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STATIC OUTPUT FEEDBACK DESIGN OF ROBUST GAIN SCHEDULED CONTROL SYSTEM

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Absract—*Gain scheduling is one of the widely used controller design approaches with successful application as well as in industrial and aerospace areas. It gives an opportunity to increase a degree of the system robustness without using adaptive loops. This paper considers gain-scheduling static output feedback controller design for linear parameter-varying system in terms of linear matrix inequalities. The obtained controller guarantees an efficient unmanned aerial vehicle's control under external disturbances within the flight envelope.*

Index terms—Gain scheduling; linear matrix inequalities; robustness; unmanned aerial vehicle.

I. Introduction

The control system designers pay a considerable attention to the problem of the robust controller design for unmanned aerial vehicles (UAVs). The modern generation of UAV provides multifunction civil and military applications. The flight envelope for modern UAV as well as piloted aircraft is widening essentially. It leads to significant changing of linearized mathematical models of aircraft. The changing of model parameters could be so extensive that even the classical robust control can't solve this compensation problem. In this case gain scheduling (GS) control becomes very powerful instrument for increasing of flight control system robustness.

Flight control system for a small UAV is restricted by low weight, size, price and power consumption. The structure of such controllers must be simple and easy to implement. The static output feedback (SOF) design in terms of linear matrix inequalities (LMIs) [1], [3], [5] – [7], [10] requires only available signals from the plant to be controlled. Also the controller design doesn't need to solve differential equations, that is important for a decreasing of power consumption and computational cost [10].

In view of the aforementioned, the gain-scheduled static output feedback controller design in terms of linear matrix inequalities is considered in the article. The model of UAV used in this research is Aerosonde which is supported by Aerosim Matlab Toolbox.

II. Analysis of Recent Research and Publications

The gain scheduling control problem has been widely developed both from theoretical and practical viewpoints, see, for example, [4], [9]. An effective approach to solve the nonlinear control problem is using gain scheduling with linear parameter-varying (LPV) controller. For example, the parameters of the mathematical model of an aircraft depend on the altitude and speed (Mach number), which determine the dynamic pressure (DP): $\overline{q} = \rho v^2/2$, where ρ is density of air, kg/m^3, v is air speed, m/s. The main advantage of DP, that this parameter is related with both flight altitude and speed values. As far as all entries of the stability and control matrices A, B could be considered as functions of $\overline{q} : \mathrm{A}(\overline{q}),\ \mathrm{B}(\overline{q})$ [2], then for these matrices it is possible to find parameters of the controller from the point of view of robust stability and robust performance for each numerical value of $\overline{q}$.

III. Problem Statement

Let us consider a LPV system in form

$$\begin{cases} \dot{x}(t) = \mathrm{A}(\overline{q})x(t) + \mathrm{B}(\overline{q})u(t) + \mathrm{B}_v(\overline{q})v(t), \\ y(t) = \mathrm{C}(\overline{q})x(t) + \mathrm{D}(\overline{q})u(t), \end{cases} \tag{1}$$

where $x \in \mathbf{R}^n$ is the state vector; $u \in \mathbf{R}^m$ is the control input vector; $y \in \mathbf{R}^p$ is the output vector; $v \in \mathrm{R}^r$ is exogenous disturbance vector; **A**, **B**, **C** and **D** are the state matrices that depend on parameter DP; B_v is the matrix external disturbance. The goal of the research is to design a family of local LMI-controllers.

The algorithm of SOF controller design in terms of LMIs was proposed in [5] – [7].

The control law is given by

$$u(t) = -\mathrm{K}y(t) = -\mathrm{KC}x(t), \tag{2}$$

where **K** is a constant output feedback gain matrix.

The exogenous disturbances v are restricted by L_2-norm

$$\|v(t)\|^2 = \int_0^\infty (v^T v)dt < \infty . \tag{3}$$

L_2-norm assures disturbance attenuation with a predefined level, ν.

