 7 the displacement of the system at initial conditions x=[-0.05, 0] tends tot he origin. Colors of the lines correspond tot he following values of k: red is when k = 1, green is when k = 2, blue is when k = 3, cyan is when k = 4, and magenta is when k = 5.

3.2 SISO systems of high order. Center of oscillations of ACC Benchmark

Let us consider ACC Benchmark system given in MATLAB Robust Toolbox Help. The mechanism itself is presented in Fig. 8.

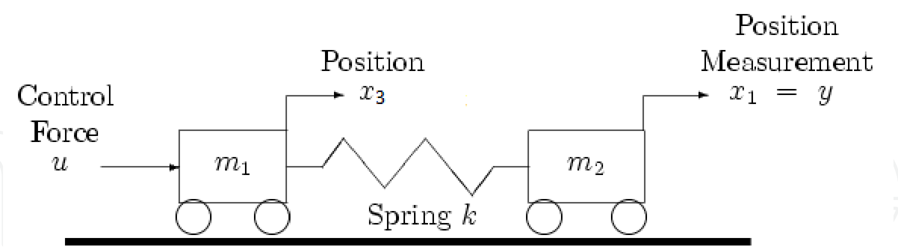

Fig. 8.

Structural diagram is presented in Fig. 9, where

$$G_1 = \frac{1}{m_1 s^2}, \; G_2 = \frac{1}{m_2 s^2}.$$

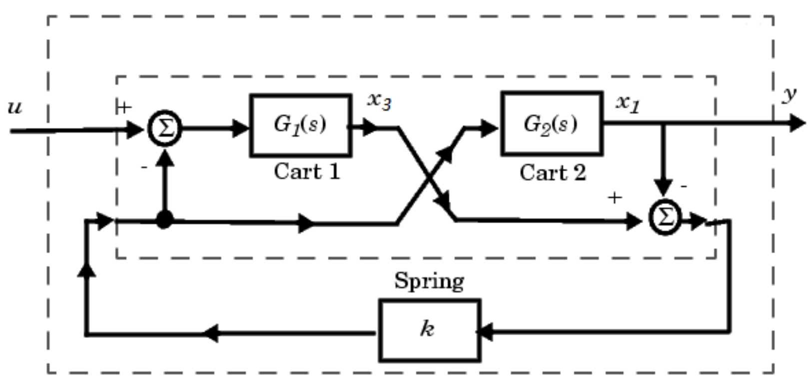

Fig. 9.

Dynamical system can be described by following equations:

$$\begin{cases} \dot{x}_1 = x_2, \\ \dot{x}_2 = -\dfrac{k}{m_2} x_1 + \dfrac{k}{m_2} x_3, \\ \dot{x}_3 = x_4, \\ \dot{x}_4 = \dfrac{k}{m_1} x_1 - \dfrac{k}{m_1} + \dfrac{1}{m_1} u. \end{cases} \tag{3.9}$$

Without no control input the system produces periodic oscillations. Magnitude and center of the oscillations are defined by initial conditions. For example, let us set the parameters of the system $k = 1$, $m_1 = 1$, $m_2 = 1$. If we assume initial conditions $x = [-0.1, 0, 0, 0]$ then center of oscillations will be displaced in negative (left) direction as it is shown in Fig. 10a. If initial conditions are $x = [0.1, 0, 0, 0]$ then the center will be displaced in positive direction as it is shown in Fig. 10b.

After settting the controller

$$u = x_1^2 - k_1 x_1 \,,$$

and obtaining new control system

$$\begin{cases} \dot{x}_1 = x_2, \\ \dot{x}_2 = -\dfrac{k}{m_2}x_1 + \dfrac{k}{m_2}x_3, \\ \dot{x}_3 = x_4, \\ \dot{x}_4 = \dfrac{k}{m_1}x_1 - \dfrac{k}{m_1} + \dfrac{1}{m_1}\left(x_1^2 - k_u x_1\right). \end{cases} \tag{3.11}$$

we can obtain less displacement of the center of oscillations.

