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l_1 -OPTIMIZATION APPROACH TO DESIGN OF DIGITAL AUTOPILOTS FOR LATERAL MOTION CONTROL OF AN AIRCRAFT

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В рамках современной теории управления поставлена и решена задача так называемой l_1 -оптимизации цифровых П- и ПИ-автопилотов для управления боковым движением некоторого летательного аппарата при наличии неконтролируемых внешних возмущений типа порыва ветра. Предложены численные методы нахождения оптимальных значений параметров автопилотов. Полученные результаты являются прикладными.

Ключевые слова: летательный аппарат, динамика бокового движения, цифровая система управления, устойчивость, l_1 -оптимизация, алгоритм случайного поиска.

В рамках сучасної теорії керування поставлено і розв'язано задачу так званої l_1 -оптимізації цифрових П- та ПІ-автопілотів для керування бічним рухом деякого літального апарату за наявності неконтрольованих зовнішніх збурень типу пориву вітру. Встановлені умови стійкості системи керування з двома зворотними зв'язками. Запропоновані чисельні методи знаходження оптимальних значень параметрів автопілотів. Отримані результати є прикладними.

Ключові слова: літальний апарат, динаміка бічного руху, цифрова система керування, стійкість, l_1 -оптимізація, алгоритм випадкового пошуку.

INTRODUCTION

The problem of efficiently controlling the motion of an aircraft in a non-stationary environment capable to ensure its high performance index is important enough from the practical point of view [1]. To solve this problem, the different approaches based on the modern control theory, including adaptive and robust control, neural networks, etc., have been reported by many researches [2–7]. Unfortunately, most of these works dealt with an ideal case when there are no disturbances. Nevertheless, they are always present in reality.

To implement approaches advanced in modern control theory, digital technique is appropriate. Point is that, by the end of the twentieth century, digital control has become a highly developed technology in control applications [8, 9]. Digital control systems have some features associated with sampling [9]. Namely, it leads to arising the discrete-time system description. It turns out that accurate dis-

crete-time models can be derived for sampled continuous-time systems under digital control [10].

One of the efficient methods devised in the modern control theory for rejecting any unmeasured disturbance is based on the l_1 -optimization concept [11–13] applicable to discrete-time control systems. This concept has been utilized in [14] to design the digital lateral autopilot for aircraft capable to cope with a gust.

This paper extends the approach which we have first reported among other authors in [14] to deal with a digital autopilot for the lateral motion control.

The purpose of the paper is to synthesize a digital autopilot which is able to maintain a given roll orientation of an aircraft with a desired accuracy and to cope with an arbitrary external disturbance (a gust). As in traditional continuous-time (analogue) control systems, the digital control system is designed as the two-circuit closed-loop control system having the inner feedback loop and the external feedback loop. Similar to [14], the digital autopilot is designed as the so-called l_1 -optimal controller containing the discrete-time PI and P controller parts. But, in contrast with [14], the aileron servo dynamics are taken into account to ensure the stability of closed loop. Again, the distinguishing feature of these controllers is that their parameters are optimized simultaneously.

STATEMENT OF THE PROBLEMS

Let $\dot{\gamma}(t)$ and $\xi(t)$ denote the roll rate angle and the aileron deflection of an aircraft, respectively, at a time t . According to [15, chap. 3] the lateral dynamics equation of an aircraft derived from the linearized lateral equation of the aircraft motion can be described by the continuous-time transfer function

$$W_{\xi}(s) := \frac{\dot{\Gamma}(s)}{\Xi(s)} = \frac{K_{\xi}}{T_{\xi}s + 1}, \quad (1)$$

where

$$\dot{\Gamma}(s) := \int_0^{\infty} \dot{\gamma}(t)e^{-st} dt \quad \text{and} \quad \Xi(s) := \int_0^{\infty} \xi(t)e^{-st} dt$$

represent the Laplace transforms of $\dot{\gamma}(t)$ and $\xi(t)$, respectively. K_{ξ} and T_{ξ} are the aerodynamic derivatives (more certainly, T_{ξ} is the damping derivative in the roll channel and K_{ξ} is the roll moment).

