AUTOMATIC CONTROL SYSTEMS

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[1]A. A. Tunik,
[2]M. M. Komnatska

ON STRUCTURES OF COMBINED UAV FLIGHT CONTROL SYSTEMS WITH ELEMENTS OF FUZZY LOGICS

Aircraft Control Systems Department, National Aviation University, Kyiv, Ukraine
E-mails: [1]aatunik@mail.ru, [2]martakomnatska@gmail.com

***Abstract*—*The paper deals with flight control system development in a form of successive loop control that involves “crisp” and fuzzy contours. The paper explores peculiarities of sharing the control functions between “crisp” and fuzzy parts of the developed autopilot. The division of the autopilot structure into “crisp” and fuzzy parts is performed by applying the* H_∞*-robust stability theory of fuzzy systems and the describing function approach. The design procedure is illustrated by a case study of unmanned aerial vehicle lateral channel control. It was proved that application of the fuzzy control is expedient for outermost contour in the successive loop structure of flight control system.*

Index Terms—Successive loop control; flight control system; sensitivity function; fuzzy control; describing function; robustness

I. INTRODUCTION

Nowadays the application and the deployment of the UAV systems are rapidly broadening (see, for example [1], where further references are cited). These circumstances lead to increasing of the complexity of the UAV flight missions and consequently to permanent improvement of their flight control laws [2]. One of the stages of this process is the incorporation of the elements of the artificial intellect and the fuzzy logics in particular in the UAV flight control laws [3] – [6] and creation of the combined control structures consisting of the “crisp” and the fuzzy parts. The key problem of the incorporation of the elements of the artificial intellect into the UAV autopilots is the distribution of the control function between the “crisp” and the fuzzy components of the combined autopilot. This problem was considered in [4], where it was proposed to solve it on the basis of the robust control theory. However, results obtained in [4] were mostly descriptive and did not contain numerical estimation of the flight control systems (FCS) robustness. This paper is devoted to the further substantiation of the structures of the combined FCS and to the principles of the sharing of the control functions between the “crisp” and the fuzzy parts of these structures. This substantiation uses theory of the H_∞-robust stability of fuzzy systems [7] and their description via describing function method [10], [11].

The basic FCS structure explored in this paper is very well-known structure created via successive loop closure method [2]. This structure is typical for majority of manned [8] as well as unmanned aircraft [2]. In order to obtain numerical results we consider lateral motion control including roll angle stabilization as the inner loop, heading angle stabilization as the intermediate loop, and the reference track stabilization in the horizontal plane as the outer loop. The mathematical model of the UAV lateral motion was taken for the UAV “Aerosonde” [9], which is frequently used as the “benchmark” model of the UAV. Despite of the particular case of the considered UAV flight control system, the final result could be extended on the other classes of the aircraft flight control systems, using application of the procedure described in this paper to other particular systems created via successive loop closure method [2]. Some more generalized conclusion, which could be derived from this investigation, consists of designing the inner loops in the successive loop architecture via traditional “crisp” control theory; meanwhile the design of the outer loop via fuzzy control theory is much more preferable from the viewpoint of the robustness and performance criteria.

II. SENSITIVITY FUNCTIONS AND H_∞-ANALYSIS OF THE “CRISP” SUCCESSIVE LOOP FCS

We consider the standard linearized mathematical model of the controlled plant (UAV Aerosonde) in the state space:

$$\dot{x} = \mathbf{A}x + \mathbf{B}u$$
$$y = \mathbf{C}x, \tag{1}$$

which is determined by:

– the state vector $x = [\beta, p, r, \varphi, \psi, \tilde{y}]^T$ with components: sideslip angle β, roll and yaw rates p, r

respectively, and roll and yaw angles φ, ψ and cross-track error $\tilde{y}$;

– the control vector $u = [\delta_a, \delta_r]^T$ with components: the deflection of ailerons and rudder respectively;

– the observation vector $y = [p, r, \varphi, \psi, \tilde{y}, V_{\tilde{y}}]^T$, where $V_{\tilde{y}}$ stands for the side velocity;

– the state propagation, control and observation matrices $\mathbf{A}, \mathbf{B}, \mathbf{C}$ respectively.

In order to diminish the order of the considered system we will neglect the dynamics of the actuators. This assumption doesn't influence on the final conclusions, because they depend on ratio between the orders of mathematical models of each consecutive loops rather than on the actual values of these orders [2]. The block diagram of the UAV lateral motion control system with successive loop closure (SLP) and "crisp" control laws in each loop is shown in Fig. 1. It represents 3 successive closed loops with standard PD control laws, so the innermost loop (roll angle control) has control law

