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SOME PROBLEMS OF REALIZABILITY OF ROBAST CONTROL SYSTEMS

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Abstract. The article examines the possibility of implementing some robust control systems that are widely used in engineering applications. It is shown that the results of H_∞-theories often lead to the violation of parametric roughness. In the method of "localization of movement", the presence of a small number of delays in the channel of measurement of the senior production causes a violation of the stability of the system. K_∞ robast systems are workable in indefinite objects of a wide class, but there is no analytical expression to determine the coefficient of K. In addition, not every object allows an infinite increase in the coefficient of amplification. On the basis of literary and computer analysis revealed deficiencies of the system, operating in special modes (sliding, auto-bending, vibration): inability to obtain vibrations in the inert objects (eg, industrial, mechanical, some electromechanical objects, etc.); arousal of high-frequency dynamics of some elements of the structure, even the occurrence of resonance.

Keywords: robust system, control, vibration, rudeness, operability, resonance, Simulink.
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1 Introduction

Uncertainty is a feature of a model that is not related to the real object, but is constructed in such a way that our knowledge of that object is not limited. Objects with such an incomplete model are called indefinite objects. The main methods of control under uncertainty are adaptive and robust (robust) methods that arose in the 80s of the twentieth century. Generally speaking, adaptation is a slow process. The condition of quasi-stationarity and weak convergence in the presence of interference slows down the adaptation process. As a result, the system performance is reduced.

The idea of the developing the robust systems is very attractive. The concept of "robust control" was apparently first proposed by the American scientist Safonov & Athans (1981).

Despite changes in the characteristics of the object and external disturbances (signal uncertainty), in contrast to adaptive systems in robust systems, the controller is not tuned.

In addition, the main difference between robust systems and classical "rough systems" Andronov & Pontryagin (1937) is that these systems allow the parameters of the object (etc.) to *change in the interval*. Non-roughness is considered to be a violation of the fundamental properties of the system (for example, stability) during any *small change* in the parameters of the object (etc.). For this reason, robustness can be called "great rudeness".

The "magic regulator" built on a one-time scheme must perform the function of an adaptive regulator, maintaining the quality of the system and the stability reserves of the system to the required level, despite the variation of the parameters of the object and the excitation effects.

It should be noted that pure robust control algorithms do not use adaptation tools, unlike adaptive-robust (hybrid) systems.

2 Robust Control

Among the main robust control methods currently used in uncertainty are the following Balandin & Kogan (2008); Zatsepilova & Chestnov (2011); Kiselyov & Polish (1999); Poznyak (1991); Polilov et al. (2010); Doyle et al. (1989); Degtyarov et al. (2018); Alhelou et al. (2018); Lu & Cannon (2019); BoÏskovic et al. (2001): LMI method (linear matrix inequality), LQ - linear-quadratic and l_1- optimization, $H_\infty-$ theory, $\mu-$ synthesis, interval analysis, Lyapunov function method, infinite increase of amplification coefficient, sliding mode, coordinate-parametric feedback, vibration control, etc.

Let's explore the methods most widely used in engineering practice.

2.1 H_∞-optimization-based robust control

Let's explore some aspects of the H_∞-optimization method, which is more relevant and developed to the end in robost control.

The main problem of this method is based on the minimization of the H_∞-norm, which characterizes the output energy (Poznyak, 1991). The H_∞-norm characterizes the maximum energy gain of a dynamic system. This norm is equal to the maximum singular number of the transmission matrix in multidimensional systems, and the maximum value of the amplitude-frequency characteristic (AFC) of the system for one-dimensional systems.

Hp - in the normal frequency range (Hardy space) is expressed as follows (Poznyak, 1991):

$$\|G(j\omega)\|_p = \left(\frac{1}{2\pi}\int_{-\infty}^{\infty} Tr[G^*(j\omega)G(j\omega)]d\omega\right)^{1/p}.$$

Here G is the transmission matrix for multidimensional systems; Tr trace of the matrix (sum of the diogonal elements); $*$ stands for adjoint relation; $p = 2, ..., \infty$.