By definition, the transfer function from $\dot{\gamma}$ to γ that is output is given by

$$W_0(s) = \frac{K_0}{s}, \quad (2)$$

where K_0 may be considered as an integrator gain whose dimension is s^{-1} .

As in [15, chap. 4], it is assumed that continuous-time transfer function describing the aileron servo dynamics is

$$W_s(s) = \frac{K_s}{T_s s + 1}, \quad (3)$$

where K_s and T_s are its gain and time constant, respectively.

Define by $d(t)$ an external signal (in particular, a gust) disturbing the angular velocity $\dot{\gamma}$. This signal plays a role of some unmeasurable arbitrary disturbance. Without loss of generality, it is assumed that it has to be upper bounded in modulus. This implies that

$$|\dot{d}(t)| \leq C_d < \infty. \quad (4)$$

Suppose that $K_\xi, K_0, K_s, T_\xi, T_s$ in (1) to (3) are known, whereas C_d may be unknown, in general.

Let $\gamma^0(t)$ denote the desired roll orientation at the time t . It is assumed that $\gamma^0(t)$ is a continuous upper bounded function of t . This means that there exists a constant C_γ such that

$$|\dot{\gamma}^0(t)| \leq C_\gamma < \infty. \quad (5)$$

Define now the output error $e(t)$ as

$$e(t) = \gamma^0(t) - \gamma(t). \quad (6)$$

Further, introduce the performance index of the control system to be designed in the following form:

$$J := \limsup_{t \rightarrow \infty} |\gamma^0(t) - \gamma(t)|. \quad (7)$$

The problem to be stated is formulated as follows. Devise a digital controller which is able to minimize J assuming that the variables $\gamma(t)$ and $\dot{\gamma}(t)$ can be measured and the constraints of the forms (4) and (5) take place. Hence, the aim of the controller design may be written as the requirement

$$\limsup_{t \rightarrow \infty} |e(t)| \rightarrow \inf_{\{u(t)\}}, \quad (8)$$

where (6) and (7) have been utilized. The controller satisfying (8) is called optimal.

DIGITAL LATERAL AUTOPILOT DESIGN

Control strategy. To implement the controller design concept proposed in this paper, two feedback loops similar to that in [14, 15] are incorporated in the autopilot system, as shown in Fig. 1. But, in contrast with [15], they are designed as the discrete-time closed-loop control circuits using two separate controllers. To this end, two samplers are incorporated in the feedback loops; see Fig. 1. These samplers are needed in order to convert analogue signals $\dot{\gamma}(t)$ and $\gamma(t)$ in digital

form at each n th time instant $t = nT_0$ ($n = 0, 1, 2, \dots$) to producing the discrete-time signals $\dot{\gamma}(nT_0)$ and $\gamma(nT_0)$, respectively, with the sampling period T_0 . On the other hand, the signal $u(nT_0)$ formed by digital controller at the same time instant converts to analogue form $u(t)$ using the so-called zero-order hold (ZOH) [8]. This makes it possible to represent the control input, $u(t)$ as follows:

$$u(t) = u(nT_0) \text{ for } nT_0 \leq t < (n+1)T_0. \quad (9)$$

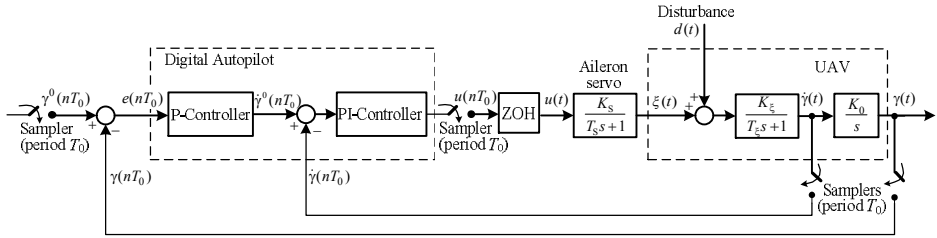


Fig. 1. Structure of digital control system containing the autopilot for the lateral motion control