$$\delta_a = K_\varphi \varphi + K_p p. \quad (2)$$

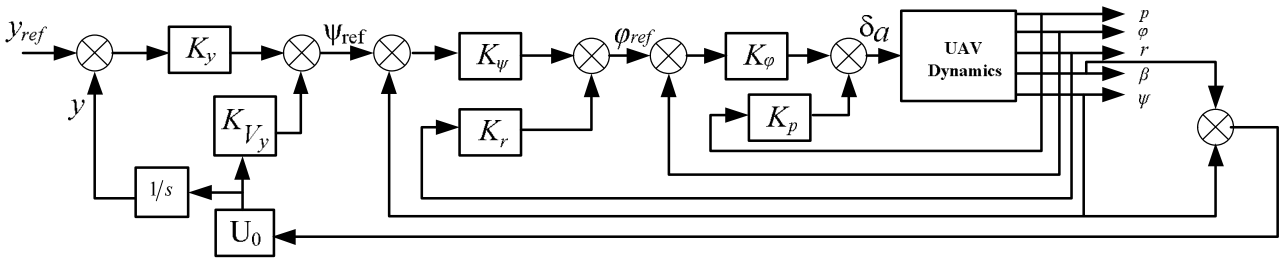


Fig. 1. Block diagram of the UAV lateral motion with successive loop control

The same PD control laws are accepted for the yaw angle control (intermediate loop) with coefficients K_ψ, K_r as well as for the outermost cross-track error y loop with coefficients $K_{\tilde{y}}$, K_{V_y}. The output of the outer control law serves as the reference (command) signal to the corresponding inner loop. It is known [2], [8] that in order to suppress sideslip angle β for the coordinated turn execution, the standard washout filter with transfer function

$$W_{wf}(s) = K_{wf} \frac{T_{wf} s}{T_{wf} s + 1},$$

is applied as a local feedback from the yaw rate r sensor to the deflection of rudder δ_r. For the sake of the further simplification we neglect the dynamics of this local loop, so we will consider only main contour with single input – deflection of the aileron δ_a, as it is shown in the Fig. 1. Taking into account accepted assumptions, we can determine the numerical values of $\mathbf{A}, \mathbf{B}$ and $\mathbf{C}$ matrices for linearized model (1) of the UAV Aerosonde [9] for trim conditions $H = 300$ m (altitude) and $U_0 = 26$ m/sec (true airspeed) as follows:

$$\mathrm{A}_0 = \begin{bmatrix} -0.72 & 1.07 & -25.98 & 9.81 & 0 & 0 \\ -4.73 & -23.3 & 11.22 & 0 & 0 & 0 \\ 0.77 & -3.02 & -1.17 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 26 & 0 & 0 & 0 & 26 & 0 \end{bmatrix}; \quad \mathrm{B}_0 = \begin{bmatrix} -1.6 \\ -140.33 \\ -5.53 \\ 0 \\ 0 \\ 0 \end{bmatrix}; \quad \mathrm{C}_0 = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 26 & 0 & 0 & 0 & 26 & 0 \end{bmatrix}. \quad (3)$$

As it is known [12], the H_∞-norm of the complementary sensitivity function (CSF) can be used as the robustness measure of the closed loop system. For the innermost loop this norm is equal

$$\left\| T_\varphi(s) \right\|_\infty = \left\| \frac{(K_\varphi + K_p s)\, W_{roll}(s)}{1 + (K_\varphi + K_p s) W_{roll}(s)} \right\|_\infty, \quad (4)$$

where

$$W_{roll}(s) = W_\varphi^a(s), \quad (5)$$

$W_\varphi^a(s)$ is the transfer function from the aileron to the roll angle determined from the model (1). The same norms for the middle and outermost loops will have the following forms:

$$\left\|T_{\psi}(s)\right\|_{\infty}=\left\|\frac{(K_{\psi}+K_{r}s)W_{roll}^{cl}(s)}{1+(K_{\psi}+K_{r}s)W_{roll}^{cl}(s)}\right\|_{\infty};$$
$$\left\|T_{\tilde{y}}(s)\right\|_{\infty}=\left\|\frac{(K_{\tilde{y}}+K_{V_y}s)W_{yaw}^{cl}(s)}{1+(K_{\tilde{y}}+K_{V_y}s)W_{yaw}^{cl}(s)}\right\|_{\infty}, \quad (6)$$

where $W_{roll}^{cl}(s)$, ($s=j\omega$) is the transfer function of the closed-loop roll hold system with input as the reference value of the roll angle φ_{ref} and output as the actual value of this angle φ, meanwhile $W_{yaw}^{cl}(s)$ stands for the transfer function of the closed-loop yaw hold system with input as the reference value of the yaw angle ψ_{ref} and output as the actual value of this angle ψ. It would be expedient also to introduce the sensitivity function with respect to the error of system. This function for the innermost loop of roll angle control will have the following form [12]:

$$S_{\varphi}(s)=\frac{1}{1+(K_{\varphi}+K_{p}s)W_{roll}(s)}, \quad (7)$$

where $W_{roll}(s)$ is determined by expression (5). The same sensitivity functions for other closed loops have the same forms:

$$S_{\psi}(s)=\frac{1}{1+(K_{\psi}+K_{r}s)W_{roll}^{cl}(s)};$$
$$S_{\tilde{y}}(s)=\frac{1}{1+(K_{\tilde{y}}+K_{V_y}s)W_{yaw}^{cl}(s)}. \quad (8)$$

As it is known [12] H_{∞}-norms of these sensitivity functions:

$$\left\|S_{\varphi}(j\omega)\right\|_{\infty},\ \left\|S_{\psi}(j\omega)\right\|_{\infty},\ \left\|S_{\tilde{y}}(j\omega)\right\|_{\infty},$$

are used as the measure of system performance.

