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ROBUST OPTIMIZATION OF THE UAV GAIN-SCHEDULED FLIGHT CONTROL SYSTEM

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Abstract**—***The paper presents Successive Loop Closure baseline controller for the entire flight envelope of small unmanned aerial vehicle. The suboptimal robust flight control system on a basis of gain-scheduling approach is proposed. Since small unmanned aerial vehicle flights are performed within low altitudes, it is enough to choose as the scheduling-variable value the true air speed only. Furthermore, the* $\mathrm{H}_2/\mathrm{H}_{\mathrm{inf}}$ *-robust optimization procedure based on the genetic algorithms is well suited to seek a compromise between multi-objectives functions and find compromise between performance and robustness. A discrete gain-scheduled controller is obtained by Lagrange interpolation between local controllers. The design procedure is given by a case study of unmanned aerial vehicle lateral channel control. From the simulation results, gain scheduling control provides a significantly better response than fixed gain control.*

Index Terms—Unmanned aerial vehicle; flight control system; genetic algorithm; gain scheduling; multi-objectives optimization.

I. INTRODUCTION

The cost, size and capabilities make small unmanned aerial vehicles (UAVs) useful for permanently expanded range of usage. It requires performing flights in a wide range of the altitudes and velocities that leads to wide variations of the parameters of the UAV dynamic model within the full flight envelope. The application of robust theory only for the autopilots design is sometimes insufficiently and requires application of the combination of the robust and classic adaptive control [4], [6]. However the application of the classic adaptive control with closed-loop adaptation contour essentially complicates the structure of the flight control system from one hand and decreases its ability to withstand abrupt parametric disturbances (due to the slow transient processes in the closed-loop adaptation contour) from the other hand. In order to avoid these disadvantages a conventional gain-scheduling (GS) technique [3], [8], and [11] can be used to handle the variations of the UAV dynamic model within complete flight envelope. It is proposed in this paper to combine the GS and the robust control principles. Thus the GS idea is the control law adjustment based on the real-time true air speed (TAS) measurement. Such approach essentially simplifies flight control system, decreases the cost of UAV and increases its dynamic properties and reliability.

The flight control system explored in this paper consists of a Successive Loop Closure (SLC) baseline controller [2]. The genetic algorithm (GA) [5] is implemented for determining SLC-controller parameters. The GA optimization procedure is adopted to ensure the best disturbance rejection performance and control system robustness for any perturbed model of the closed loop system. In order to obtain numerical results we consider lateral motion control, which includes in accordance with SLC-principle the roll angle stabilization as the inner loop and the heading angle stabilization as the outer loop (Fig. 1). For this Case Study the mathematical model of small UAV Aerosonde was chosen, which is supported by the Aerosim Matlab® Packet [14].

II. PROBLEM STATEMENT

Let mathematical model of the controlled plant (CP) is described in the state space by the following system of equations:

$$\begin{cases} \dfrac{dX}{dt} = A(\overline{q})X(t) + B(\overline{q})U(t) + B_w(\overline{q})W(t), \\ Y(t) = CX(t), \end{cases} \tag{1}$$

where the state $\vec{X}$, the control $\vec{U}$ vectors, the observation vector $\vec{Y}$, the disturbance input (turbulent wind) for the lateral dynamics model of UAV can be defined as follows: $\vec{X} = [\beta, p, r, \varphi, \psi]^{\mathrm{T}}$, $\vec{U} = [\delta_a, \delta_r]^{\mathrm{T}}$ $\vec{Y} = [p, r, \varphi, \psi]^{\mathrm{T}}$ $\vec{W} = [\beta_g, r_g]^{\mathrm{T}}$ and involve the following components: sideslip angle β, roll and yaw rates p, r respectively, and roll and yaw angles φ, ψ respectively, the ailerons deflections δ_a and rudder deflections δ_r, turbulent sideslip angle β_g and turbulent yaw rate r_g.