This method is heuristic in a sense, i.e. is based on the assumptions. It is assumed that this type of minimization can provide high dynamic and static performance in addition to providing robustness. Let's look at an example that confirms that this hypothesis is not so adequate.

The nominal model of the object is given in the form of the following transfer function (Xue et al., 2007)

$$W_{ob}(p) = \frac{400}{p^2 + \delta p + 400}.$$

Parametric uncertainty is considered. Nominal value of the parameter is $\delta = 2$. The object is unstable for the case $\delta < 0$.

Despite the fact that the order of the object is $n = 2$, the order of the optimal H_∞ - regulator

$$W_c(p) = \frac{505249.169(p + 48.42)(p^2 + 2p + 400)}{(p + 9617)(p + 216.4)(p + 5)^2}$$

is equal to 4.

As can be seen, the robust controller includes an inverted model of the nominal object. For this reason, the nominal model of the indefinite object must be known.

Figure 1 shows the time characteristic (step (.) Function) of the closed system at the nominal value of the parameter $\delta = 2$, $y(t)$ a) and the corresponding control signal b).

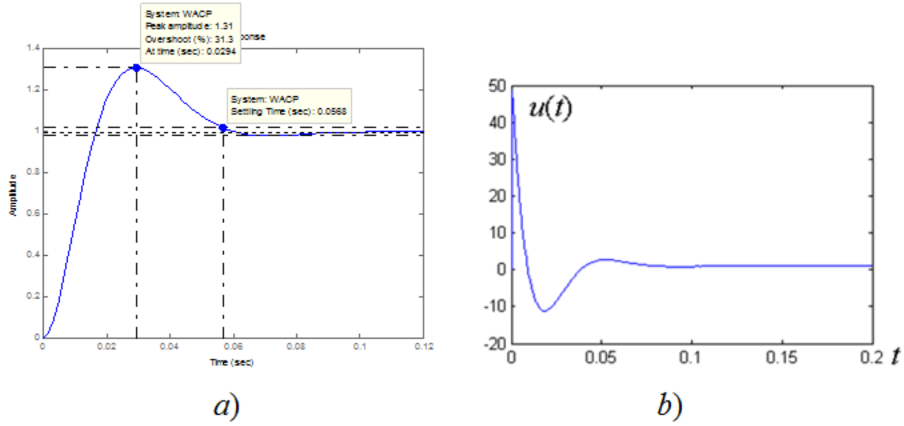

Figure 1: Time characteristic and control signal of the H_∞-optimal robast system

As can be seen, the transition characteristic $y(t)$ has a high $\sigma = 31.3$ overshoot. The control received a relatively large price at the beginning $u_{max} = 50$.

In Figure 2, a) and b) show the set of transition characteristics $y(t)$ and the corresponding control signals $u(t)$ for the 21 values of the parameter δ taken from the interval.

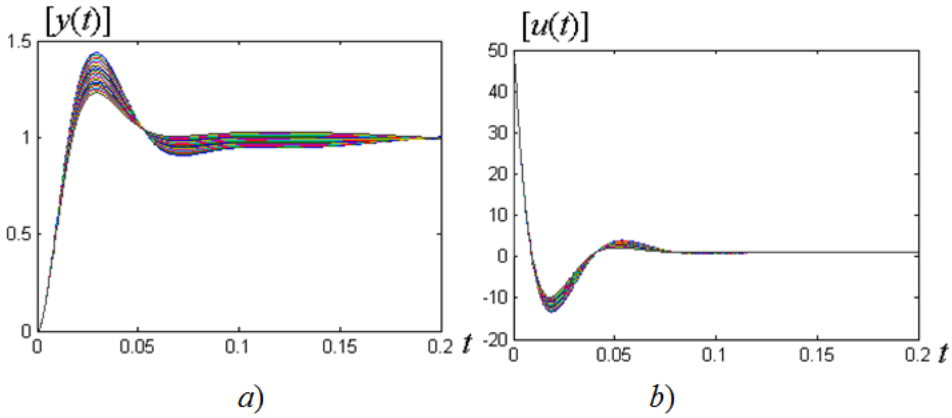

Figure 2: Dynamic characteristics set of the robust system

As can be seen, in the dynamic mode, the robustness property is weak - scattering is observed around the nominal trajectory. In settling mode, all trajectories tend to the task $g = 1$.