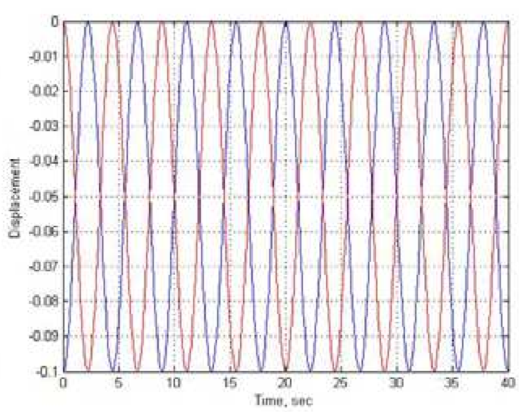

Fig. 10.a

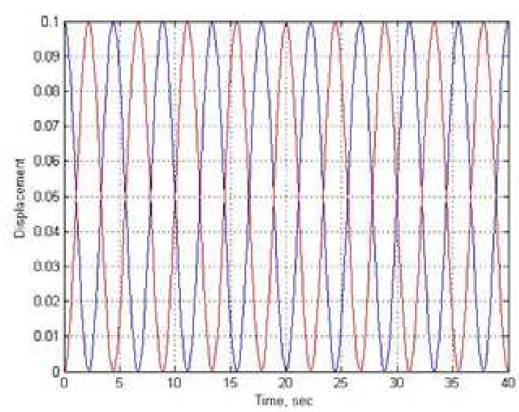

Fig. 10.b

Fig. 10.

In Fig. 11 and Fig.12 the results of MATLAB simulation are presented. At the same parameters k = 1, m_1 = 1, m_2 = 1 and initial conditions x = [-0.1, 0, 0, 0], the center is ‘almost’ not displaced from the zero point (Fig. 11).

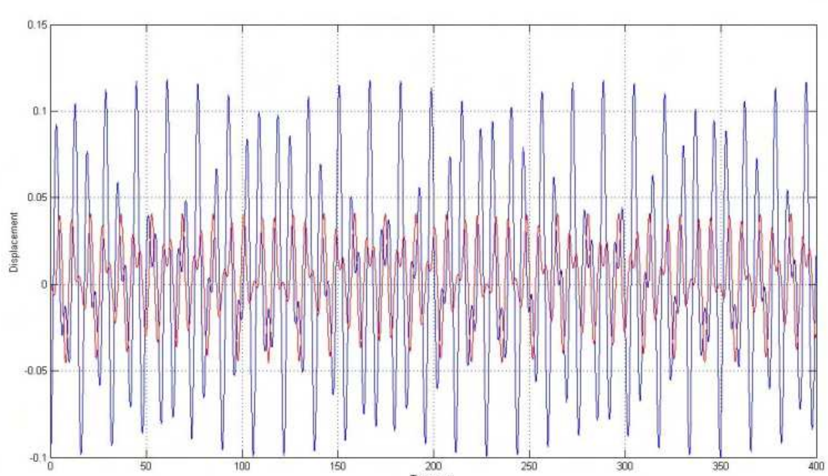

Fig. 11.

At the same parameters k = 1, $m_1 = 1$, $m_2 = 1$ and initial conditions x = [0.1, 0, 0, 0], the center is also displaced very close from the zero point (Fig. 12).

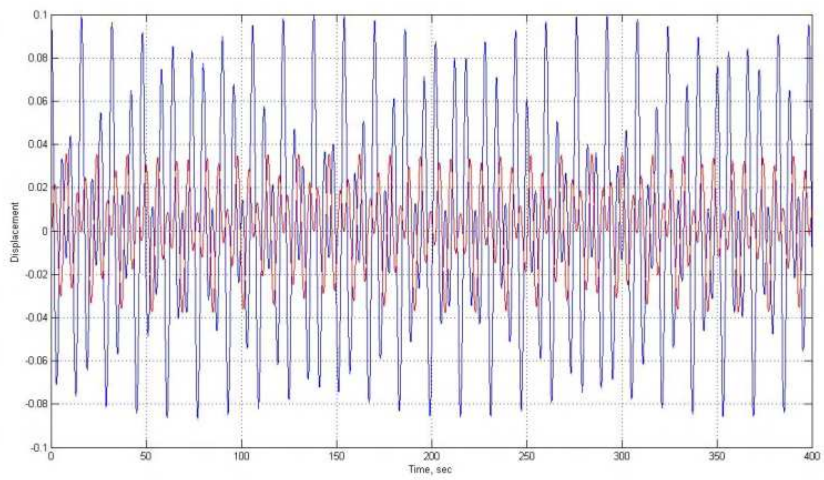

Fig. 12.

3.3 Alternative opportunities. Submarine depth control

Let us consider dynamics of angular motion of a controlled submarine. The important vectors of submarine's motion are shown in the Fig.13.