Corresponding matrices of this model $A(\bar{q}), B(\bar{q}), B_w(\bar{q})$ depend on the value of the dynamic pressure $\bar{q} = \frac{\rho V_t^2}{2}$, where ρ stands for the air density at the flight altitude, and V_t is the TAS [2], [7]. Dynamic pressure depends on the altitude-speed parameters within the flight envelope of the UAV and defines the parametric disturbance. As far as for small UAV the range of the flight altitudes is restricted, the value of the air density can be considered as constant [2]. So it is possible to assume, that the entries of the matrices in (1) are the functions of the TAS only, and the small deflection of the air density from its constant value could be treated as the component of the model uncertainty. Using the standard transform of the system (1) from the continuous to the discrete time [7] we will obtain the following system of equations:

$$\begin{cases} X(k+1) = A_d(V_t)Y(k) + B_d(V_t)U(k) + B_d^W(V_t)W(k), \\ Y(t) = CX(k). \end{cases} \quad (2)$$

The block diagram of the UAV lateral motion of gain-scheduled control system with SLC is shown in Fig. 1, where ADS is the air data system.

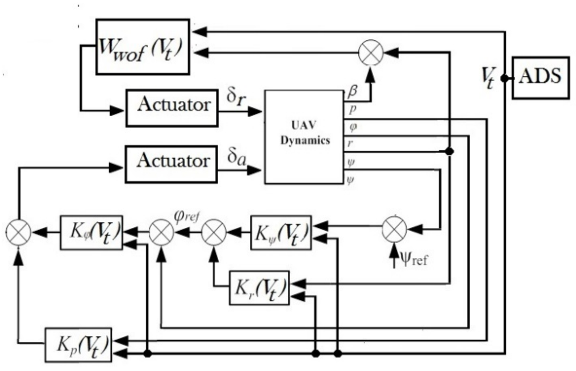


Fig. 1. Block diagram of the UAV lateral motion

The roll angle and yaw angle controls are represented by two SLPs with standard PD control laws:

$$\begin{aligned} \psi_{\text{ref}} &= L_\varphi(V_t)\varphi + L_p(V_t)p, \\ \varphi_{\text{ref}} &= L_\psi(V_t)\psi + L_r(V_t)r. \end{aligned} \quad (3)$$

The output of the loop of roll angle control serves as the reference signal to inner loop (yaw angle control). Sideslip angle β is suppressed for the coordinated turn execution [8], [9] by the standard washout filter with transfer function in discrete form

$$W_{wf}(z) = L_{wf} \frac{z-1}{z - \exp\left(-\frac{T_s}{\tau}\right)},$$

where L_{wf} is the washout filter gain, T_s and τ are the sampling interval (s) and time constant (s) respectively. Parameters of controller are the entries of the following matrix:

$$L(V_t) = \begin{bmatrix} L_p(V_t) & L_r(V_t) & L_\varphi(V_t) & L_\psi(V_t) & L_{wof}(V_t) \end{bmatrix}, \quad (4)$$

where L_i stand for gains of the corresponding output variables of plant.

The algorithm of a GS control system design can be summarized in the following steps [2]:

1) Divide the full range of TAS in the given flight conditions by n small sub-ranges.

2) Obtain a plant model for each sub-range. It needs to linearize the plant at several equilibrium operating points. In our case we need to select a representative set of V_t values for the average cruise altitude.

3) Design a family of the linear SLC-controllers for the obtained plant models.

4) Provide optimization procedure to the family of controllers. This stage starts from the definition of the performance index to be minimized. For the reason to find the compromise between the disturbance rejection performance and robustness, it is used a multi-objectives optimization problem, based on including several objectives in one cost function and try to satisfy them at the same time finding compromise solution [1], [9].

5) Implement a scheduling mechanism. It means to apply interpolation method (for example Lagrange polynomials) in order to obtain dependence of each controller coefficient on parametric disturbance (TAS).

6) Assess control performance with simulation.

A. Parametric Robust Optimization

In accordance with aforementioned item 3 it is necessary to find the trade-off between performance and robustness of control system using H_2-norm of its sensitivity function and H_∞-norm of its complementary sensitivity function [1], [9]. For this reason, we use a multi-objective robust H_∞ / H_2-optimization procedure [1]. For this procedure it is necessary first of all to define the composite "performance-robustness" performance index. As far as UAV must follow deterministic command from the guidance system and must fly in the turbulent stochastic atmosphere, this performance index must include components reflecting both of these cases, which are illustrated by Fig. 2.