K matrix minimizes a performance index:

$$J(K)=\int_0^\infty \|z(t)\|^2\,dt=\int_0^\infty\left(x^TQx+u^TRu\right)dt\le\gamma^2\int_0^\infty v^Tv\,dt,$$
$$\forall v(t)\ne 0,$$

where $Q\ge 0$, $R>0$ are diagonal matrices, weighting each state and control variables, respectively. Output signal $z(t)$ used for performance evaluation is defined as follows:

$$z=\begin{bmatrix}\sqrt{Q} & 0\\ 0 & \sqrt{R}\end{bmatrix}\begin{bmatrix}x\\ u\end{bmatrix}.$$

The system L_2 gain is said to be bounded or attenuated by γ if [3], [5], [6], [10]:

$$\frac{\int_0^\infty \|z(t)\|^2\,dt}{\int_0^\infty \|v(t)\|^2\,dt}=\frac{\int_0^\infty\left(x^TQx+u^TRu\right)dt}{\int_0^\infty v^Tv\,dt}\le\gamma^2.$$

Therefore, it is necessary to find constant output feedback gain matrix **K** that stabilizes the control plant such that the infinity norm of the transfer function referring exogenous input to performance output $z(t)$ approaches minimum. The minimum L_2-gain (3) is denoted by γ^*.

The output feedback gain matrix **K**(2) could be found by solving the following LMI [5], [6]

$$\begin{bmatrix}PA_i+A_i^TP+Q & P_nB & P_nB_{iv} & 0\\ B_i^TP & -R & 0 & 0\\ B_{iv}^TP & 0 & -\gamma^2I & 0\\ 0 & 0 & 0 & -R\end{bmatrix}\le 0, \qquad (4)$$

where $i=1, ..., N$ in (4) denotes the set of models associated with scheduled operating conditions within the flight envelope.

The matrices **K** are:

$$K_i=R^{-1}B_i^TP_iCi^T(C_iC_i^T)^{-1}.$$

It is desired to find a family of static output-feedback control gain matrices **K** such that the system is stable and the L_2 gain is bounded by a prescribed value γ.

III. Gain Scheduling Controller

A gain scheduling control system design takes following steps:

1. Choose the operating points or region in the scheduling space, which is defined by flight envelope of UAV. Obtain a plant model for each operating region by linearizing the plant's model in the several equilibrium operating points.
2. Design a family of local LMI-controllers for the obtained plant models.
3. Implement a scheduling mechanism.
4. Assess the GS closed loop stability and performance.

The block-scheme of a GS-feedback loop is shown on Fig. 1.

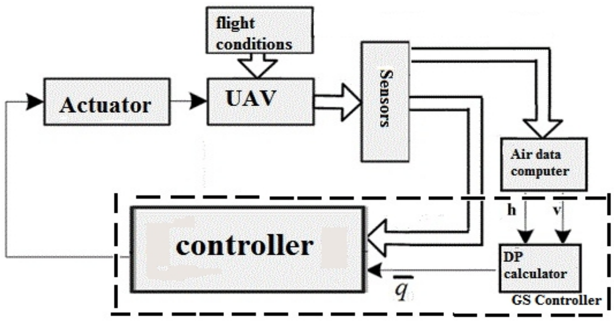


Fig. 1. The block scheme of a hold feedback loop

The vector of adjustable parameters of the autopilot **K** has the following components:

$$K(\bar{q})=\left[K_v(\bar{q}),K_\alpha(\bar{q}),K_q(\bar{q}),K_\vartheta(\bar{q}),K_h(\bar{q})\right], \qquad (5)$$

where K_v is speed gain; K_α is angle of attack gain; K_q and K_θ are pitch rate, pitch angle gains respectively; K_h is altitude gain.

The objective of linearization scheduling is that the equilibrium family of the controller (5) matches the equilibrium family of the plant (1), such that:

– the closed-loop system still can be tuned appropriately with respect to performance and robustness demands;

– the linearization family of the controller equals the designed family of linear controllers.

