AN INTELLIGENT ABS CONTROL BASED ON FUZZY LOGIC. AIRCRAFT APPLICATION

by
Ioan Ursu, Felicia Ursu

Abstract. Over the past ten years, fuzzy logic, as main component of artificial intelligence, has significantly influenced the design of controlled systems. Focusing on applied mathematics field, the paper proposes an antilock-braking system (ABS) for a Romanian military jet. It is well known that in the ABS brake, the control is considered from a "panic stop" viewpoint: the ABS is designed to stop the vehicle as safely and quickly as possible. The control target is to maintain friction coefficients between tire and road within "safe" ranges, to ensure the avoiding of wheel's blockage and, consequently, the preservation of vehicle lateral stability and an as reduced as possible stopping distance. As matters stand as physical phenomenon, the ABS control strategy synthesis was thought using fuzzy logic. In brief, the description of this control strategy is as follows. The slip ratios of rear aircraft wheels are inferred, having from measurements (or from integration, in the case of model simulation) angular velocities of front wheels. The observing of these slip ratios, resulting from control variables applied in system, serves as basis of a phenomenological scenario – a road label inferring diagram – conceived to on line decide, via a fuzzy logic reasoning, upon the most suitable new control variables to apply at the current sample step. Control variables are synthesized in last component of a standard Mamdani type fuzzy logic control triplet: fuzzyfier, rules base and defuzzyfier. A rules base, clustered according to three road conditions – dry, wet and ice – is defined. The obtained fuzzy control variable is tuned taking into account the strong changes in the aircraft speed during the landing brake process. A sui generis searching of optimal braking is also sketched. The simulation results show that proposed ABS algorithm ensures the avoiding of wheel's blockage, even in the worst road conditions, with additive measurement noise. Moreover, as a free model strategy, the obtained fuzzy control is advantageous from viewpoint of reducing design complexity and, also, antisaturating, antichattering and robustness properties of the controlled system. Considering previous researches of the authors, fuzzy logic is likely to be the most efficient technique in certain fields of control synthesis.
Key words: fuzzy control, Mamdani fuzzy controller, antilock-braking system (ABS), aircraft landing, mathematical modelling, numerical simulation.

1. Introduction

The main difficulties arising in the design of ABS control is due to the strong nonlinearities and uncertainties in process, which make the ABS control problem challenging. Such difficulties can be overcame using fuzzy logic controllers, which, in the last years, have proved to be a viable alternative in controller design (see, e.g., Wang, 1994; Yen *et al*., 1995; Passino and Yurkovitch, 1998; Ursu *et al*., 2000, 2001; I. Ursu and F. Ursu, 2002;). These represent a control strategy that is rather independent of mathematical models of the plants, thus achieving a certain robustness and reducing design complexity. Philosophically, the essential part of intelligent control research was carried out on the same premises as Han's vision on control theory (Han, 1989), which is free of a few fundamental limitations, such as linearity, time invariance, accurate mathematical representation of plant etc.

In the present paper, a new fuzzy controller is proposed. The numerical illustration of ABS algorithm working is given using the data concerning the Romanian military jet IAR 99.

2. Airplane brake mathematical model

In this section the construction of a airplane brake model is performed with a view to obtain a framework of ABS fuzzy logic controller validation. The controlled system is represented by the main wheels rear wheels of the landing gear. The motion dynamics arising from the rotation of the vehicle about the vertical axis, or from uneven braking forces applied on wheels, are not considered. The straight-line braking maneuver holds on horizontal road. Thus, the lateral tire forces are neglected; the effects of pitch and roll are also neglected. Consequently, when the airplane is braking or accelerating, the tractive forces F_f , F_{rl}, F_{rr}, developed by the road on the tire, are proportional to the normal forces Z_1 and $Z_{2l} = Z_{2r} = Z_2$ of the road acting on the tire, as illustrated in Fig. 1: $F_f = \varphi_l Z_1$, $F_{rl} = \varphi_l Z_2$, $F_{rr} = \varphi_r Z_2$. In the above, by F_f, F_{rl}, Frr were denoted the front, the left rear and the right rear tractive forces; is the road adhesion coefficient at front wheel; φ_l , φ_r are the road adhesion coefficients at rear wheels. The coefficient φ is taken constant and the coefficients φ_l, φ_l are functions of the wheel slip α and depend, as parameters, on the airplane velocity v and the road conditions c: dry, wet or ice. Thus, $\varphi_l := \varphi_l(\alpha, v, c)$, $\varphi_r := \varphi_r(\alpha, v, c)$.