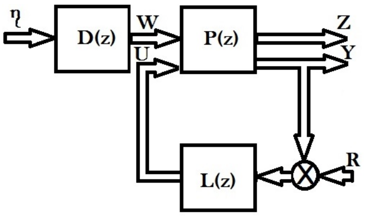


Fig. 2. Block-diagram of feedback loop

In this Fig. 2 vectors **X**, **U**, **W**, and **Y** are the same as it was assumed in system (1) and the vector $\mathbf{Z}_d$ is vector of desired output, which can be described as follows:

$$\mathbf{Z}_d = \begin{bmatrix} \mathbf{Q} & \mathbf{0} \\ \mathbf{0} & \mathbf{R} \end{bmatrix} \times \begin{bmatrix} \mathbf{X} \\ \mathbf{U} \end{bmatrix}, \qquad (5)$$

where **Q**,**R** are weighting matrices and **0** is zero matrix with corresponding sizes.

It is necessary to notice that the turbulent wind W in (1), (2) is simulated by Dryden model represented by matrix of transfer functions (MTF) $D(s)$, which is described in [2], [7]. Discrete version of the Dryden model $D(z)$ is also available in Aerospace Blockset of the Matlab® Packet [14]. The input of this block is the unit white noise η and the outputs the same as components of W (1). Other blocks include: MTF $P(z)$, $K(z)$ of the UAV model and controller respectively, $R-$ is deterministic reference signal. These transfer functions can be found as a result of the Z-transform of system (2). Now we can define the MTF of the following close-loop systems between inputs η, R and outputs Y, Z_d and the following norms associated with them:

1) H_2-norms of a model in deterministic case [10]:

$$J_d = \sqrt{\frac{1}{2\pi j} \oint_L \mathrm{tr}\left[W^{\mathrm{T}}_{RZ_d}(z^{-1}) W_{RZ_d}(z) \right] \frac{dz}{z}}, \qquad (6)$$

where L is unit circle.

2) H_2-norms of a model in stochastic case:

$$J_s = \sqrt{\frac{1}{2\pi j} \oint_L \mathrm{tr}\left[W^{\mathrm{T}}_{\eta Z_d}(z^{-1}) W_{\eta Z_d}(z) \right] \frac{dz}{z}}. \qquad (7)$$

3) The complementary sensitivity function in this case is described with MTF $W_{RY}(z)$, so $T(z)=W_{RY}(z)$. The robustness of system is defined by H_∞-norm of this function [10]:

$$\|\mathbf{T}\|_\infty = \sup_\omega \bar{\sigma}\left(\mathbf{T}(j\omega)\right) \qquad (8)$$

where $\bar{\sigma}$ is the maximum singular value of **T** matrix over infinite frequency range: $0 \le \omega \le \infty$. Norms (7), (6) define the performance of system and norm (8) – its robustness.

As far as these norms can be applied only for stable systems, it is necessary to define the penalty function (PF), restricting location's area of the closed loop system poles in the predefined domain M in the complex plane [14]. This penalty function is demonstrated as vertical section through real axis of the complex plane of roots on the Fig. 3, where shaded area represents the domain M. The penalty function is defined by minimal distance d_m to the borders of the predefined domain M [14]:

$$PF(d_m) = \begin{cases} 0, \text{ if } \; d_m \ge d_{m1}, \\ \dfrac{P}{2}\left[1 + \cos\left(\dfrac{\pi(d_m - d_0)}{(d_{m1} - d_0)}\right)\right], \text{if } \; d_0 < d_m < d_{m1}, \\ P, \text{ if } \; d_m \le d_0, \\ 0, \text{ if } \; |z(\omega_*(i))| - |E_{\mathrm{sys}}(i)| > 0 \; \text{ and } \; |E_{\mathrm{sys}}(i)| \le d_0, \\ P, \text{ if } \; |z(\omega_*(i))| - |E_{\mathrm{sys}}(i)| < 0, \; |E_{\mathrm{sys}}(i)| > d_0. \end{cases} \qquad (9)$$

where P is a large value (for instance, $P = 10^4 - 10^6$), $E_{\mathrm{sys}}(i)$, $i = 1,...,n$ are the eigenvalues of the close-loop system, and

$$\omega_*(i) = \ln\left(\frac{\mathrm{Im}\left(E_{\mathrm{sys}}(i)\right)}{\mathrm{Re}\left(E_{\mathrm{sys}}(i)\right)}\right) / \left(2\pi \tan\beta / \omega_s + 2\pi / \omega_s\right),$$

are frequencies that determine the points $z(\omega_*(i)) = \exp(-j\omega_*(i))$ on the logarithmic spiral 1 segments (Fig. 3) corresponding to the eigenvalues $E_{\mathrm{sys}}(i)$. This spiral restricts the oscillation ability of discrete system, and $\tan\beta$ defines this ability for the continuous system in the complex plane.