It is also useful to introduce sensitivity functions with respect to the parameters of controller; in our case these are proportional ($K_{\varphi}, K_{\psi}, K_{\tilde{y}}$) and differential ($K_p, K_r, K_{V_y},$) coefficients of corresponding control laws. In accordance with [13] they can be determined for the innermost loop in the frequency domain by the following expressions:

$$\frac{\partial T_{\varphi}(K_{\varphi 0},s)}{\partial K_{\varphi}}=\frac{W_{roll}(s)}{1+(K_{\varphi 0}+K_{p0}s)W_{roll}(s)}S(s);$$
$$\frac{\partial T_{\varphi}(K_{p0},s)}{\partial K_{p}}=\frac{sW_{roll}(s)}{1+(K_{\varphi 0}+K_{p0}s)W_{roll}(s)}S(s), \quad (9)$$

where $K_{\varphi 0}$, K_{p0} are constant values of the proportional and differential gains determined from some certain procedure of the closed-loop system design. The same expressions could be derived for the middle and outermost loops using expressions (7). $\mathbf{H}_{\infty}$-norms of the sensitivity functions defined by expressions (9) are the numerical characteristics of the robustness with respect to the parameters variations of corresponding controller.

Using mathematical models (1) – (4) with vector $\vec{P}_0$ of the adjustable unknown parameters

$$\vec{P}_0=\left[K_{\varphi 0},\ K_{p0},\ K_{\psi 0},\ K_{r0},\ K_{\tilde{y}0},\ K_{V_{\tilde{y}}0}\right]^T,$$

we applied the PD control law optimization procedure included in the Simulink Design Optimization Software in order to determine this vector. This procedure was applied consecutively from the innermost to the outermost loop and the following values of these parameters were determined:

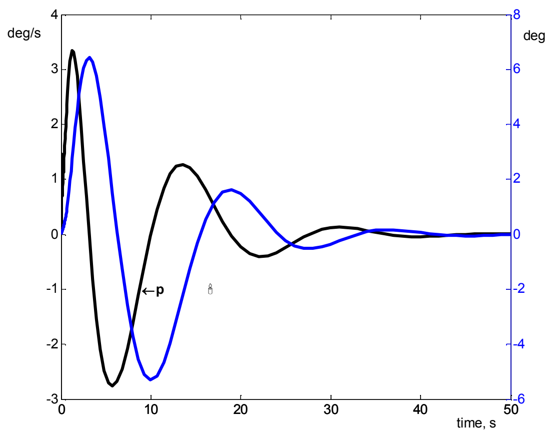
$$\vec{P}_0=\left[12.9, 9.5, 7.5, 3.5, 0.3, 0.2\right]^T. \quad (10)$$

Partial derivatives in expressions (9) are determined in the vicinity of these numerical values. Using parameters defined by (10) it is possible to determine the characteristics of robustness and performance of considered closed loop system defined by expressions (4) – (9). They are represented in the Table 1. As it could be seen from the Table 1, the numerical characteristics of robustness $\left\|T_i(s)\right\|_{\infty}$ and performance $\left\|S_i(s)\right\|_{\infty}$ (i denotes state variables φ, ψ, $\tilde{y}$). are deteriorating from the inner to the outer loop; especially it is noticeable for the cross-track mode. Transient processes in different loops for the input step function $\tilde{y}_{ref}=20$ m are shown in the Fig. 2. They demonstrate pretty good performance of the lateral motion control system.

TABLE 1

PERFORMANCE AND ROBUSTNESS INDICES OF THE CLOSED LOOP SYSTEM WITH SUCCESSIVE CONTROL

Roll mode				Yaw mode				Cross-track mode			
$\left\|T_{\varphi}(s)\right\|_{\infty}$	$\left\|S_{\varphi}(s)\right\|_{\infty}$	$\left\|\frac{\partial T_{\varphi}}{\partial K_{\varphi}}\right\|_{\infty}$	$\left\|\frac{\partial T_{p}}{\partial K_{p}}\right\|_{\infty}$	$\left\|T_{\psi}(s)\right\|_{\infty}$	$\left\|S_{\psi}(s)\right\|_{\infty}$	$\left\|\frac{\partial T_{\psi}}{\partial K_{\psi}}\right\|_{\infty}$	$\left\|\frac{\partial T_{r}}{\partial K_{r}}\right\|_{\infty}$	$\left\|T_{\tilde{y}}(s)\right\|_{\infty}$	$\left\|S_{\tilde{y}}(s)\right\|_{\infty}$	$\left\|\frac{\partial T_{\tilde{y}}}{\partial K_{\tilde{y}}}\right\|_{\infty}$	$\left\|\frac{\partial T_{V_y}}{\partial K_{V_y}}\right\|_{\infty}$
1	1.001	0.001	0.052	1	1.66	0.077	0.275	3.29	3.48	0.077	0.57