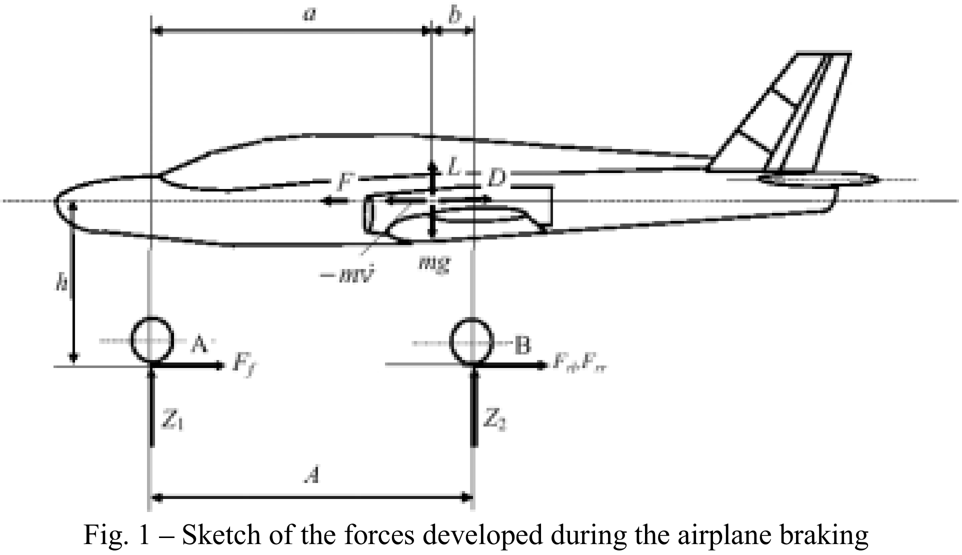

Fig. 1 – Sketch of the forces developed during the airplane braking

Considering the Newton's second law along the horizontal axis, the moments about the contact points A, B of the tire and the front and rear wheel dynamics, respectively, gives:

$$
\begin{gathered}
-m\dot{v} = (\omega_l + \omega_r)Z_2 + \varphi Z_1 - F + D \\
-m\dot{v}h + 2Z_2A - mga + aL + (F-D)h = 0, \quad -m\dot{v}h - Z_1A + mg(A-a) - (A-a)L + (F-D)h = 0 \\
-I\dot{\omega}_l - M_{bl} + \varphi_l Z_2 R = 0, \quad -I\dot{\omega}_r - M_{br} + \varphi_r Z_2 R = 0 \\
D := \rho S C_D v^2/2, \quad L := \rho S C_L v^2/2
\end{gathered} \tag{1}
$$

where: m – total mass of the airplane; F – thrust; D – drag; L - lift; φ – air density; C_D – drag coefficient; C_L - lift coefficient; S - wing area; h - height of the airplane sprung mass; A - distance between front wheel and rear axle; g - acceleration due to gravity; a - distance from center of gravity to front landing gear's wheel; b - distance from center of gravity to (rear) landing gear's axle; I - moment of inertia of the each rear wheel; R - radius of tire; ω_l, ω_r angular velocities of the left and, respectively, right rear wheels; M_{bl}, M_{br} left and, respectively, right rear wheel brake torques.