Let us assume that θ is a small angle and the velocity v is constant and equal to 25 ft/s. The state variables of the submarine, considering only vertical control, are $x_1 = \theta$, $x_2 = \frac{d\theta}{dt}$, $x_3 = \alpha$, where α is the angle of attack and output. Thus the state vector differential equation for this system, when the submarine has an Albacore type hull, is:

$$\dot{x} = Ax + B\delta_s(t), \tag{3.12}$$

where

$$A = \begin{pmatrix} 0 & a_{12} & 0 \\ a_{21} & a_{22} & a_{23} \\ 0 & a_{32} & a_{33} \end{pmatrix}, \quad B = \begin{pmatrix} 0 \\ b_2 \\ b_3 \end{pmatrix},$$

parameters of the matrices are equal to:

$$a_{12} = 1, \; a_{21} = -0.0071, \; a_{22} = -0.111, \; a_{23} = 0.12, \; a_{32} = 0.07, \; a_{33} = -0.3,$$

$$b_2 = -0.095, \; b_3 = 0.072,$$

and $\delta_s(t)$ is the deflection of the stern plane.

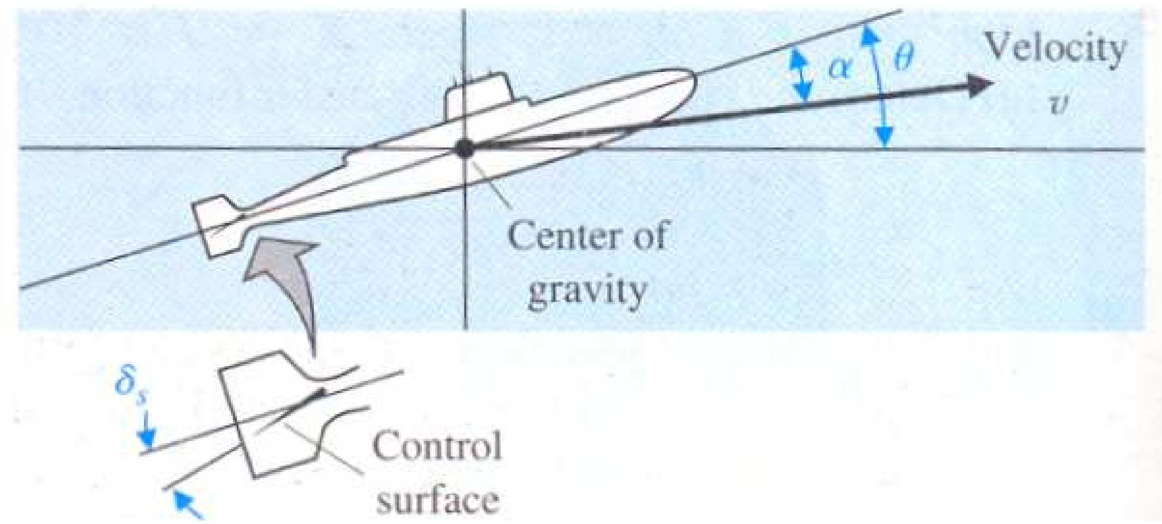

Fig. 13. Angles of submarine's depth dynamics.

Let us study the behavior of the system (3.12). In general form it is described as:

$$\begin{cases} \frac{dx_1}{dt} = x_2, \\ \frac{dx_2}{dt} = a_{21}x_1 + a_{22}x_2 + a_{23}x_3 + b_2\delta_S(t), \\ \frac{dx_3}{dt} = a_{32}x_2 + a_{33}x_3 + b_3\delta_S(t). \end{cases} \quad (3.13)$$

where input $\delta_s(t)=1$. By turn let us simulate by MATLAB the changing of the value of each parameter deviated from nominal value.

In the Fig.14 the behavior of output of the system (3.13) at various value of a_{21} (varies from -0.0121 to 0.0009 with step 0.00125) and all left constant parameters with nominal values is presented.

In the Fig.15 the behavior of output of the system (3.13) at various value of a_{22} (varies from -0.611 to 0.289 with step 0.125) and all left constant parameters with nominal values is presented.

In the Fig.16 the behavior of output of the system (3.13) at various value of a_{23} (varies from -0.88 to 1.120 with step 0.2) and all left constant parameters with nominal values is presented.

In the Fig.17 the behavior of output of the system (3.13) at various value of a_{32} (varies from -0.43 to 0.57 with step 0.125) and all left constant parameters with nominal values is presented.