The aim of the inner control loop exploiting the discrete-time PI control is to stabilize the roll rate $\dot{\gamma}(nT_0)$ at a given value, $\dot{\gamma}^0(nT_0)$, which is the output of the external control loop, as shown in Fig. 1. The feedback control law is

$$u(nT_0) = k_p^{\text{in}} e_{\dot{\gamma}}(nT_0) + k_i^{\text{in}} \sum_{i=0}^n e_{\dot{\gamma}}(iT_0), \quad (10)$$

where $e_{\dot{\gamma}}(nT_0)$ is the deflection of the true angular velocity, $\dot{\gamma}(nT_0)$, from a given angular velocity, $\dot{\gamma}^0(nT_0)$, at the time instant $t = nT_0$ given by

$$e_{\dot{\gamma}}(nT_0) = \dot{\gamma}^0(nT_0) - \dot{\gamma}(nT_0), \quad (11)$$

and k_p^{in} and k_i^{in} represent its parameters.

The sampled-data transfer function of the PI controller derived from (10) is determined as follows:

$$C^{\text{in}}(z) := \frac{U(z)}{E_{\dot{\gamma}}(z)} = k_p^{\text{in}} + \frac{k_i^{\text{in}} z}{z-1}, \quad (12)$$

where $U(z) := Z\{u(nT_0)\}$ and $E_{\dot{\gamma}}(z) := Z\{e_{\dot{\gamma}}(nT_0)\}$ are the Z-transforms [16, 17].

The external feedback loop which contains the usual P controller is used to stabilize the roll angle, $\gamma(nT_0)$, around the desired value, $\gamma^0(nT_0)$. Its control law is defined by

$$\dot{\gamma}^0(nT_0) = k_p^{\text{ex}} e_\gamma(nT_0) \quad (13)$$

together with the error

$$e(nT_0) = \gamma^0(nT_0) - \gamma(nT_0), \quad (14)$$

where $\gamma^0(nT_0)$ and $\gamma(nT_0)$ are a desired and true roll orientation at the time instant $t = nT_0$, respectively. Then the sampled-data transfer function corresponding to (13) will be defined as

$$C^{\text{ex}}(z) = k_p^{\text{ex}}. \quad (15)$$

In order to choose the optimal parameters of both digital controllers, the so-called l_1 -optimization approach is utilized.

Stability analysis. Inspecting Fig. 1 and taking (9) into account, one gets the discrete-time transfer function of inner feedback loop from $\dot{\gamma}^0$ to $\dot{\gamma}$ as

$$H^{\text{in}}(z) = \frac{C^{\text{in}}(z)W_S W_\xi(z)}{1 + C^{\text{in}}(z)W_S W_\xi(z)}, \quad (16)$$

where $W_S W_\xi(z) = (1 - z^{-1})Z \left\{ L^{-1} \left\{ W_S(s)W_\xi(s) \right\}_{t=nT_0} \right\}$ [16]. Then, using (1), (3), (11) and (12), the expression (16) gives

$$H^{\text{in}}(z) = \frac{a_1 z^2 + a_2 z + a_3}{z^3 + b_1 z^2 + b_2 z + b_3}, \quad (17)$$

where

$$\left. \begin{aligned} a_1 &= (k_p^{\text{in}} + k_1^{\text{in}})c_1, \\ a_2 &= -k_p^{\text{in}}c_1 + k_p^{\text{in}}c_2 + k_1^{\text{in}}c_2, \\ a_3 &= -k_p^{\text{in}}c_2, \\ b_1 &= d_1 - 1 + k_p^{\text{in}}c_1 + k_1^{\text{in}}c_1, \\ b_2 &= d_2 - d_1 - k_p^{\text{in}}c_1 + k_p^{\text{in}}c_2 + k_1^{\text{in}}c_2, \\ b_3 &= -k_p^{\text{in}}c_2 - d_2 \end{aligned} \right\} \quad (18)$$