It was considered the interpolation of the SOF control signals generated by linear interpolation [11].

The model of the atmospheric conditions is a Dryden filter defined by the following transfer functions [8]:

1. Longitudinal transfer function

$$H_u(s)=\sigma_u\sqrt{\frac{2L_u}{\pi V}}\cdot\frac{1}{1+\frac{L_u}{V}s}.$$

2. Lateral transfer function

$$H_r(s)=\frac{\frac{s}{V}}{1+\frac{3b}{\pi V}s}\cdot\sigma_v\sqrt{\frac{L_v}{\pi V}}\cdot\frac{1+\sqrt{3}\frac{L_v}{V}s}{\left(1+\frac{L_v}{V}s\right)^2}.$$

3. Vertical transfer function

$$H_q(s)=\frac{\frac{s}{V}}{1+\frac{4b}{\pi V}s}\cdot\sigma_w\sqrt{\frac{L_w}{\pi V}}\cdot\frac{1+\sqrt{3}\frac{L_w}{V}s}{\left(1+\frac{L_w}{V}s\right)^2}.$$

The variable b represents the aircraft wingspan. The variables L_u, L_v, L_w represent the turbulence scale lengths. The variables σ_u, σ_v, σ_w represent the turbulence intensities.

The performance and robustness indices are possible to estimate after a family of gain-scheduled static output controllers is obtained using proposed approach. Thus, performance is estimated by H_2-norm of system function with respect to disturbance, whereas the robustness is estimated by H_∞-norm of the complementary sensitivity function [12].

1. H_2-norms of system sensitivity function in deterministic case:

$$\|H\|_{2\det}^{n}=\sqrt{trace(C_nW_nC_n^{\ T})},$$

where W_n is a controllability gramian and C_n is a weighting matrix in deterministic.

2. H_2-of system sensitivity function in stochastic case:

$$\|H\|_{2st}^{n}=\sqrt{trace(C_{st}W_{st}C_{st}^{\ T})},$$

where W_{st} is a controllability gramian and C_{st} is weighting matrix in stochastic case.

3. H_∞-norm of the complementary sensitivity function:

$$\|H(j\omega)\|_\infty=\sup_\omega\bar{\sigma}(H(j\omega)),$$

where σ is the singular value of complementary sensitivity matrix; $\bar{\sigma}$ is the maximum singular value on the current frequency.

IV. CASE STUDY

The block-diagram of the closed-loop system for control of longitudinal motion is depicted on Fig. 2, where η is white noise vector, h_{ref} is altitude reference signal, h_{ADC}, $V_{T_{ADC}}$ are altitude and true speed measured by Air Data Computer. The state space vector of the longitudinal channel is $x=[V_T,\alpha,q,\theta,h]^T$, where V_T is the true air speed, m/s; α is the angle of attack, deg; q is the pitch rate, deg/s; θ is the pitch angle, deg; h is altitude, m.

The control input vector is represented by throttle and elevator deflections. The nonlinear model of the Aerosonde is linearized for range of operating conditions respected to the range of DP from 200 to 650 kg/(ms^2) with a granularity of 50 kg/(ms^2). The state space matrices **A** and **B** in general form filled with stability and control derivatives are given below [2]:

$$\mathrm{A}=\begin{bmatrix} X_V+X_{Tv}\cos\alpha_e & X_\alpha & 0 & -g_0\cos\gamma_e & 0\\ Z_V+Z_{Tv}\sin\alpha_e & Z_\alpha & V_T+Z_q & -g_0\sin\gamma_e & 0\\ M_V+M_{Tv} & M_\alpha & M_q & 0 & 0\\ 0 & 0 & 1 & 0 & 0\\ -Z_V & -Z_\alpha & 0 & 0 & 0\end{bmatrix},\quad \mathrm{B}=\begin{bmatrix} X_{\delta th}\cos\alpha_e & X_{\delta e}\\ -X_{\delta th}\sin\alpha_e & Z_{\delta e}\\ M_{\delta th} & M_{\delta e}\\ 0 & 0\\ X_{\delta th} & Z_{\delta e}\end{bmatrix},$$

where $X_V=-\frac{\bar{q}S}{mV_T}(2C_L-C_{Dv})$;