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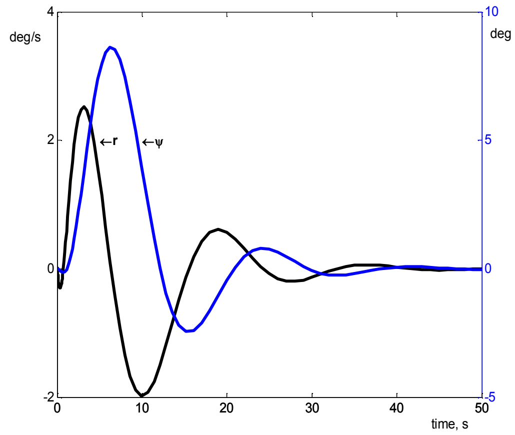

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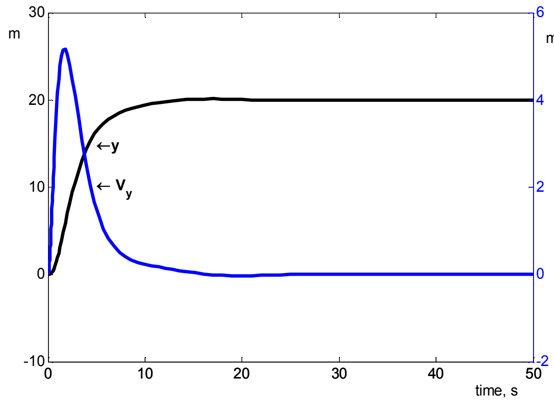

c

Fig. 2. Transient processes with successive loop control: (a) φ is a roll angle, deg; *p* is a roll rate, deg/sec; (b) *r* is a yaw rate, deg/sec ; ψ is a heading angle, deg; (c) $\tilde{y}$ is a cross-track distance, m; $V_{\tilde{y}}$ is a side velocity, m/s

III. Estimation of the Robustness and Performance of the Lateral Motion Control System with Fuzzy Controller in the Cross-Track Stabilization Contour

As far as robustness of the fuzzy control systems is declared in many sources [3] – [7], [10], [11], it is obvious that it is expedient to apply the fuzzy controller in the outermost contour of successive loop closure structure. As it could be seen from Table 1, that inner roll and yaw contours provide pretty good performance and robustness with the simplest “crisp” structures, which are much simpler and less expensive than fuzzy controllers.

The estimation of the robustness and performance of system with fuzzy outer controller and the comparison of these characteristics with “crisp” system must be done using the same estimation for both cases. That is why it is necessary to estimate the $\mathbf{H}_\infty$-norms of corresponding sensitivity functions of system with fuzzy controller. So we begin with the choice of the fuzzy controller. As it is shown in [5], [6], [11] the Mamdani type fuzzy controller provides more flexible and robust structure comparatively with other structures. So we used this fuzzy PD-controller with 5 triangle membership function with following linguistic variables: “negative big” (NB), “negative small” (NS), “zero value” (ZV), “positive small” (PS), “positive big” (PB); variable “value” is “error” (e) and “error derivative” (de) for inputs and “control” (u) for output of the fuzzy controller. Here the normalized universe of discourse for all variables is used [-1, 1], that is why we are using the input and output scaling factors $SF_{in} = 0.05$ for both input variables (e, de) and $SF_{out} = 0.6$ for output variable (u). The technique of adjustment of membership functions distributions over the universes of discourse for better fuzzy controller performance represented in [4], [11] and based on the MRAC (Model Reference Adaptive Control) principle was applied and final results of this adjustment is represented in Fig. 3 for variable (e). The same distribution was used for other variables (de) and (u).

The standard rule base for fuzzy PD-controllers is represented in the Table 2.

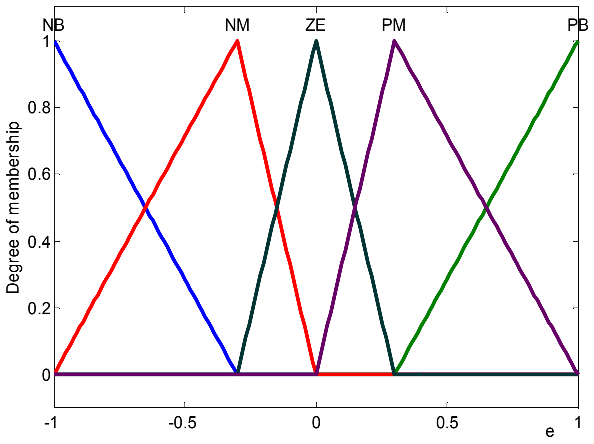

Fig. 3. Membership functions distribution on the universe of discourse

TABLE 2

RULE BASE OF FUZZY CONTROLLER

Output u		Change-in-error, Δe				
		NB	**NS**	**ZE**	**PS**	**PB**
Error, e	**NB**	PB	PB	PB	PS	ZU
	NS	PB	PB	PS	ZU	NS
	ZE	PB	PS	ZU	NS	NB
	PS	PS	ZU	NS	NB	NB
	PB	ZU	NS	NB	NB	NB

The block diagram of the lateral motion control system with fuzzy controller in the outmost loop is represented in the Fig. 4. As far as fuzzy controller is complicated nonlinear control system, in [7], [10], [11] it was proposed to estimate robustness of such systems using describing function method.