In the Fig.18 the behavior of output of the system (3.13) at various value of a_{33} (varies from -1.3 to 0.7 to with step 0.25) and all left constant parameters with nominal values is presented.

It is clear that the perturbation of only one parameter makes the system unstable.

Let us set the feedback control law in the following form:

$$u = -k_1\left(x_3^2 + x_2^2\right) + k_2x_3 + k_3x_2 \, . \quad (3.14)$$

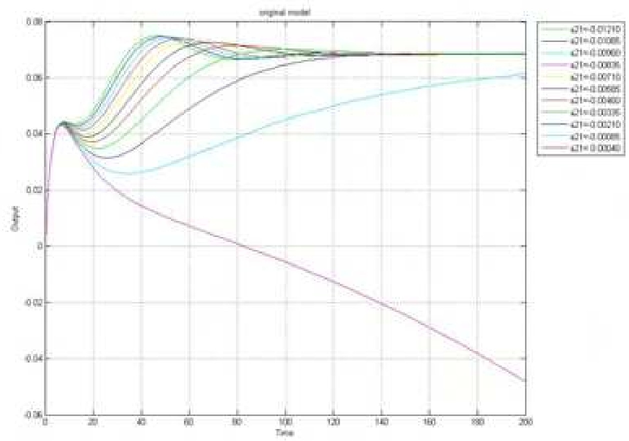

Fig. 14. Behavior of output dynamics of submarine’s depth at various a_{21}.

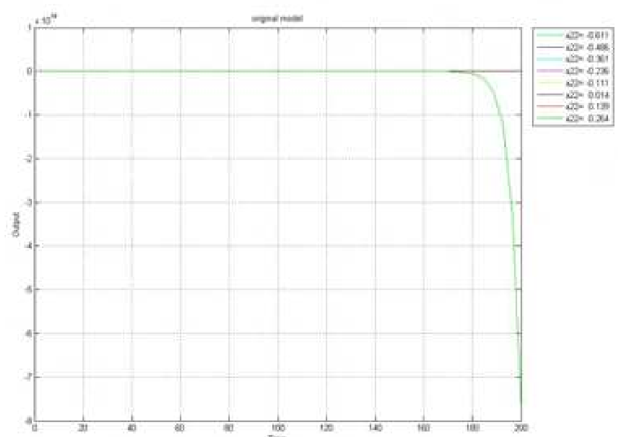

Fig. 15. Behavior of output dynamics of submarine’s depth at various a_{22}.

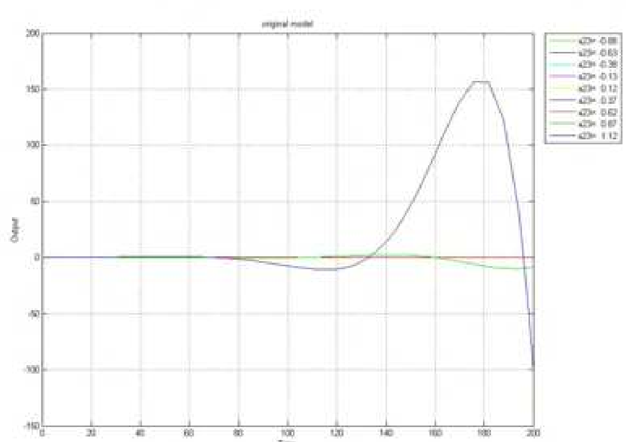

Fig. 16. Behavior of output dynamics of submarine’s depth at various a_{23}.

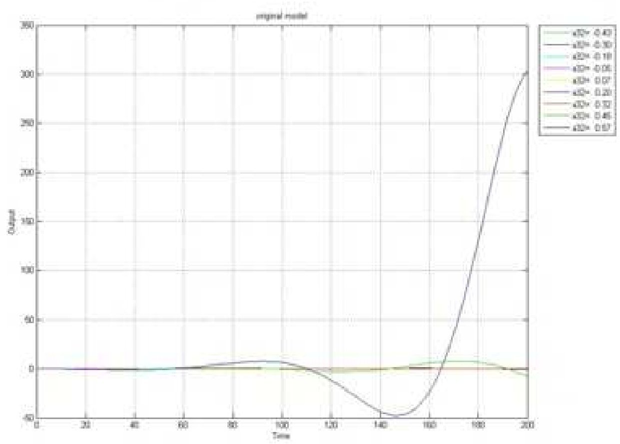

Fig. 17. Behavior of output dynamics of submarine’s depth at various a_{32}.