$X_{\delta e}=\frac{\bar{q}S}{m}C_{D\delta e}$; $X_\alpha=\frac{\bar{q}S}{m}(C_L-C_{D\alpha})$;

$Z_V=-\frac{\bar{q}S}{mV_T}(2C_L-C_{Lv})$;

$Z_\alpha=-\frac{\bar{q}S}{m}(C_D-C_{L\alpha})$;

$Z_{\delta e}=-\frac{\bar{q}S}{m}C_{L\delta e}$; $Z_q=-\frac{\bar{q}S\bar{c}}{2mV_T}C_{Lq}$;

$M_V=\frac{\bar{q}S\bar{c}}{J_ymV_T}(2C_M+C_{mv})$;

$M_\alpha=\frac{\bar{q}S\bar{c}}{J_y}C_{m\alpha}$; $M_{\delta e}=-\frac{\bar{q}S\bar{c}}{J_y}C_{m\delta e}$;

$M_q=-\frac{\bar{q}S\bar{c}}{J_Y}\frac{\bar{c}}{2V_T}C_{mq}$;

$\gamma=\gamma_e$, $\alpha=\alpha_e$ are equilibrium (steady-state) conditions.

As seen from the description of space matrices coefficients, the aircraft flight dynamic depends on DP value. The LPV controller model is a finite set of linear controller models obtained for the operating grid of DP values. The set of linear controllers are shown in Table I. Linear interpolation on a set of data points (K_{v_i},q_i), (K_{α_i},q_i), (K_{q_i},q_i), (K_{θ_i},q_i), (K_{h_i},q_i) is defined as the concatenation of linear interpolants between each pair of data points.

To demonstrate the altitude hold was chosen the following flight conditions (Fig. 3).

The flight condition 1: the flight altitude is 200 m, speed is 19 m/s, dynamic pressure is 173 kg·m/s^2;

$$A_1 = \begin{bmatrix} -0.178 & 0.803 & -2.312 & -9.711 & 0 \\ -0.632 & -3.331 & 17.912 & -1.244 & 0 \\ 0.657 & -3.848 & -3.828 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0.127 & -0.992 & 0 & 18.5 & 0 \end{bmatrix};$$

$$B_1 = \begin{bmatrix} 0.27 & 0 \\ -1.377 & 0 \\ -19.299 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}.$$

The flight condition 2: the flight altitude is 900 m and speed is 25 m/s, dynamic pressure is 350 kg·m/s^2;

$$A_2 = \begin{bmatrix} -0.1738 & 0.57 & -2.088 & -9.778 & 0 \\ -0.5084 & -3.261 & 24.479 & -0.83 & 0 \\ 0.6098 & -4.764 & -4.808 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0.0845 & -0.996 & 0 & 25.5 & 0 \end{bmatrix};$$

$$B_2 = \begin{bmatrix} 0.304 & 0 \\ -1.843 & 0 \\ -32.775 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}.$$

The flight condition 3: the flight altitude is 1460 m, speed is 35 m/s, dynamic pressure is 650 kg·m/s^2.

$$A_3 = \begin{bmatrix} -0.233 & 0.343 & -0.825 & -9.804 & 0 \\ -0.458 & -4.297 & 34.42 & -0.234 & 0 \\ 0.396 & -5.904 & -6.343 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0.024 & -0.999 & 0 & 35 & 0 \end{bmatrix};$$

$$B_3 = \begin{bmatrix} 0.3 & 0 \\ -3.5 & 0 \\ -59.9 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}.$$