The expression composite performance index (CPI) is given as,

$$J_\Sigma = \lambda_d J_d^2 + \lambda_d^p \left(J_d^p\right)^2 + \lambda_s J_s^2 + \lambda_s^p \left(J_s^p\right)^2 + \lambda_\infty \|\mathrm{T}\|^2_\infty + \lambda_\infty^p \|\mathrm{T}^p\|^2_\infty + \mathrm{PF}, \qquad (10)$$

where $\lambda_d, \lambda_d^p, \lambda_s, \lambda_s^p, \lambda_\infty, \lambda_\infty^p$ is the LaGrange factors, J_d and J_{dp} define the H_2-norms of the models in deterministic cases for particular TAS range. J_s and J_{sp} – define the performances of the stochastic models. $\|\mathrm{T}\|_\infty$ and $\|\mathrm{T}^p\|_\infty$ are the H_∞-norms and gives the estimation of the robustness of the "nominal" and the parametrically disturbed plants, PF is the penalty function. It is considered that ending of each sub-range is parametrically disturbed case and beginning is nominal case.

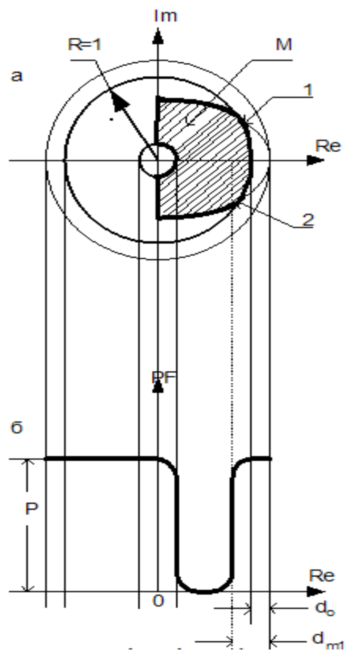


Fig. 3. Penalty function in the complex plan:
(a) is the domain M for closed loop system poles location;
(b) is the $\mathrm{PF}(d_m)$ -vertical section through real axis "$\mathrm{PF-Re}$"

The cost functions in the expression (10) is the function of controller gain vector $\vec{L_i}$ (4), where i indicates a number of the TAS range, that's why the result of optimization procedure will be following: $\vec{L_i}^* = \arg\min J_{\Sigma}(\vec{L_i}),\quad \vec{L_i} \in M_c$, where M_c is the stability domain of controller gains.

B. Genetic Algorithm Optimization Approach

Composite performance index (10), which must be minimized, is complicated function due to the high order of mathematical model of controlled plant. That is why the assumption, that CPI (10) would be convex function, is irrelevant in the majority of practical cases, and the multi-extremum optimization problem with multiple local extremal points is much more probable. So in this situation it is necessary to apply the global optimization algorithms.

One of the most successful methods of the global optimization is the application of the genetic algorithms (GA) [5]. In this case the space of all possible solutions is the set of the controller parameters (chromosomes). First of all, it is necessary to generate the start parent population of chromosomes and their fitness function calculation (CPI in this case). Each chromosome represents a string of five controller parameters (4). The fitness function values are calculated for each string. If any of chromosomes achieves the best value, than without any change it moved to the next generation. Next a new „reproduction" group of chromosomes selected either according to their fitness values, or randomly selected, or selected combining both methods, etc. are used for crossover and mutation operations. After each step we have a new completed parent population. The algorithm exit condition can be following: the fitness function of the best string in some population fulfills the predefined condition or until the predefined number of populations is put into life.

III. CASE STUDY: GAIN SHEDULED HEADING STABILIZATION

Nonlinear models of Aerosonde were linearized via procedures supported by the Aerosim Matlab® Packet [14].The models of the actuators represented by the transfer functions $W_{ac}(p) = \dfrac{1}{0.25p+1}$ [14].