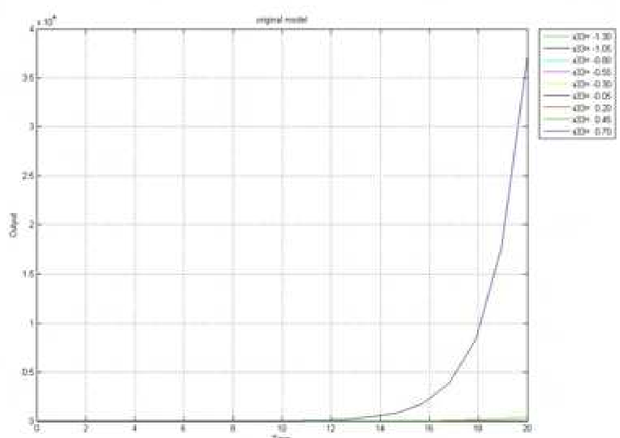

Fig. 18. Behavior of output dynamics of submarine’s depth at various a_{33}.

Hence, designed control system is:

$$\begin{cases} \dfrac{dx_1}{dt} = x_2, \\ \dfrac{dx_2}{dt} = a_{21}x_1 + a_{22}x_2 + a_{23}x_3 + b_2\delta_S(t), \\ \dfrac{dx_3}{dt} = a_{32}x_2 + a_{33}x_3 + b_3\delta_S(t) - k_1\left(x_2^2 + x_3^2\right) + k_2x_3 + k_3x_2. \end{cases} \tag{3.15}$$

The results of MATLAB simulation of the control system (3.15) with each changing (disturbed) parameter are presented in the figures 19, 20, 21, 22, and 23.
In the Fig.19 the behavior designed control system (3.15) at various value of a_{21} (varies from -0.0121 to 0.0009 with step 0.00125) and all left constant parameters with nominal values is presented
In the Fig.20 the behavior of output of the system (3.15) at various value of a_{22} (varies from -0.611 to 0.289 with step 0.125) and all left constant parameters with nominal values is presented.

In the Fig.21 the behavior of output of the system (3.15) at various value of a_{23} (varies from -0.88 to 1.120 with step 0.2) and all left constant parameters with nominal values is presented.
In the Fig.22 the behavior of output of the system (3.15) at various value of a_{32} (varies from -0.43 to 0.57 with step 0.125) and all left constant parameters with nominal values is presented.
In the Fig.23 the behavior of output of the system (3.15) at various value of a_{33} (varies from -1.3 to 0.7 to with step 0.25) and all left constant parameters with nominal values is presented.
Results of simulation confirm that chosen controller (3.14) provides stability to the system. In some cases, especially in the last the systems does not tend to original equilibrium (zero) but to additional one.

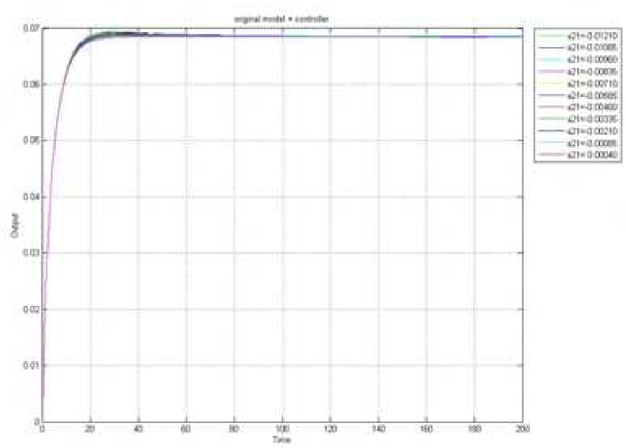

Fig. 19. Behavior of output of the submarine depth control system at various a_{21}.

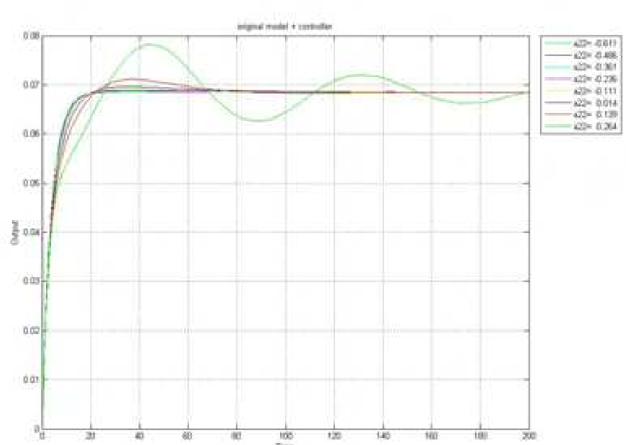

Fig. 20. Behavior of output of the submarine depth control system at various a_{22}.