TABLE I

CONTROLLER GAINS

DP, kg·m/s^2	Controller gains
200	[0.0217 0.0775 –0.273 –1.2362 –0.0180; 0.0642 0.73 0.0015 –0.0009 0.0024]
250	[0.002 0.0958 –0.2501 –1.2833 –0.0160; 0.0804 0.68 0.0027 –0.1367 –0.0001]
300	[0.0260 0.1035 –0.1987 –3.1689 –0.02; 0.0652 1.34 –0.012 –0.1944 0.0007]
350	[0.0354 0.0952 –0.2721 –3.4638 –0.0235; 0.0984 1.51 –0.0268 –0.0325 0.0011]
400	[0.0457 0.0856 –0.3569 –3.6424 –0.0235; 0.0764 1.54 –0.0115 –.1270 .0011]
450	[0.0292 0.0858 –0.2541 –3.7986 –0.0266; 0.0653 0.39 0.0284 –0.4018 –0.0026]
500	[0.0175 0.0757 –0.1485 –3.2438 –0.018; 0.0437 0.63 –0.0073 –0.1306 –0.001]
550	[0.0071 0.0733 –0.1679 –3.3771 –0.0202; 0.0364 0.49 –0.0175 –0.1729 –0.0018]
600	[0.0011 0.0666 –0.2111 –3.3452 –0.0196; 0.0726 0.45 –0.0152 –0.3263 –.0062]
650	[0.0017 0.0659 –0.1369 –3.3763 –0.0183; 0.031 0.17 –0.0051 –0.0005 –0.0016]

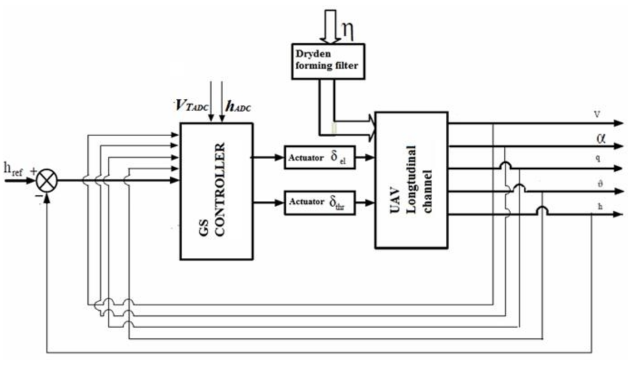


Fig. 2. Block diagram of the UAV longitudinal motion

Table II reflects standard deviations of the UAV outputs in a stochastic case of parametrically perturbed model with the static output feedback controller in a control loop.

From above given data we can conclude that noisy deviations of useful signals are quite low. Performance and robustness indices are shown in Table III.

The low variation of the values of H_∞–norms proves the high degree of the system robustness. Basing on the results of the H_2-norm values, it is possible to conclude that the norms vary in small ranges. Their close values give a possibility to state that the efficiency of the closed-loop system is held at the desired level.

After developing and analyzing the behavior of the system at the first step, at the second step, the closed-loop system was simulated via Simulink®. The simulation results are shown in Fig. 3.

From the shown above graphs it is evident that results are quite satisfying. Deflections of UAV angular characteristics are possible from the practical point of view. The altitude is held at the reference signal *href* = 50 m with acceptable deflections. These figures along with numerical results, represented in Tables II, III show that desired robustness-performance trade-off is achieved. It can be seen that the handling quality of the nominal and the perturbed models are satisfied.