are the coefficients depending on

$$\left. \begin{aligned} c_1 &= [-K_S K_\xi T_S + K_S K_\xi T_S e^{-T_0/T_S} + K_S K_\xi T_\xi - K_S K_\xi T_\xi e^{-T_0/T_\xi}] / (T_\xi - T_S), \\ c_2 &= [-K_S K_\xi T_S e^{-T_0(T_S+T_\xi)/T_S T_\xi} + K_S K_\xi T_S e^{-T_0/T_S} + \\ &\quad + [K_S K_\xi T_\xi e^{-T_0(T_S+T_\xi)/T_S T_\xi} - K_S K_\xi T_\xi e^{-T_0/T_\xi}] / (T_\xi - T_S) \\ d_1 &= -e^{-T_0/T_\xi} - e^{-T_0/T_S}, \\ d_2 &= e^{-T_0(T_S+T_\xi)/T_S T_\xi}. \end{aligned} \right\} \quad (19)$$

By applying the stability results with respect to the three-order control system which can be found in [17, subsect. 1.12], to the denominator of $H^{\text{in}}(z)$ in (17) we derive the conditions guaranteeing the stability of inner closed loop in the form

$$\left. \begin{aligned} \beta_j &> 0 \quad j = 0, 1, 2, 3, \\ \beta_1 \beta_2 - \beta_0 \beta_3 &> 0 \end{aligned} \right\} \quad (20)$$

with

$$\left. \begin{aligned} \beta_0 &= 1 + b_1 + b_2 + b_3, \\ \beta_1 &= 3(1 - b_3) + b_1 - b_2, \\ \beta_2 &= 3(1 + b_3) - b_1 - b_2, \\ \beta_3 &= 1 - b_1 + b_2 - b_3. \end{aligned} \right\} \quad (21)$$

To study the stability of the external closed loop, we again inspect Fig. 1 to obtain the discrete-time transfer function of the corresponding open loop as

$$G(z) = k_p^{\text{ex}} G'(z), \quad (22)$$

where

$$G'(z) = \frac{W_S W_\xi W_0(z)}{1 + C^{\text{in}}(z) W_S W_\xi(z)}. \quad (23)$$

Applying the frequency stability criterion taken from [18] we establish that the necessary and sufficient condition under which the closed loop will be stable is given by

$$0 < k_p^{\text{ex}} < -m, \quad (24)$$

where

$$m = \min \{ \operatorname{Re} G(e^{j\omega}) : \operatorname{Im} G(e^{j\omega}) = 0 \} \quad (< 0). \quad (25)$$

l_1 -optimization algorithm. It can be finally established that:

$$\limsup_{n \rightarrow \infty} |e_\gamma(nT_0)| \leq \|H^{\text{ex}}(k_C)\|_1 \|v^{\text{ex}}\|_\infty + O(\|\delta v\|_\infty) < \infty,$$

where

$$H^{\text{ex}}(z, k_c) = \frac{1}{1 + C^{\text{in}}(z)W_s W_\xi(z) + C^{\text{in}}(z)C^{\text{ex}}(z) + W_s W_\xi W_0(z)} \quad (26)$$

depends on the vector $k_c = [k_p^{\text{in}}, k_1^{\text{in}}, k_p^{\text{ex}}]^T$ of the controller parameters and $\|v^{\text{ex}}\|_\infty$ is the ∞ -norm of $\{v^{\text{ex}}(nT_0)\}$ defined as $v^{\text{ex}}(nT_0) = Z\{L^{-1}\{W_\xi(s)W_0(s)D(s)\}_{t=nT_0}\}$ in which $D(s) = L\{d(t)\}$. (Due to space limitation, details are omitted.)

It turned out that the set Ω^{in} of pairs $(k_p^{\text{in}}, k_1^{\text{in}})$ under which the inner loop will be stable is bounded. According to (24), the set Ω^{ex} of k_p^{ex} s guaranteeing the stability of the external loop for these k_p^{in} s and k_1^{in} s is also bounded. These facts make it possible to utilize the well-known Weierstrass theorem [19, chap. 1, sect 3]. By virtue of this theorem, there exists some

$$k_c^* = \arg \min_{k_c \in \Omega^{\text{in}} \times \Omega^{\text{ex}}} \|H^{\text{ex}}(k_c)\|_1 \quad (27)$$

minimizing l_1 -norm of the transfer function (26) in k_c .