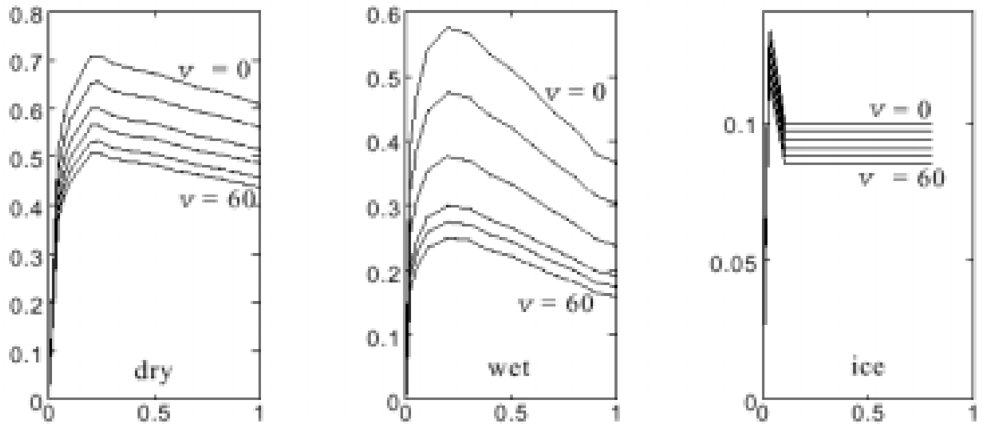

Fig. 2 – Parametric dependencies of road adhesion coefficients $\varphi_l(\alpha, v, c)$, $\varphi_r(\alpha, v, c)$

Solving for Z_1 and Z_2 the first three equations of the system (1), one obtains

$$
\dot{v} = -\frac{(\varphi_l + \varphi_r)Z_2 + \varphi Z_1 - F + D}{m}, \quad \dot{\omega}_l = (\varphi_l Z_2 R - M_{bl})/I, \quad \dot{\omega}_r = (\varphi_r Z_2 R - M_{br})/I \tag{2}
$$

$$
Z_1 := \frac{(mg - L)[2(A-a) + (\varphi_l + \varphi_r)h]}{2(A - \varphi h) + (\varphi_l + \varphi_r)h}, \quad Z_2 := \frac{(mg - L)(a - \varphi h)}{2(A - \varphi h) + (\varphi_l + \varphi_r)h}. \tag{2'}
$$

Thus, performing the numerical integration, the wheel slips are defined as

$$\alpha_l = \frac{v - \omega_l R}{v}, \quad \alpha_r = \frac{v - \omega_r R}{v}.$$

Without braking, $v = \omega R$ and, therefore, $\alpha = 0$. In severe braking, it is common to have $\omega = 0$ while $v \neq 0$, or $\alpha = 1$, which is called wheel lockup.

The brake proportionality constant k_b relates, via the relations

$$M_{bl} = k_b P_l,\ M_{br} = k_b P_r \tag{4}$$

the torques M_{bl}, M_{br} on the one hand, and pressures P_l, P_r in brake cylinders, on the other hand. The following first order linear differential equation was considered representative for the valve-brake cylinder system

$$\tau_{bc}\dot{P}(t) + P(t) = k_p u(t), \quad u(t) = u_k, \quad kT \le t \le (k+1)T, \quad k = 1, 2, \ldots \tag{5}$$

where k_p is a proportionality ratio P_{max} / u_{max} , P is the pressure in brake cylinder, u is the control variable (current to servovalve), τ_{bc} is time constant of brake cylinder and k is the step of control insertion; the pressures P_l and P_r are thus the following solutions of the equations (5)

$$P_w(t, k+1) = e^{-(t-kT)/\tau_{bc}} P_{w,k} + \left(1 - e^{-(t-kT)/\tau_{bc}}\right) k_p u_{w,k}, \quad kT \le t \le (k+1)T, \quad k = 0, 1, \ldots \quad w = l, r. \tag{6}$$

Index w marks the left or right wheel. Initial control $u_{w,0} = u^*, w = l, r$, are given on $0 \le t \le T$; also, the initial pressures $P_{w,0} = 0, w = l, r$ P are settled at $k = 0$. The constant pressures $P_{w,k}$ are given by recurrence equations

$$P_{w,k} = e^{-T/\tau_{bc}} P_{w,k-1} + \left(1 - e^{-T/\tau_{bc}}\right) k_p u_{w,k-1}, \quad k = 1, 2, \ldots \tag{7}$$

because $P_{w,k}$, are defined by continuous evolution of pressures as

$$P_{w,k} =: P_w(t, k)\big|_{t=kT}, \quad k = 1, 2, \ldots \tag{8}$$

In defining the road adhesion coefficients φ_l, φ_r, three road conditions c were considered as representative for all road conditions: dry, wet and ice. The graphic functions $\varphi_l(\alpha, v, c), \varphi_r(\alpha, v, c)$

were assumed from table representasions (see Alexandru *et al*., 2000) and are shown as interpolated versions in Fig. 2. These functions represent an extended Pacejka model (Mauer, 1995) for longitudinal braking, which takes into account the decreasing of road adhesion coefficients by about 50-60% as the velocity v increases from 0 to 60 m/s.