TABLE II

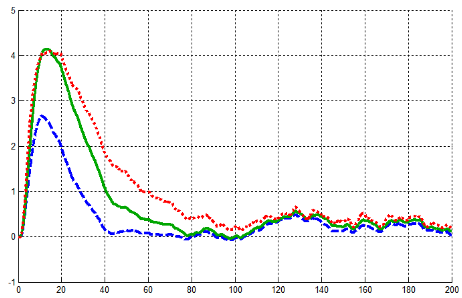
STANDARD DEVIATIONS

DP, kg·m/s²	Standard deviations						
	σ_V, m/s	σ_α, deg	σ_q, 10^{-1} x deg/s	σ_θ, 10^{-2} x deg	σ_h, m	σ_{el}, deg	σ_{th}, %
173	0.932	0.099	0.363	0.93	0.236	0.0226	0.039
350	0.842	0.132	0.456	0.73	0.165	0.0207	0.024
650	1.01	0.213	0.615	0.88	0.282	0.0217	0.033

TABLE III

PERFORMANCE INDICES

DP, kg·m/s²	H_2-norm		H_∞-norm
	Deterministic case	Stochastic case	
173	0.0243	0.1002	0.0930
350	0.0171	0.3471	0.1469
650	0.0457	0.6559	0.1852



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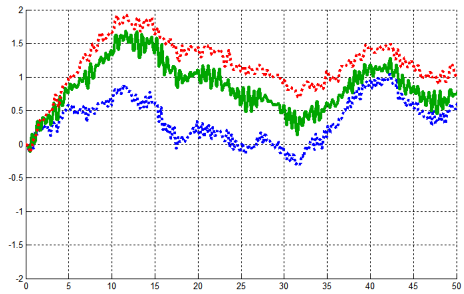

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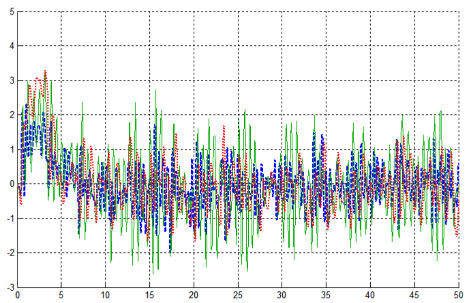

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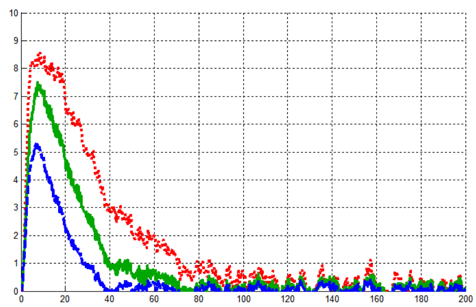

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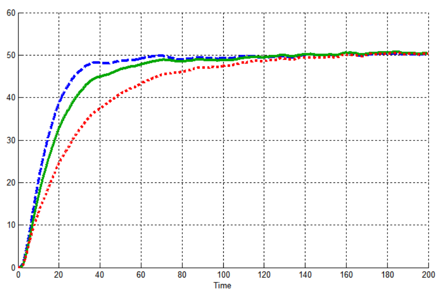

e

Fig. 3. Simulation results for longitudinal channel of the UAV in the presence of external disturbances (flight condition 1-*dot line*; the flight condition 2-*solid line*; the flight condition 3-*dash line*): (a) is speed; (b) is angle of attack; *c* is pitch rate; (d) is pitch angle; (e) is altitude

V. CONCLUSION

Motivated by an UAV with a wide flight envelope has large parametric variations in the presence of uncertainties, the paper presents a procedure of robust GS controller design. The flight control system consists of a SOF baseline controller which can be obtained conveniently by solving LMI with reduced computational complexity. The flight envelope of the UAV refers to the capabilities of operating ranges in terms of speed and altitude. The dynamic pressure as function of altitude and speed was proposed as simple gain scheduled tool for controller design. The efficiency of the proposed approach is illustrated by a case study.

The main advantages of gain scheduled static controller application are their simplicity and assurance of high performance and robustness properties of the closed loop system which is held during the operation mode.

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REFERENCES

[1] O. P. Basanets, A. A. Tunik, M. M. Komnatska,"LMI-based static output feedback design for rotating solid body," presented at I-st Intern.Conf. Methods and Systems of Navigation and Motion Control, Kyiv, 2010, pp. 88–90.

[2] R. W. Beard and T. W. Randal, *Small Unmanned Aircraft : Theory and Practice.* Princeton: Princeton University Press, 317 p.