The choice of k_c^* according to (27) solves the l_1 -optimization problem formulated as the requirement (8), and it is the main result of this paper.

Unfortunately, the l_1 -norm of $H^{\text{ex}}(z, k_c)$ given by (26) is non-differentiable function with respect to the components $k_p^{\text{in}}, k_1^{\text{in}}, k_p^{\text{ex}}$ of k_c . Therefore, the random search technique is proposed to find the optimal parameter vector, k_c^* , defined in (27).

The l_1 -optimization algorithm employing the random search is as follows [19, chap. 6, item 4]:

Step #1: Setting $k = 0$ choose an arbitrary $\hat{k}_c^0 \in \Omega$, where $\Omega = \Omega^{\text{in}} \times \Omega^{\text{ex}}$ is the bounded set depicted in Fig. 3.

Step #2: Compute a trial point $\hat{k}_c^{k+} \in \Omega$, according to the rule

$$\hat{k}_c^{k+} = \hat{k}_c^k + r^k,$$

where r^k is a realization of a suitably distributed random vector.

Step #3: If $\|H(\hat{k}_c^{k+})\|_1 < \|H(\hat{k}_c^k)\|_1$ then $\hat{k}_c^{k+1} = \hat{k}_c^{k+}$, else $\hat{k}_c^{k+1} = \hat{k}_c^k$.

Step #4: Increment k by one and go to Step #2.

Numerical example. Let the parameters of aircraft be $K_\xi = 10.84$, $K_0 = 1\text{s}^{-1}$, $T_\xi = 0.4926\text{s}$ and the parameters of the aileron servo be $K_s = 1$, $T_s = 0.1\text{s}$ (as in [15]). Choose the sampling period equal to $T_0 = 0.01\text{s}$.

By formulas (19), we first calculate $c_1 = 0.0106$, $c_2 = 0.0102$, $d_1 = -1.8847$, $d_2 = 0.8867$. Next by using these values and the inequalities (20) together with (21), we specify the stability region Ω^{in} of the inner closed loop depicted in Fig. 2. Further, exploiting the inequalities (24) together with (25), we are capable to design the three-dimensional stability region $\Omega = \Omega^{\text{in}} \times \Omega^{\text{ex}}$ as shown in Fig. 3. Note that $\Omega \subset \Omega_0$, where Ω_0 is an outer parallelepiped.

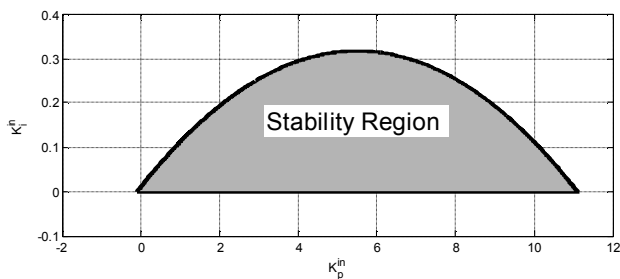


Fig. 2. Stability region of the inner circuit under the conditions of the numerical example

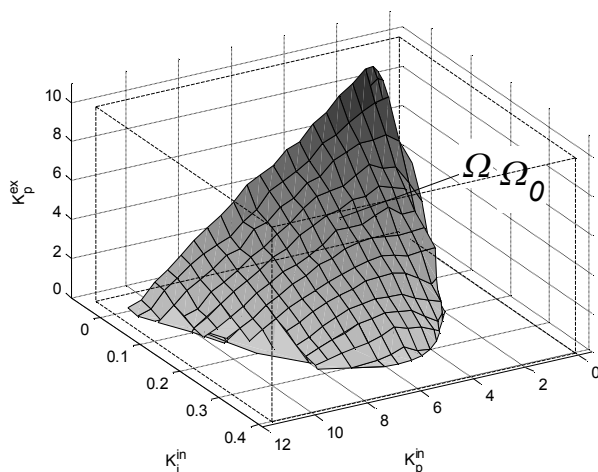


Fig. 3. Stability region of the control system under the conditions of the numerical example