The admissible range of the TAS variations is 20–32 m/s (at the altitude 900 m) was divided by 6 sub-ranges ($n = 6$). Within these sub-ranges model (1) can be considered as time invariant.

In accordance with steps 1–3 of aforementioned algorithm (described in the problem statement) for each sub-range it was calculated the gains and the family of 6 controllers was obtained (Table I). The CPI for the sub-range 32 m/s or higher includes J_d , J_s , $\|T\|_\infty$ norms for nominal case only.

For decreasing of order of the Lagrange interpolation polynomials the sensitivity analysis of the closed loop system with respect to the variations of the SCL gains was performed. This sensitivity can be evaluated using the sensitivity transfer functions with respect to the each gain L_{ij} variations [13]: $W_{ij}(z) = \dfrac{\partial T_j^i(z)}{\partial L_j^i}$, where $T_j^i(z)$ is the transfer function of the closed loop system from the ith input (i = 1,2) to the jth output (j = 1, ..., 5) and physical sense of each input and output can be realized from the matrix $L(V_t)$ (4).

Table II represents numerical values of the sensitivity functions H_∞-norms for 3 TAS values, which characterizing 3 flight conditions (minimal, normal and maximal TAS).

As far as the value of the L_{wof} gain is sufficiently small as well as the sensitivity with respect to its variations, then this gain could be taken as constant $L_{\mathrm{wof}} = 0.1$.

TABLE I. FAMILY OF CONTROLLER GAINS

Altitude 900 m					
Speed subranges	L_p	L_r	L_φ	L_ψ	L_{wof}
20–22	6.7	3.746	1.4784	15.2	0.1012
22–24	6.078	2.6712	1.4869	15.2512	0.1012
24–26	5.3028	2.7298	1.4965	16.4016	0.1
26–28	4.4505	2.6846	1.5021	10.8064	0.1232
28–30	3.589	2.4984	1.4987	13.62	0.1101
30–32	2.785	2.334	1.4813	14	0.1002
32 >	2.1054	1.543	1.4449	15.099	0.1

TABLE II. SENSITIVITY FUNCTIONS

no	**True airspeed, m/s (altitude 900 m)**	$\left\|\frac{\partial T_\psi}{\partial L_p}\right\|_\infty$	$\left\|\frac{\partial T_\psi}{\partial L_\varphi}\right\|_\infty$	$\left\|\frac{\partial T_\psi}{\partial L_r}\right\|_\infty$	$\left\|\frac{\partial T_\psi}{\partial L_\psi}\right\|_\infty$
1	20	0.0459	0.0415	0.0078	0.0056
2	26	0.3702	0.0791	0.8654	0.0619
3	32	0. 2241	0.3066	0.3075	0.0462

In the Figure 4 crosses symbols correspond to L_ψ gains obtained as a result of the robust optimization, solid line corresponds to Lagrange polynomial $L_\psi(V_t)$. The maximum deviation of the obtained gain from third order Lagrange polynomial equals $\Delta L_\psi \approx 0.6$ (Fig. 4), in this case the upper limit estimation of the maximum deviation of the output coordinate ψ is less than:

$$\left\|\frac{\partial T_\psi}{\partial L_\psi}\right\|_\infty \cdot 0.5 \simeq 0.03 \text{ rad}, \quad (1.72 \text{ deg}).$$

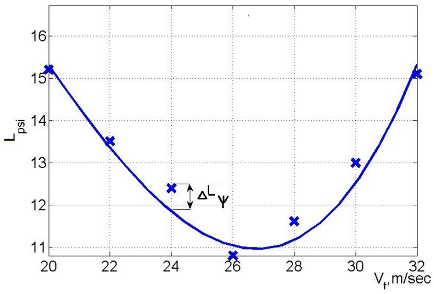


Fig. 4. Polynomial interpolation of $L_\psi(V_t)$

Taking into consideration given sensitivity functions (Table I) it is possible to substantiate the approximations of gains by the third order Lagrange-polynomials:

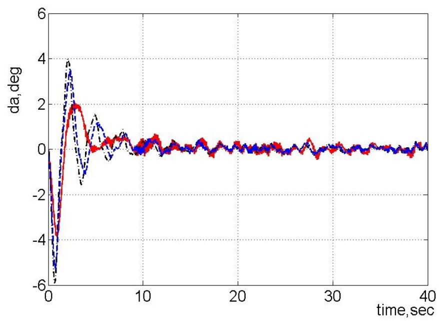
$$L_p(V_t) = 1.3595 \cdot 10^{-3} V_t^3 - 0.11 V_t^2 + 2.457 V_t - 9.59,$$

$$L_r(V_t) = 5.29 \cdot 10^{-3} V_t^3 - 0.2931 V_t^2 + 4.36 V_t + 3308,$$

$$L_\varphi(V_t) = -1.044 \cdot 10^{-4} V_t^3 + 70.19 \cdot 10^{-4} V_t^2 - 0.1523 V_t + 2.552,$$

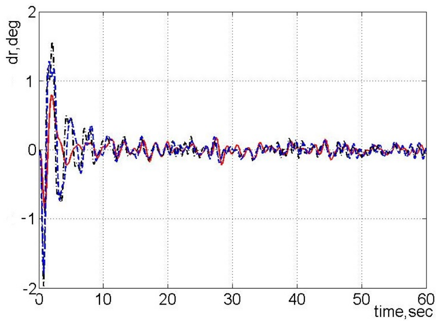
$$L_\psi(V_t) = -6.56 \cdot 10^{-3} V_t^3 + 0.5179 V_t^2 - 13.572 V_t + 120.6.$$

The simulation of heading stabilization was made for 3 flight conditions indicated in Table II. Transient processes in different loops for the input step function ψ_{ref} are shown in the Fig. 5, where solid lines correspond to the case 1, dash-and-dot line to the case 2, and dashed line to the case 3. The transient process of aileron deflection, rudder deflection, roll angle, heading, roll and yaw rates are shown in Figs 5a–f. They demonstrate pretty good performance of the lateral motion control system. Note that heading transient processes are the same for wide range of TAS (Fig. 5d). For the case of a fixed gains controller, the UAV lost stability for high speed mode (see Fig. 6, Transient processes of aileron deflection for case 3 with fixed gains controller). Gain scheduled controller widens the acceptable operating range in comparison with fixed gains controller.

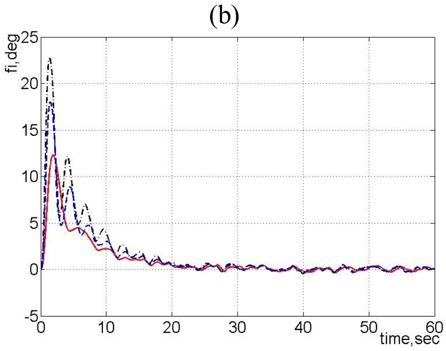


(a)

Fig. 5. Simulation results for lateral channel of the UAV in the presence of external disturbances (flight condition *1* is the *solid line*; the flight condition; *2* is *dash-and-dot line*; the flight condition *3* is *dash line*): (a) aileron deflection; (b) rudder deflection; (c) roll angle; (d) heading; (e) roll rates; (f) yaw rates



(b)



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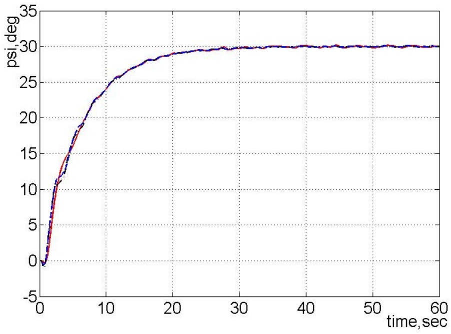
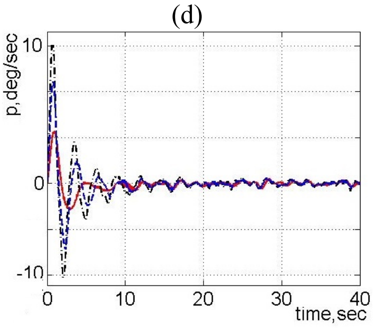
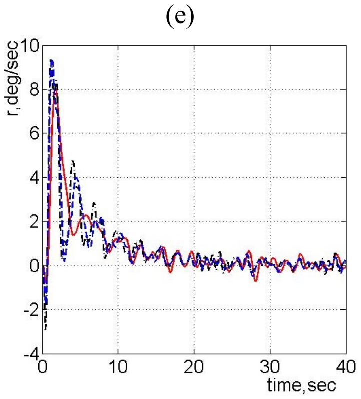