3. Fuzzy logic control synthesis

ABS control conception is based on detection of slip ratio α and of road label *"l"* inferring.

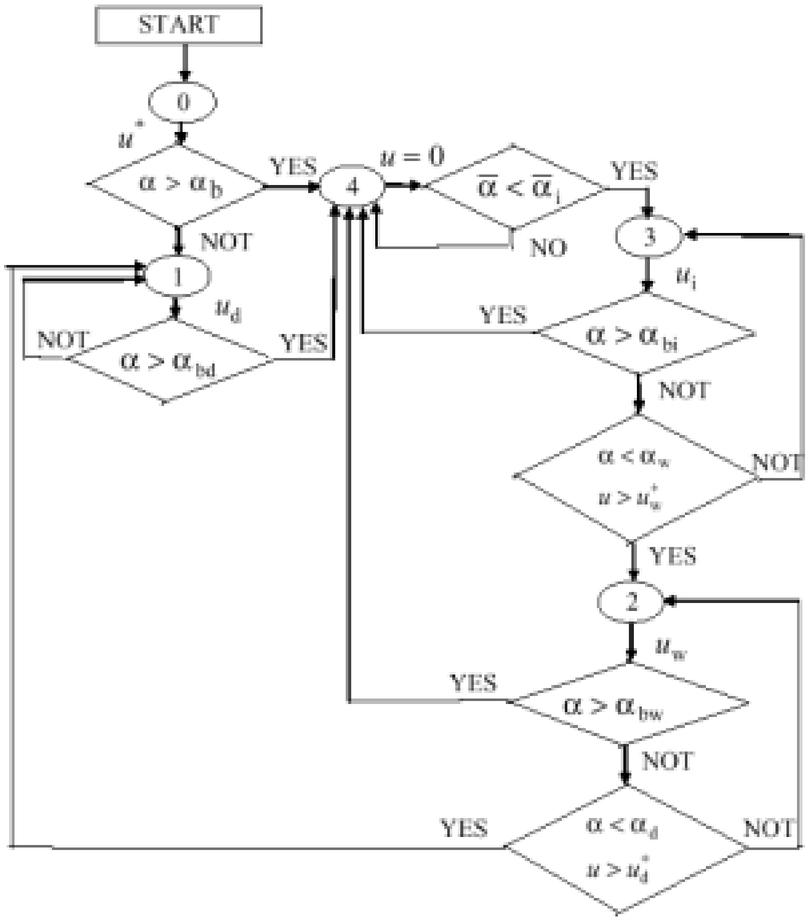

Fig. 3 – Phenomenological algorithm for road label decision diagram.
Legend: 1 – "dry"; 2 – "wet"; 3 – "ice"; 4 – "blockage".

To avoid supplementary difficulties generated by the braking of all wheels of the landing gear, consider only braking of the main wheels - the rear wheels; thus, one has at command the real velocity of the airplane, as given by the angular velocity of the front wheel. The slip ratios of rear wheels are thus obtained, having from measurements angular velocities of these wheels. The road label *"l"* can be inferred by observing the slip ratio resulting from a given control variable: this is the basis of a phenomenological scenario conceived to on line decide via a fuzzy logic reasoning upon the most timely new control variables to apply at the current sample step. This scenario is shown in Fig. 3. At each decision step k, when t = kT, for each braked wheel the three input variables of the road label *"l"* inferring diagram are: 1) wheel slip α; 2) predicted wheel slip $\overline{\alpha}$; 3) previous value of control variable, $u(k-1)$. To partially compensate for the delay effect of the time constant τ_{bc} (six sampling periods τ, in our problem), a predicted slip ratio $\overline{\alpha}$ is computed from a linear regression of the last three sampled values of the slip (see Fig. 4) and is extrapolated to the next period of length $\tau_{bc}/2$ considering at step k the control as unapplied: thus, the algorithm causes the fuzzy logic controller to issue a new control variable at each three sample periods, i.e., at each T = 0.015 s (see Fig. 4).