Although this idea is the basis for the synthesis of many robust control systems, H_∞ minimization methods have many shortcomings in terms of a priori information, synthesis methodology and system technology:

- generalized integrated indicators used as optimization criteria and different energy norms are not directly related to the dynamic and static quality indicators of the system and stability resources;
- the nominal model of the indefinite object must be known;
- additive or multicative uncertainties and unknown change interval;
- only robustness of static mode is provided;

- inability to provide required quality indicators in advance;
- high robust regulator design (Kiselyov & Polish, 1999);
- excessive setting parameters, etc.

The reason for the high order of the robast regulator is that it includes a nominal inverse model of the object. This type of construction allows one to compensate the poles of the object with the zeros of the closed system. As a result, the object loses its previous properties and "roughs". In Ho & Lin (2003) the 10-th order and in Nikiforov et al. (2011) - the 4th order robust control was obtained for the 2nd order object.

In addition, in Keel & Bnattacharyya (1997) for the first time revealed a broke of the parametric roughness in systems with optimal regulators synthesized on the basis of H_∞ - optimization method. In general, as a result of solving the optimization problem, a violation of the parametric roughness is often observed in the robust control. The reason for this has not been fully investigated. "... optimality to become dangerous, if it is taken seriously" (Tukey, 1962).

2.2 The method based on the identification of the uncertainties

In this regard, the use of"uncertainty observers" synthesized in both deterministic (Potapenko, 1995, 1996; Rustamov, 2014) and fuzzy (Ho et al., 2001; Lagrat et al., 2006; Lee & Tomizuka, 1995; Le et al., 2007) approaches can be noted.

However, the"cleansing" of the nominal model from various uncertainties becomes a tedious and non-linear task. For this reason, additive and slowly changing uncertainties are often considered.

Although significant results have been obtained for basic electromechanical systems, this method is somewhat trivial and assumes that the change in uncertainty is additive and slow. Thus, in (Kazurova & Potapenko, 2009) it is assumed that the rate of change of uncertainties is zero in the observation interval:

$$d\, f_{c\Sigma}/d\, t = 0\,,$$

where $f_{c\Sigma}$ is a sum of uncertainties. This condition is the same as the quasi-stationary condition in adaptive control, and its fulfillment is limited.

In the above studies, the main results were obtained for linear systems in the case of additive uncertainty and external stimuli. The lack of analytical expressions to determine the tuning parameters that provide pre-given quality indicators complicates the tuning and makes it impossible for high-order systems.

Unlike linear systems, nonlinear systems are difficult to distinguish from the signal that carries information about uncertain parameters and external disturbances ("motion separation" problem). In addition, the methods used by the uncertainty observer discussed here are weak against structural uncertainty.

These shortcomings severely limit the scope of methods used to assess or identify uncertainties. In the "localization of motion" method discussed below, this problem is eliminated by using a high-order derivative $y^{(n)}$.

2.3 A. Vostrikov's method of "localization of movement" (Vostrikov, 2008; Vostrikov & Frantsuzova, 2015)

In general, a control object with functional uncertainty is given by the following scalar equation:

$$y^{(n)} = f(t, x) + b(t, x)u, \tag{1}$$

where $x = (y, \dot{y}, ..., y^{(n-1)})^T = (x_1, x_2, ..., x_n)^T \in R^n$ is a measurable or estimated state vector; $y \in R$ is a controlled output; $u \in R$ control influence; $f(t,x)$ *and* $b(t,x)$ are unknown, nonlinear, bounded functions.

Since $f(t,x), b(t,x) > 0$ - $f(\cdot), b(\cdot)$ are unknown, they should be replaced with appropriate estimates. In this case, estimation methods based on fuzzy (**?**Krutko, 2004) or inverse dynamics (Meerov, 1947) can be used. In the latter case, the high derivative $y^{(n)}$ is an exact estimate of the right-hand side of the object (1) that then is parried by division by the large K amplification factor.