(d)



(e)



(f)

Fig. 5. Ending. (See also p. 71)

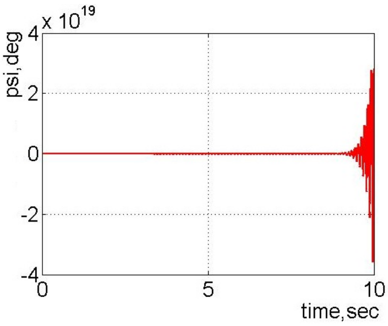


Fig. 6. Heading holding with fixed gain control in the presence of external disturbances for 3rd flight condition

IV. CONCLUSIONS

In this paper, the gain-scheduled controller synthesis problem for a small UAV is presented.

1) The proposed gain-scheduled controller design method avoids the problem induced by the conventional controller for controlled plants with large-scale parameter variations and unmodelled dynamics. Furthermore, the result control structure is simpler and requiring less computational time in comparison with application of the adaptive system with closed-loop adaptation contour. That is desired for practical engineering.

2) Proposed optimization procedure permits to achieve desirable compromise between performance and robustness of the flight control system.

The robustness property allows finding the simplest approximation of the controller gains as functions of the parametric disturbance (in a UAV case that is the true air speed).

3) The polynomial approximation of gain-scheduled SCL is successfully provided by the Lagrange interpolation polynomials.

A simulation results of the gain-scheduled heading stabilization system for the small UAV Aerosonde demonstrates efficiency of the proposed method of the gain-scheduled flight control system synthesis.

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А. А. Тунік, О. І. Надсадна. Робастна оптимізація системи керування безпілотним літальним апаратом з програмною адаптацією коефіцієнтів підсилення

У статті представлений регулятор з програмною адаптацією коефіцієнтів посилення для всього діапазону польоту малого безпілотного літального апарату. Запропоновано субоптимальну робастну систему керування польотом на основі підходу, заснованого на програмній адаптації коефіцієнтів підсилення. Оскільки малі безпілотні літальні апарати виконують польоти на малих висотах, досить вибрати в якості значення змінної, що визначає зміну динаміки об'єкта істинну повітряну швидкість. Крім того, процедура робастної оптимізації, заснована на генетичних алгоритмах, добре підходить для пошуку компромісу при вирішенні задачі багатокритеріальної оптимізації та пошуку компромісу між робастністю і якістю. Дискретне керування з використанням програмної адаптації коефіцієнтів посилення забезпечується за допомогою інтерполяції Лагранжа між локальними регуляторами. Процедуру синтезу наведено для системи керування бічним каналом безпілотного літального апарату. З результатів моделювання видно, що запропонована система керування забезпечує значно кращий результат, ніж регулятор з фіксованими значеннями.

Ключові слова: безпілотний літальний апарат; система керування; генетичний алгоритм; програмна адаптація коефіцієнтів підсилення; багатокритеріальна оптимізація.

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А. А. Туник, О. И. Надсадная. Робастная оптимизация системы управления беспилотным летательным аппаратом с программной адаптацией коэффициентов усиления

В статье представлен регулятор с программной адаптацией коэффициентов усиления для всего диапазона полета малого беспилотного летательного аппарата. Предложена субоптимальная робастная система правления полетом на основе подхода, основанного на программной адаптации коэффициентов усиления. Поскольку малые БПЛА выполняют полеты на малых высотах, достаточно выбрать в качестве значения переменной определяющей изменение динамики объекта истинную воздушную скорость. Кроме того, процедура робастной оптимизации, основанная на генетических алгоритмах, хорошо подходит для поиска компромисса при решении задачи многокритериальной оптимизации и поиска компромисса между робастностью и качеством. Дискретное управление с использованием программной адаптации коэффициентов усиления обеспечивается с помощью интерполяции Лагранжа между локальными регуляторами. Процедура синтеза приведена для системы управления боковым каналом беспилотного летательного аппарата. Из результатов моделирования видно, что предложенная система управления обеспечивает значительно лучший результат, чем регулятор с фиксированными значениями.

Ключевые слова: беспилотный летательный аппарат; система управления; генетический алгоритм; программная адаптация коэффициентов усиления; многокритериальная оптимизация.

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