Fig. 4 is presented to demonstrate how the random search process goes step by step utilizing the algorithm described in the previous subsection. Additionally, Fig. 5 shows how the vector sequence $\{k_C^k\}$ converges to a $k_C^* \approx [k_p^{\text{in}*}, k_{t_1}^{\text{in}*}, k_p^{\text{ex}*}]^T$.

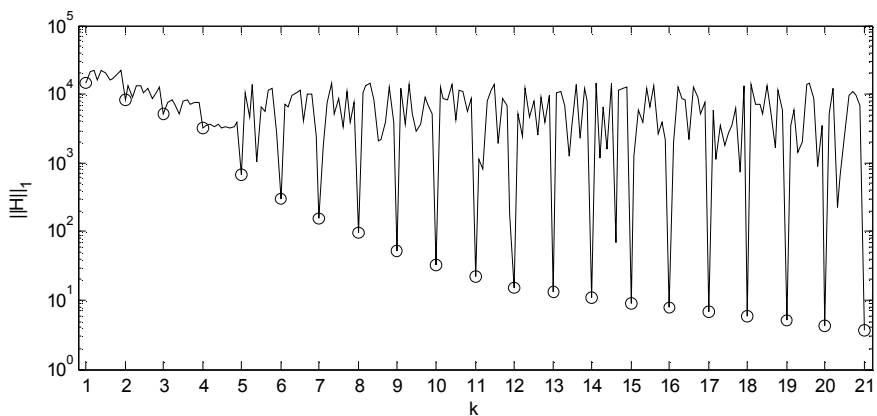


Fig. 4. Evolution $\|H(k_c)\|_1$ with k

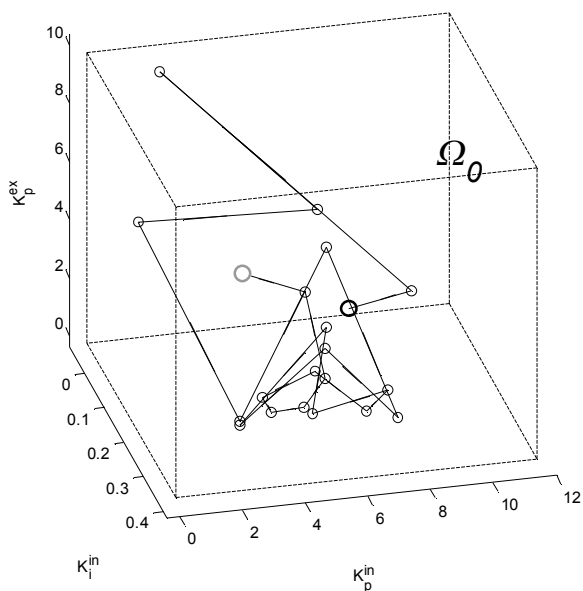


Fig. 5. Trajectory of vector sequence $\{k_c\}$ (from initial k_c^0 (black point) to final $k_c^{21} \approx k_c^*$ (grey point)) within the region Ω_0

SIMULATIONS

To evaluate the performance index of the control system that uses the l_1 -optimization approach, several simulation experiments were conducted. In these experiments, variable $d(t)$ similar to the wind gust was simulated as Dryden Wind Turbulence Model.

The duration of the observations was 500 s.

Results of six experiments are presented in Table 1.

Table 1

Performance indices of the control system for different controller parameters

Number of experiment	k_p^{in}	k_1^{in}	k_p^{ex}	Maximum $ e(nT_0) $ for $n \in [0, 50000]$
1	4	0.08	3.7	0.0203
2	4	0.1	3.7	0.0173
3	4	0.1	3.5	0.0180
4	4	0.1	3.8	0.0169
5	4	0.1	4.1	0.0160
6	3	0.05	6.8	0.0382

The first simulation experiment corresponded to the case where the controller parameters were optimized using the method proposed in the work [14]. In this case, we first optimized the two parameters of the inner controller. Next, based on these parameters, we calculated the one optimal parameter of the external controller.