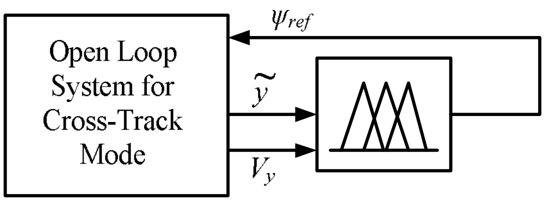

Fig. 4. Block-scheme of the lateral motion control system with fuzzy controller in the outmost loop

It is known that if the linear part of system satisfies conditions of the filter hypothesis (i.e. it effectively depresses high harmonics), then input signals (e and $\dot{e}$) to the nonlinear element (fuzzy controller in our case) could be considered as "sine" and "cosine" functions:

$$e(t) = A\sin(\omega t); \qquad \dot{e}(t) = A\omega\cos(\omega t). \qquad (11)$$

Nonlinear transformation of these signals made by fuzzy controller in general case could be represented in general case as follows:

$$u(t) = F(e, \dot{e}). \qquad (12)$$

Output signal of controller $u(t)$ can be expressed in term of Fourier series [10], [11]:

$$u(t) = \frac{a_0}{2} + \sum_{k=1}^{\infty}[a_n \cos(k\omega t) + b_n \sin(k\omega t)], \qquad (13)$$

where

$$a_0 = \frac{1}{\pi}\int_{-\pi}^{\pi} F(e,\dot{e})d(\omega t);$$

$$a_k = \frac{1}{\pi}\int_{-\pi}^{\pi} F(e,\dot{e})\cos(k\omega t)d(\omega t); \qquad (14)$$

$$b_k = \frac{1}{\pi}\int_{-\pi}^{\pi} F(e,\dot{e})\sin(k\omega t)d(\omega t).$$

In our case the membership functions and rule base of fuzzy controller are symmetrical with respect to the input signals, that is why $a_0 = 0$ as well as amplitudes of all even harmonics. In accordance with describing function method it is necessary to estimate the 1st harmonic at the output of the fuzzy controller, so for $k = 1$ and taking in account (13), (14) we have:

$$u_1(t) = a_1\cos(\omega t) + b_1\sin(\omega t) = M(A,\omega)\sin(\omega t + \varphi(A,\omega)), \qquad (15)$$

where

$$M(A,\omega) = \sqrt{a_1^2 + b_1^2}, \quad \varphi(A,\omega) = \arctan\left(\frac{a_1}{b_1}\right), \qquad (16)$$

Taking in account (15), (16) we can define the describing function of fuzzy controller as follows [10], [11]:

$$D(A,\omega) = M_D(A,\omega)\exp(\varphi(A,\omega)), \qquad (17)$$

where $M_D(A,\omega) = \frac{\sqrt{a_1^2 + b_1^2}}{A}$ is the module of the describing function and $\varphi(A,\omega)$ is its phase.

The influence of the higher harmonics could be estimated as follows:

$$\Delta_k = \sum_{k=2}^{\infty}\frac{\sqrt{a_k^2 + b_k^2}}{A}\exp[j((k-1)\omega t + \varphi_k)]; \quad \varphi_k = \arctan\left(\frac{a_k}{b_k}\right). \qquad (18)$$

The main problem, which arises in application of the expressions (14) – (18), consists of the complexity of the nonlinear transformation (12) caused by difficulties of the analytical approximation in term of the traditional mathematical functions the fuzzy logic inference mechanism used in the fuzzy controller. In order to avoid these difficulties it was proposed in [10] to use experimental estimation of describing function (17) and weight of higher harmonics (18), which can be easily executed in the Simulink package. The scheme of this experiment is shown in the Fig. 5.

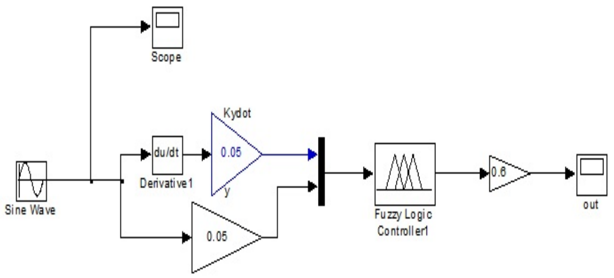

Fig. 5. Block-scheme for experimental determination of the describing function

Changing the amplitude and frequency of the generator of sinusoidal signals "Sine Wave" and analyzing the output signal "out", it is possible to estimate numerically describing function (17) and weight of higher harmonics (18). Results of simulation can be summarized as follows.