[3] S. Boyd, L. El. Ghaoui, E. Feron, and V. Balakrishnan, *Linear matrix inequalities in system and control theory*, Philadelphia: PA SIAM, 1994, 205 p.

[4] X.Chen, J. Song and G. Cai, "Robust gain-scheduled autopilot design with LPV reference model for portable missile," presented at IEEE Aerospace Conference, Montana, 2012. pp. 1–10.

[5] J. Gadewadikar, F. Lewis, and M. Abu-Khalaf, "Necessary and sufficient conditions for H-infinity static output feedback control," *Journal of Guidance, Control and Dynamics*, vol. 29, pp. 915–921, 2006.

[6] J. Gadewadikar, and F. Lewis, "Aircraft flight controller tracking design using H-infinity static output-feedback," *Transactions of the Institute of Measurement and Control,* vol. 28, no. 8, pp. 429–440, 2006.

[7] M. M. Komnatska, "Flight control system design VIA LMI-approach," *Electronics and Control Systems*, no. 3(37), pp. 49–52, 2013

[8] M. O. Rauw, *A Simulink Toolbox for Flight Dynamics and Control Analysis*, oct 11, 2000, 263 p.

[9] J. W. Rugh and S. J. Shamma, "Research on gain scheduling," *Automatica,* vol. 36, pp. 1401–1425, 2000.

[10] V. L. Syrmos, C. Abdallah, P. Dorato,"Static output feedback: a survey." In *Proc. of 33rd IEEE Conference on Decision and Control*,Orlando, FL, 1997. pp. 837–842.

[11] V. Saeed Vaseghi, *Advanced Digital Signal Processing and Noise Reduction, Second Edition*, John Wiley & Sons. 2000, pp. 297–330.

[12] O. O. Abramovich, and A. A. Tunik, "Multi-Model Approach to Parametric Robust Optimization of Digital Flight Control Systems," *Journal of Automation and Information Sciences*, Begell House Inc., no. 36(3), pp. 25–34, 2004.

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О. І. Надсадна. Синтез статичного зворотнього зв'язку для робастної системи керування з програмним забезпеченням коефіцієнтів підсилення

Використано метод програмного забезпечення коефіцієнтів посилення, який є одним з популярних підходів в області проектування регуляторів з успішним застосуванням в різних галузях промисловості, у тому числі в авіаприладобудуванні. Це дає можливість збільшити ступінь стійкості системи, без використання складних адаптивних систем із замкнутим контуром. Розглянуто синтез регулятора з програмним забезпеченням коефіцієнтів посилення для системи із змінними параметрами за допомогою апарату лінійних матричних нерівностей. Отриманий регулятор гарантує ефективне керування безпілотним літальним апаратом під впливом зовнішніх збурень в робочому діапазоні експлуатації об'єкту.

Ключові слова: програмне забезпечення коефіцієнтів підсилення; лінійні матричні нерівності; робастність; безпілотний літальний апарат.

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Напрям наукової діяльності: теорія автоматичного керування та її застосування.
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О. И. Надсадная. Проектирование робастной системы стабилизации на основе табличного регулятора

Использован метод программного обеспечения коэффициентов усиления, который является одним из наиболее используемых подходов в области проектированию регуляторов с успешным применением в различных отраслях промышленности, в том числе в авиаприборостоении. Это дает возможность увеличить степень устойчивости системы, без использования сложных адаптивных систем с замкнутым контуром. Рассмотрен синтез регулятора с программным обеспечением коэффициентов усиления для системы с переменными параметрами с помощью аппарата линейных матричных неравенств. Полученный регулятор гарантирует эффективного управление беспилотным летательным аппаратом под воздействием внешних возмущений в рабочем диапазоне эксплуатации объекта.
Ключевые слова: программное обеспечение коэффициентов усиления; линейные матричные неравенства; робастность; беспилотный летательный аппарат.

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