In the fifth experiment, the optimal parameters of both controllers were calculated simultaneously (according to the proposed approach). It turns out that the parameter k_p^{in} of the both l_1 -optimal controllers are same whereas k_1^{in} and k_p^{ex} becomes somewhat different. This leads to the different performance indices. Namely, in the first experiment, the estimate $\max |e(nT_0)|$ were greater than in fifth experiment. This fact shows that the simultaneous l_1 -optimization is more efficient.

We observe that if k_p^{in} and k_1^{in} become approximately equal but k_p^{ex} increases then $\max |e(nT_0)|$ decreases (see Table 1).

Note that if the controller parameters essentially differ from their optimal values (as in sixth experiment), then the performance index of the control system becomes unsatisfactory.

Results of the optimal and nonoptimal control observed in first, fifth and sixth experiments, respectively, are presented in Figs 6 and 7. These figures confirm the theoretical analysis with respect to l_1 -optimal control performance in the presence of unmeasured external disturbance.

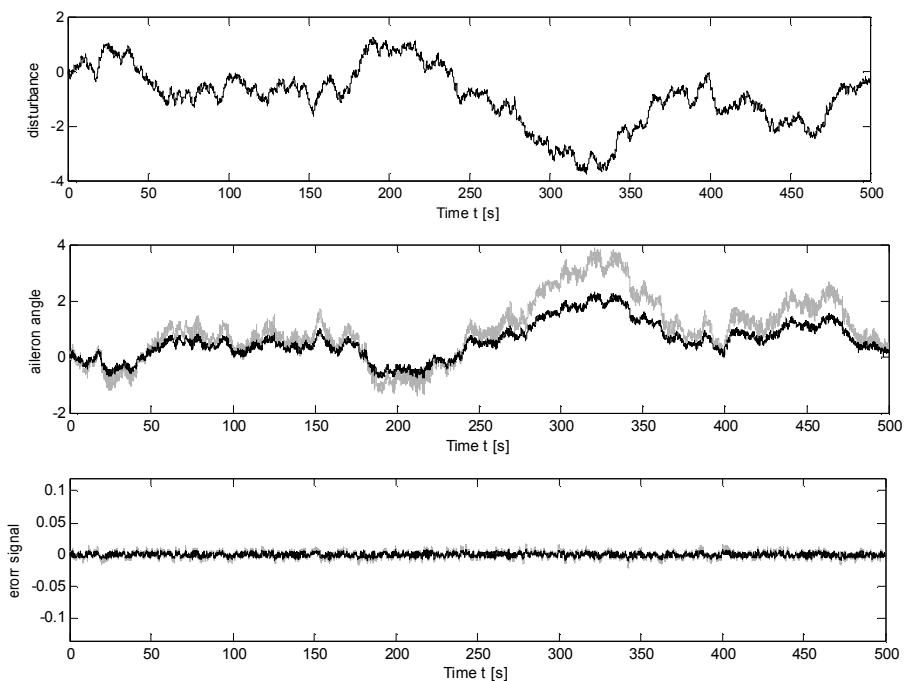


Fig. 6. Behavior of autopilot under conditions of first experiment (gray color) and of fifth experiment (black color)