1. The module of describing function $M_D(A,\omega)$ (17) practically doesn't depend on the frequency ω.

2. The dependence of the module of describing function $M_D(A)$ on amplitude of input signal A is shown in the Fig. 6.

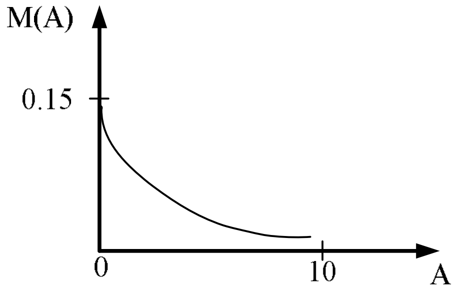

Fig. 6. Dependence of the module of describing function $M_D(A)$ on amplitude of input signal A

3. The dependence of the phase of describing function on the amplitude of the input signal for its different frequencies is shown in the Fig. 7. As it could be seen from this Figure, the dependence of the describing function's phase on frequency ω is more noticeable than in the previous case.

In order to compare the robustness and performance of fuzzy and "crisp" cross-track stabilization system we will restrict with comparison of the $\mathbf{H}_\infty$-norms of sensitivity and complementary sensitivity functions. In accordance with [7] we can introduce quasi-linear open and closed loop cross-track systems respectively:

$$W_{QL}^{op}(s) = W_{yaw}^{cl}(s)D(A,\omega), \tag{19}$$

$$W_{QL}^{cl}(s) = T_{QL}(s) = \frac{W_{yaw}^{cl}(s)\,D(A,\omega)}{1 + W_{yaw}^{cl}(s)\,D(A,\omega)}, \tag{20}$$

$$S_{QL}(s) = \frac{1}{1 + W_{yaw}^{cl}(s)\;D(A,\omega)}. \tag{21}$$

It is obvious that (20) is the complementary sensitivity function and (19) is the sensitivity function with respect to the error of system.

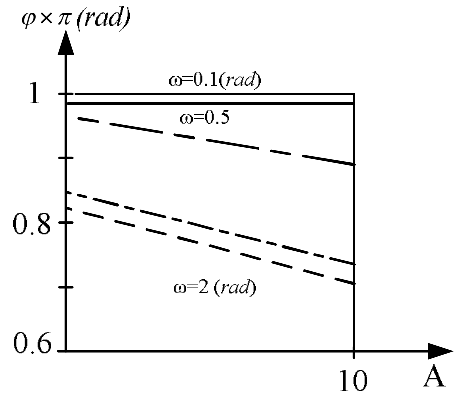

Fig. 7. Dependence of describing function phase on the amplitude of the input signal

IV. $\mathbf{H}_\infty$-ANALYSIS OF FUZZY CONTROL SYSTEM

As it was proved in [7], [14], the $\mathbf{H}_\infty$-norm of the quasi-linear open loop system (19) can be expressed in the following form:

$$\left\|W_{QL}^{op}(s)\right\|_\infty = \sup_A\left[\sup_\omega \bar{\sigma}(W_{QL}^{op}(A,\omega,s))\right], \tag{22}$$

where $\bar{\sigma}(W_{QL}^{op}(A,\omega,s))$ is maximal singular value of the quasi-linear open loop system. As far as the $\mathbf{H}_\infty$-norm of the single variable system is the maximal value of the magnitude frequency response, then this norm could be estimated as:

$$\left\|W_{QL}^{op}(s)\right\|_\infty = \left\|W_{yaw}^{cl}(s)\right\|_\infty \sup_A\left[\sup_\omega \bar{\sigma}(D(A,\omega))\right]. \tag{23}$$

Taking in account results of the experimental estimation of the describing function $D(A,\omega)$ summarized in Figs 6 and 7, it is possible to estimate numerically the 2nd factor in the expression (23): $\sup_A\left[\sup_\omega \bar{\sigma}(D(A,\omega))\right] = 0.148$. Then it is easy to estimate $\mathbf{H}_\infty$-norms of the sensitivity and complementary sensitivity functions (21) and (20). The estimation of the $\mathbf{H}_\infty$-norms of the specific sensitivity functions with respect to the proportional and differential gains of the PD-fuzzy controller defined by expressions (9) can not be done strictly, because the output of this controller is complicated nonlinear function (12) of these gains. Nevertheless it is expedient to estimate at least the orders of these norms rather than their numerical values, that is why we have formally used quasi-linear interpretations of the sensitivity functions (9) with respect to the proportional and differential gains of fuzzy PD-controller.

Comparison of the robustness and performance characteristics of the "crisp" and fuzzy outermost control loop of the cross-track stabilization system is represented in the Table 3.

As it can be seen from this Table, all $\mathbf{H}_\infty$-norms for fuzzy system are essentially smaller than the same norms for "crisp" system, therefore the usage of fuzzy system instead of "crisp" system in the outermost control loop is preferable. In the Fig. 8 the transient processes in the fuzzy control system are represented.