Using the control

$$u = K[F(x, \upsilon) - y^{(n)}(t)] \tag{2}$$

that contains higher derivative, for $K \to \infty$ we get the desired etalon motion

$$y^{(n)} + F(x, \upsilon) = 0.$$

The results of computer modeling show that a slight delay of the high derivative used in the regulator at the final value of K leads to a violation of the stability of the system $\tilde{y}^{(n)} = y^{(n)}(t-\tau)$.

Let's consider a concrete example. For the sake of simplicity, we consider the object with 1-order parametric uncertainty:

$$\dot{y}(t) = -ay + bu + \zeta(t), \; y(0) = 0;$$

with $a = \{1\ 2\ 5\}, b = \{1\ 2\ 4\}$. Perturbation is taken as $\zeta(t) = 2\sin(t)$.

Here $f(t,x) = -ay + \zeta(t), \quad b(t,x) = const.$

Given the delay of the high-order derivative, control (2) turns to $\tilde{u} = K(F + \dot{\tilde{y}}) = K(F + \dot{y}(t-\tau))$. $K = 100$, $\tau = 0.0001\ s$. Assume that the task is a single impulse i.e. $\upsilon = 1(t)$. In this case $F = 1 - y$. Summarizing the hierarchical functions as a task, let's choose an astatic PI-regulator as a reference model:

$$F = -(k_p\varepsilon + k_8 \int_0^t \varepsilon dt),$$

where $\varepsilon = \upsilon - y$ is stabilizing period. The tuning parameters correspond to Batterworth's 2nd order polynomial: $k_p = 1.41, k_u = 1$.

Figure 3 shows the tramsmission characteristics of the system modeling scheme at (a), and $\tau = 0$ (b), $\tau = 10^{-4}c.$ (c).

However, despite the very small delay timeτ of the higher derivative $y^{(n)}(t)$, $n = 1$, a stability violation is observed at the finite value of $K = 100$ (Figure 3, c).

Simple and effective robust approaches that do not use adaptation tools can provide systems with high gain.

2.4 An approach based on the large gain coefficient

These systems belong to the"limit control systems" with a large gain coefficient. This direction began with the classical works of Meerov (1986); Vostrikov (2007) and developed by Filimonov & Filimonov (2014); Rustamov et al. (2015) and others. The synthesis is based on the fact that the static error depends on the gain of the open system. The solution of this problem, which seems simple at first glance, faces a fundamental difficulty - increasing the gain increases the stability of the closed system. Existing research in this area is focused on solving this problem.

The key is to create a structure that allows for an infinite increase in the gain without compromising stability. The problem is brought to the structural synthesis, and at present there is no general solution to this problem. Heuristic approaches prevail.

The main difference of the considered method is that the nominal model of the indefinite object is not used during synthesis. This feature is a very important advantage.

The main shortcomings of the existing work are:

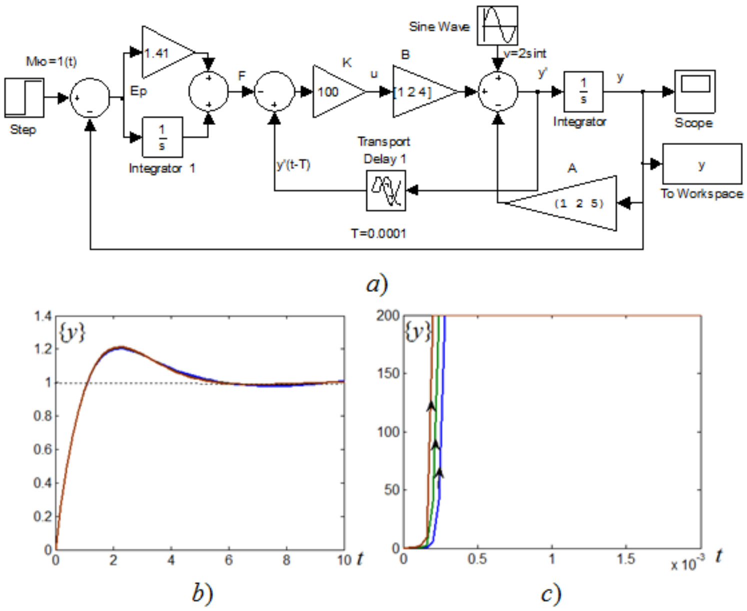

Figure 3: System modeling scheme and dynamic characteristics

- can be applied mainly to linear systems;
- for wide class objects with $m = n$, increasing the K violates the stability of the system;
- increase of high-frequency noise passing through the regulator;
- lack of analytical expression to determine the amplification coefficient K;
- no restrictions on management;

Further development of this method is presented mainly under the name of K_∞ -robast control systems (Arnold, 1884). The difference between the proposed method and the previous ones is that the synthesis problem is solved on the basis of the Lyapunov function method, which brings a unified approach and methodological clarity to the construction of systems with high gain.