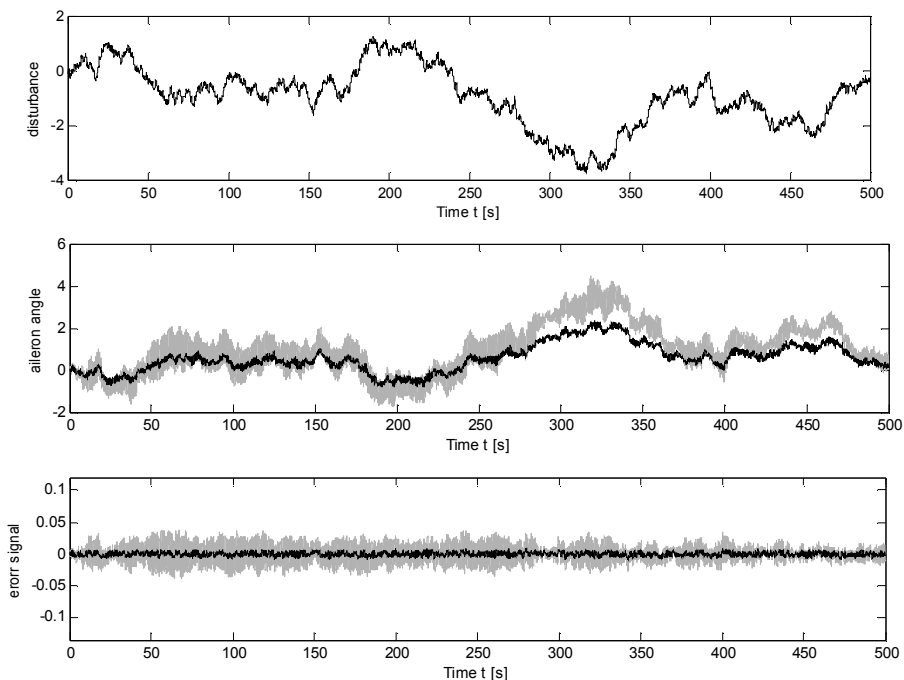


Fig. 7. Behavior of autopilot under conditions of fifth experiment (black color) and sixth experiment (gray color)

CONCLUSIONS

This paper dealt with the l_1 -optimization concept applied for synthesizing the lateral autopilot for aircraft. It was established that the two-circuit l_1 -optimal PI and P control laws can cope with the wind gust and ensure the desired roll orientation. This makes it possible to achieve the control objective given in (8).

A distinguishing feature of the control algorithms is that they are sufficiently simple. This is important from the practical point of view.

Of course, the results obtained in this work oriented on an ideal case because they do not take parametric and nonparametric uncertainties, nonlinearities, etc., into account. Therefore, the future study will be conducted to analyze the robustness properties of the controller similar to that we considered in this paper.

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Introduction. The optimal digital autopilot needed to control of the roll for an aircraft in the presence of an arbitrary unmeasured disturbances is addressed in this paper. This autopilot has to achieve a desired lateral motion control via minimizing the upper bound on the absolute value of the difference between the given and true roll angles. It is ensured by means of the two digital controllers. The inner controller is designed as the discrete-time PI controller in order to stabilize a given roll rate. This variable is formed by the external discrete-time P controller. To optimize this control system, the controller parameters are derived utilizing the so-called l_1 -optimization approach advanced in modern control theory. The motion parameters are assumed to be known.

The purpose of the paper is to synthesize a digital autopilot which is able to maintain a given roll orientation of an aircraft with a desired accuracy and to cope with an arbitrary external disturbance (a gust) whose bounds may be unknown.

Results. The necessary and sufficient conditions guaranteeing the stability of the two-circuit feedback discrete-time control system are established. First, the l_1 -optimal PI and P controller parameters are calculated simultaneously (in contrast with [14]). Second, the aileron servo dynamics are taken into account to establish the stability condition for optimizing the controller parameters. Third, random search algorithm is used to calculate the three optimal values of the autopilot parameters. To support the theoretical results obtained, in this work, several simulation experiments were conducted. We have established that the simultaneous l_1 -optimization of both controllers was more efficient than the sequential l_1 -optimization of inner and external controllers.

Conclusion. It was established that the two-circuit l_1 -optimal PI and P control laws can cope with the wind gust and ensure the desired roll orientation. This makes it possible to achieve the control objective which was stated. A distinguishing feature of the control algorithms is that they are sufficiently simple. This is important from the practical point of view.

Keywords: aircraft, lateral dynamics, digital control system, discrete time, stability, l_1 -optimization, random search algorithm.

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