TABLE 3

PERFORMANCE AND ROBUSTNESS INDICES FOR CRISP AND FUZZY CONTROL LOOPS

Type of the system	$\left\Vert T_{\tilde{y}}(s)\right\Vert_\infty$	$\left\Vert S_{\tilde{y}}(s)\right\Vert_\infty$	$\left\Vert \frac{\partial T_{\tilde{y}}}{\partial K_{\tilde{y}}}\right\Vert_\infty$	$\left\Vert \frac{\partial T_{V_y}}{\partial K_{V_y}}\right\Vert_\infty$
"Crisp" system	3.29	3.48	0.077	0.57
Fuzzy system	0.174	1.173	0.029	0.022

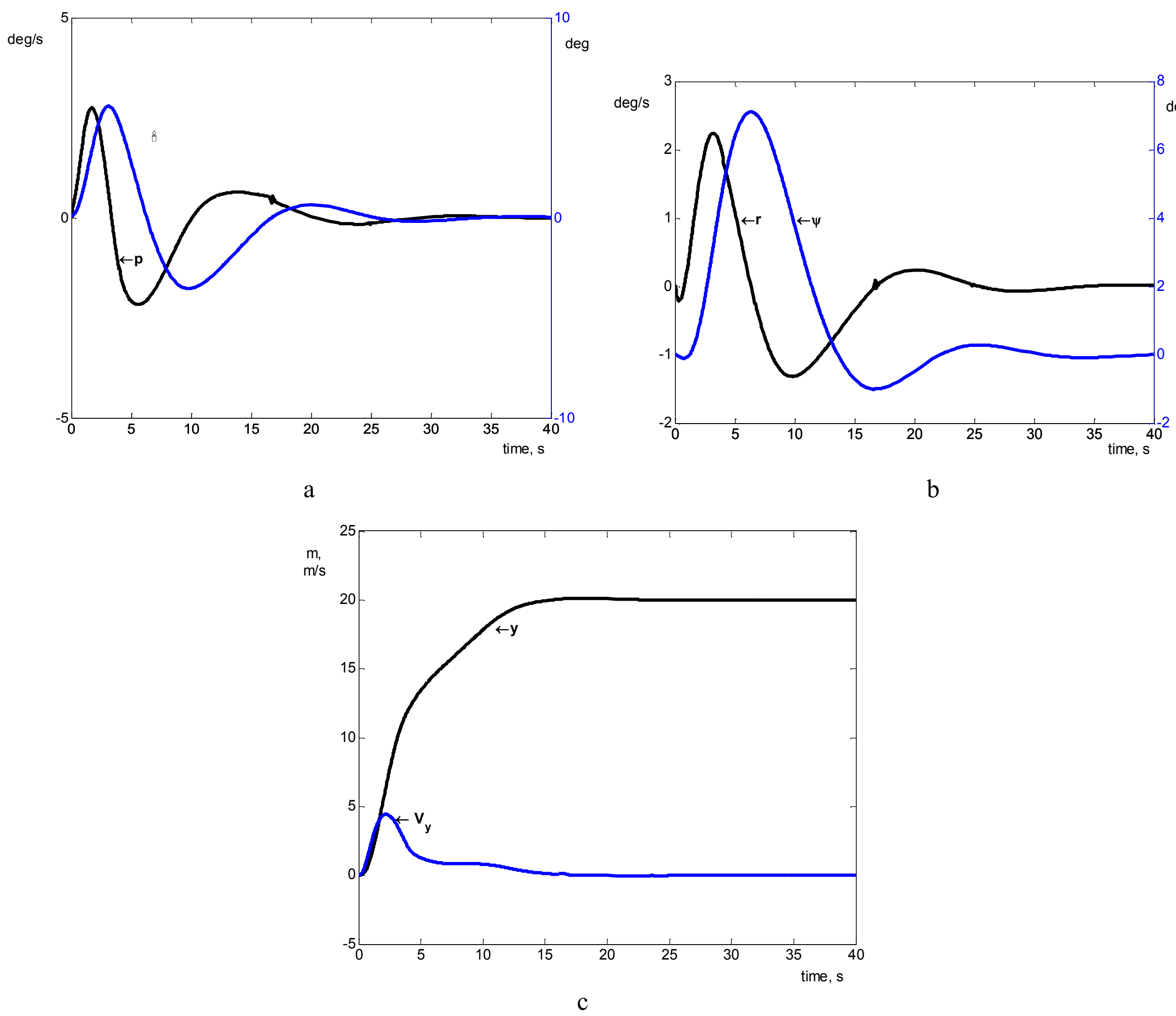

Fig. 8. Transient processes with fuzzy loop control: (a) φ is a roll angle, deg; p is a roll rate, deg/sec;
(b) r is a yaw rate, deg/sec ; ψ is a heading angle, deg; (c) $\tilde{y}$ is a cross-track error, m; $V_{\tilde{y}}$ is a side velocity, m/s

These transient processes demonstrate good performance of the flight control system with fuzzy controller in the outermost contour.