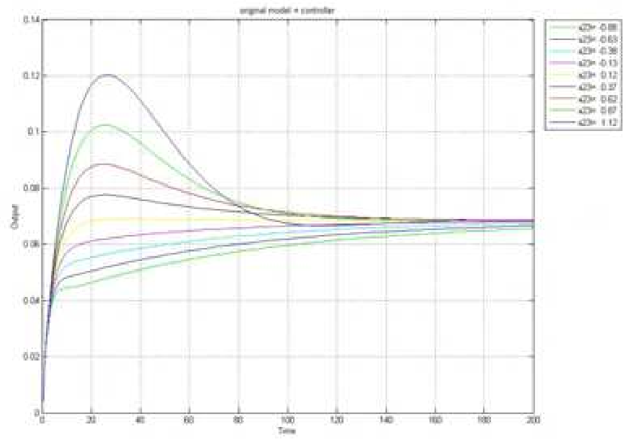

Fig. 21. Behavior of output of the submarine depth control system at various a_{23}.

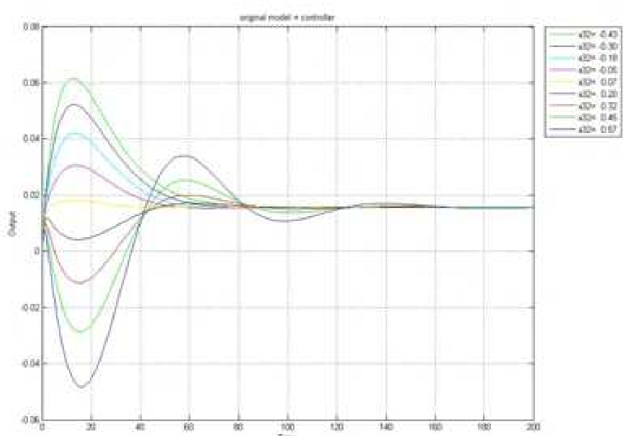

Fig. 22. Behavior of output of the submarine depth control system at various a_{32}.

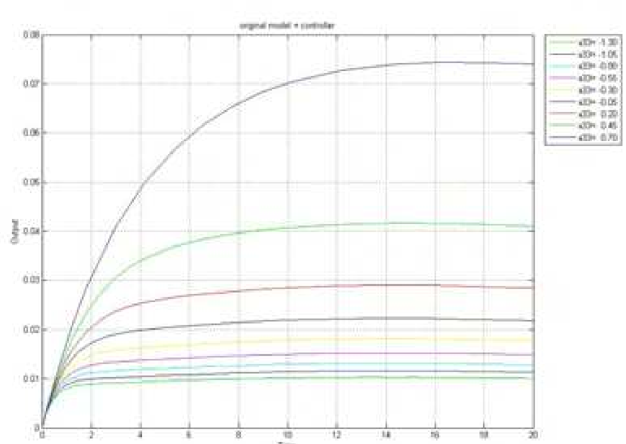

Fig. 23. Behavior of output of the submarine depth control system at various a_{33}.

4. Conclusion

Adding the equilibria that attracts the motion of the system and makes it stable can give many advantages. The main of them is that the safe ranges of parameters are widened significantly because the designed system stay stable within unbounded ranges of perturbation of parameters even the sign of them changes. The behaviors of designed control systems obtained by MATLAB simulation such that control of linear and nonlinear dynamic plants confirm the efficiency of the offered method. For further research and investigation many perspective tasks can occur such that synthesis of control systems with special requirements, design of optimal control and many others.

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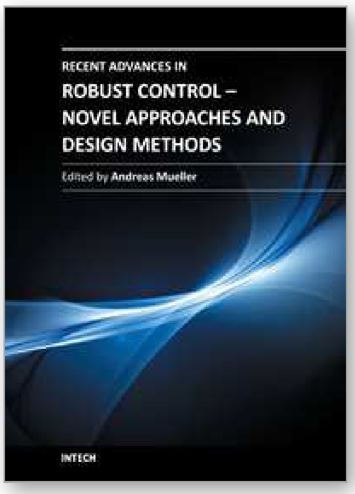

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