Consider the control of a mathematical dancer (Rustamov, 2015), under the conditions of parametric and signal uncertainty:

$$d^2\theta/dt^2 = -k_1 \sin\theta + k_2 u + \upsilon(t),$$

$$k_1 = g/l, \quad k_2 = 2/(ml^2),$$

where m is the mass of the load; θ - angle of inclination from the equilibrium (vertical) position; l is the length of the pencil; $\upsilon(t)$ is the uncontrolled outside perturbation.

Denote

$$y = x_1 = \theta, x_2 = \dot{y} = \dot{\theta}$$

and write the equation of the dancer in the control coordinates

$$\begin{aligned}
&\dot{x} = x_1, \\
&\dot{x}_2 = -k_1 \sin x_1 + k_2 u + \upsilon(t), \\
&y = x_1.
\end{aligned}$$

Suppose that the perturbation is $v(t) = 1 + \sin(10t) + \cos(4t)$, the etalon trajectory (implicit etalon model) is $y_d = 0.5\sin(0.5t) + 0.5\cos(t)$. The quality performances are as follows: t_s=2 c., $\delta_s = 2\%$, and initial state is $x(0) = (x_{10}, x_{20})^T = (2, 0)^T$.

When n = 2 accordingly Blechman (2017) we determine the equilibrium of the robust regulator as $u = Ks = K(ce + \dot{e})$, $c = 2.16$.

Nominal parameters of the object are $m = l = 1$. The model has a wide range of parametric uncertainties: $0.5 \le m \le 1.5$, $0.5 \le l \le 1.5$.

In Figure 4(a-e) shows the dynamic characteristics of the system at $K = 120$. The modeling was performed for three discrete values of parameters: According to these values: k_1=[19.6; 9.8; 6.5], k_2=[16; 2; 0.6].

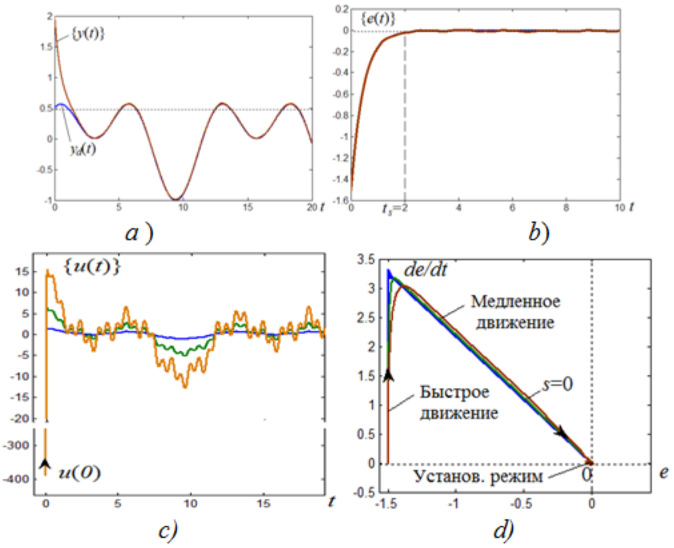

Figure 4: Characteristics of the K_∞- robast system. a - the set of transition characteristics for the output; b - tracking error; c - control signal; d- phase portrait in $T = 10sec$.

During the moving in the transverse corridor of width $2|\delta_s|$, settling occurs immediately after the time $t_s = 2c$. (Figure 4, b). In this mode, the phase trajectories do not leave a small neighborhood of the equilibrium point (Fig. 4, d).

A phase portrait constructed in the three-dimensional coordinate system $(e, \dot{e}, t)$ can be used to visualize different intervals of motion (Figure 5).