CONCLUSION

1. As far as the characteristics of robustness and performance for the angular attitude control loops do not differ from each other essentially and both of them are sufficiently small, then it is not expedient to use fuzzy controllers for them, because traditional PD-controllers are cheaper and more reliable. However the cross-track control, which is actually control of the position of the UAV center of gravity with respect to the reference track, needs in usage of fuzzy controller, because it provides much better characteristics of robustness and performance.

2. There is some temptation to compare the human (and some high organized animals) central nervous system (CNS) with aforementioned structure. As it is known [15] that CNS consists of the brain and spinal cord. The spinal cord "allows for voluntary and involuntary motions of muscles, as well as the perception of senses" via the "transmission of efferent motor as well as afferent sensory signals and stimuli", meanwhile "the brain is the major functional unit of the central nervous system. While the spinal cord has certain processing ability such as that of spinal locomotion and can process reflexes, the brain is the major processing unit of the nervous system" [15] responsible for the behavior of organism in the environment. So attitude control could be considered as the simplest spinal cord, meanwhile the fuzzy controller of the cross-track contour (artificial intellect) could be compared with simplest brain (natural intellect).

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Tunik Anatoliy. Doctor of Science (Engineering), PhD, Professor.
Aircraft control systems Department, National Aviation University, Kyiv, Ukraine.
Education: Kharkiv Polytechnic Institute, Kharkiv, Ukraine (1961).
Research area: control systems and data processing.
Publications: more than 300 papers.
E-mail: aatunik@mail.ru

Komnatska Marta. Ph. D. Associate Professor.
Aircraft control systems Department, National Aviation University, Kyiv, Ukraine.
Education: National Aviation University, Kyiv, Ukraine (2007).
Research interests: control systems and data processing.
Publications: 32.
E-mail: martakomnatska@gmail.com

А. А. Тунік, М. М. Комнацька. Про структури систем управління польотом БПЛА з елементами нечіткої логіки
Розглянуто багатоконтурну систему управління польотом, що включає в себе контури чіткого та нечіткого управління. Стаття розкриває особливості розділення функцій управління між чітким та нечітким контурами синтезованого автопілоту. Процедура розділення структури автопілоту на чіткий та нечіткий контури здійснена із застосуванням теорії $\mathbf{H}_\infty$ -робастної стійкості нечітких систем та їх описання за допомогою методу гармонічної лінеаризації. Дослідження проведено на прикладі бічного руху безпілотного літального апарату.
Ключові слова: багатоконтурна система управління; система управління польотом; функція чутливості; нечітке управління; описувальна функція; робастність.

Тунік Анатолій Азарійович. Доктор технічних наук. Професор.
Кафедра систем управління літальних апаратів, Національний авіаційний університет, Київ, Україна.
Освіта: Харківський політехнічний університет, Харків, Україна (1961).
Напрям наукової діяльності: системи управління та обробка інформації.
Кількість публікацій: більше 300 наукових робіт.
E-mail: aatunik@mail.ru

Комнацька Марта Миколаївна. Кандидат технічних наук. Доцент.
Кафедра систем управління літальних апаратів, Національний авіаційний університет, Київ, Україна.
Освіта: Національний авіаційний університет, Київ, Україна (2007).
Напрямок наукової діяльності: системи управління та обробка інформації.
Кількість публікацій: 32.
E-mail: martakomnatska@gmail.com

А. А. Туник, М. Н. Комнацкая. О структурах систем управления полетом БПЛА с элементами нечеткого управления
Рассмотрено многоконтурную систему управления полетом, состоящую из четкого и нечеткого контуров управления. Статья раскрывает особенности разделения функций управления между четким и нечетким контурами синтезированного автопилота. Процедура разделения структуры автопилота на четкий и нечеткий контура осуществлена с применением теории $\mathbf{H}_\infty$ -робастной устойчивости нечетких систем управления и их описания с помощью метода гармонической линеаризации. Исследование проведено на примере бокового движения беспилотного летательного аппарата.
Ключевые слова: многоконтурная система управления; система управления полетом; функция чувствительности; нечеткое управление; описывающая функция; робастность.

Туник Анатолий Азариевич. Доктор технических наук. Профессор.
Кафедра систем управления летательных аппаратов, Национальный авиационный университет, Киев, Украина.
Образование: Харьковский политехнический университет, Харьков, Украина (1961).
Направление научной деятельности: системы управления и обработка информации.
Количество публикаций: более 300 научных работ.
E-mail: aatunik@mail.ru

Комнацкая Марта Николаевна. Кандидат технических наук, доцент.
Кафедра систем управления летательных аппаратов, Национальный авиационный университет, Киев, Украина.
Образование: Национальный авиационный университет, Киев, Украина (2007).
Направление научной деятельности: системы управления и обработка информации.
Количество публикаций: 32.
E-mail: martakomnatska@gmail.com