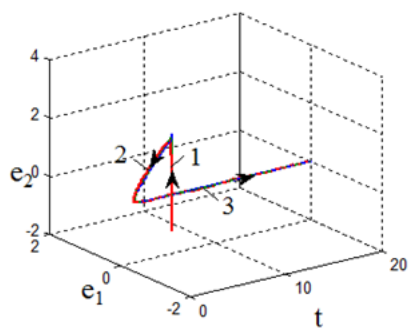

Figure 5: The nature of motion of the system in the three-dimensional space

In the Figure 1:
1 is the fast motion trajectory;
2 is the slow trajectory on the line $s = 0$;
3 is the stabilized mode.
As the advantages of K_∞ robast control systems we can note the followings:

- can be applied to non-stationary and non-linear objects;
- no need to know the nominal model;
- mathematical simplicity of the method of synthesis;
- simplicity of the intersystem structure.

As the disadvantages of the method may be noted:

- lack of analytical expression to determine K;
- obtaining of the robast regulator in the form of PDn-1-regulator.

The D-differential organizer of the regulator law increases the variance of the regulated quantity $y(t)$ by "amplifying" high-frequency noise. If we can choose the Lyapunov function properly, we can prevent the appearance of a pure D-occurrence.

2.5 Application of special modes

The advantage of vibration control (high frequency beats) is that there is no need to know the model of the object, to measure situational variables and excitatory effects. The disadvantage is the inability to obtain vibrations in inert objects (eg, industrial, mechanical, some electromechanical objects, etc.) and the defining the high-frequency dynamics of some elements of the structure, and even resonance. Currently, sliding and vibration modes are widely used as special modes (Arnold, 1884; Rustamov, 2015).

2.5.1 Vibration control (VI)

Contrary to well-known principles, vibration control does not require the measurement of situation variables and excitatory effects. For this reason, VI is mainly based on the principle of non-contact management. Thus VI differs from the principles of compensation for feedback and perturbation effects (Arnold, 1884; Rustamov, 2015; Blechman, 2017; Gozbenko, 2004; Meerkov, 1974; Bogolyubov, 1945).

Academician Bogolyubov's averaging method is used to linearize nonlinear equations in order to facilitate the study of vibrating systems (Sofiev & Shauro, 2004). An example of the application of VI is the asymptotic stability of the polymerization reactor and the inverted dancer in the oscillating mode at the point of unstable equilibrium (Kapitsa, 1951). VI control can be applied to particle acceleration, laser control processes (Meerkov, 1973).

This principle was first demonstrated by Kapitsa in the example of the stabilization of the upper unsteady position of the dancer by P.L. Researched. In this case, the reverse hanging point of the dancer is vibrated in a vertical line with high frequency and small amplitude (Sofiev & Shauro, 2004; Kapitsa, 1951).

Figure 6 shows an experimental scheme of a vibrating device (Kapitsa-Stephenson pendulum) to keep the inverted dancer in a vertical position (Kapitsa, 1951).

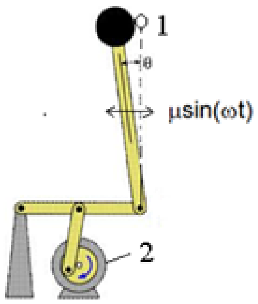

Figure 6: Vibrating device to keep the inverted dancer in vertical position

In the figure, the unstable equilibrium state with 1 is indicated. To keep the dancer in this position, it is vibrated by a signal of μ amplitude and ω frequency with the help of 2 motors. If the parameters μ and ω are chosen correctly, the dancer will vibrate and remain in an unstable position.

The main disadvantage of the vibration principle is the inability to obtain inertial vibrations (for example, in industrial, mechanical and some electromechanical systems).

3 Conclusion

The paper examines the implementation features of pobast systems widely used in engineering practice. Reasons that hinder the practical implementation of H_2, H_∞-optimal, "localization of motion" and "large amplification coefficient" methods have been identified. It is shown that robust synthesis methods based on optimization methods often lead to violation of roughness. The proposed provisions are confirmed by modeling in the *Simulink* package in concrete examples.

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