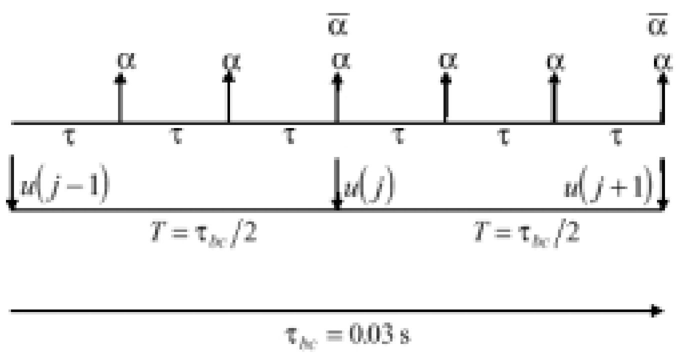

Fig. 4 – Frequencies of data acquisition and processing and control insertion.

The following nine threshold-values concerning input variables in the road label *"l"* inferring diagram mean: α_b - blockage threshold slip at the braking start point; α_{bd} - blockage threshold slip in the case *"l"* = "dry"; α_{bw} - blockage threshold slip in the case *"l"* = "wet"; α_{bi} - blockage threshold slip in the case *"l"* = "ice"; $\overline{\alpha}_i$ - predicted slip for "ice" road label setting; α_w threshold slip for "wet" road label setting in logical conjunction ("and") with threshold control u_w^*; u_w^* - threshold control for "wet" road label setting in logical conjunction with threshold slip α_w; α_d threshold slip for "dry" road label setting in logical conjunction with threshold control u_d^*; u_d^* - threshold-control for "dry" road label setting in logical conjunction with threshold-slip α_d.

These threshold values and the value u^* of the control variable delivered to the system at the braking start point can be fine tuned by a trial and error type process, but with no guarantee of finding optimal results. To automate this process, one can use genetic algorithms. This alternative concerns both the cases of numerical simulation and on line airplane brake testing, but was not considered in the paper.

Generally, a fuzzy logic controller consists of three main components: a fuzzyfier, a fuzzy reasoning or inference engine, and a defuzzyfier (Ghazi Zadeh *et a*l., 1997) .

The fuzzyfier component convert the crisp input signals into their relevant fuzzy variables using a set of linguistic terms. Let us remember the crisp input signals at decision step k: wheel slip α, predicted wheel slip $\overline{\alpha}$ and previous value of control variable u_{k-1} . The following fuzzy variables will be considered: *Z* (zero), *Zs* (zero small), *s* (small), *m* (medium), *L* (large), *VL* (very large). Thus, fuzzy sets and their pertinent membership functions are produced, see Fig. 5; for the sake of simplicity, triangular membership functions were chosen for α and $\overline{\alpha}$ and a singleton type membership function for *u*. Scaled input variables and scaled fuzzy control ensure an unified, independent of various applications, calculus. The fuzzy reasoning characterizes ABS controller as a Mamdani fuzzy controller: a set of expert-type IF... THEN... rules, generally derived from a human operator experience or intuition, will be finally exploited in control rule deriving, by Mamdani's method of minimum. This rules base is clustered having in view the road label *"l"* and represents a some processing of the rules base given by Mauer (1995): *"l "* = **"dry**": 1) IF $\overline{\alpha} \neq VL$ THEN *u* = L; 2) IF α = *L* and *u* = *L* THEN *u* = m; 3) IF α = *s* and *u* = *L* and $\overline{\alpha} \neq VL$ THEN *u* = L; 4) IF α = *m* and $\overline{\alpha} \neq VL$ THEN *u* = L; *"l "*= **"ice**": 1) IF α = *Zs* and *u* = *Zs* THEN *u* = *Z*s; 2) IF α = *Z* THEN *u* = s; 3) IF α = *s* THEN *u* = Z; *"l "* = **"wet**": 1) IF α = *Zs* and $\overline{\alpha} \neq L$ THEN *u* = s; 2) IF α = *s* THEN *u* = *Z*s; 3) IF α = *Z* and $\overline{\alpha} \neq L$ THEN *u* = s; *"l "* = **"blockag**e" : *u* = 0 (in fact, $u_{w,k} = 0$, see (6)).

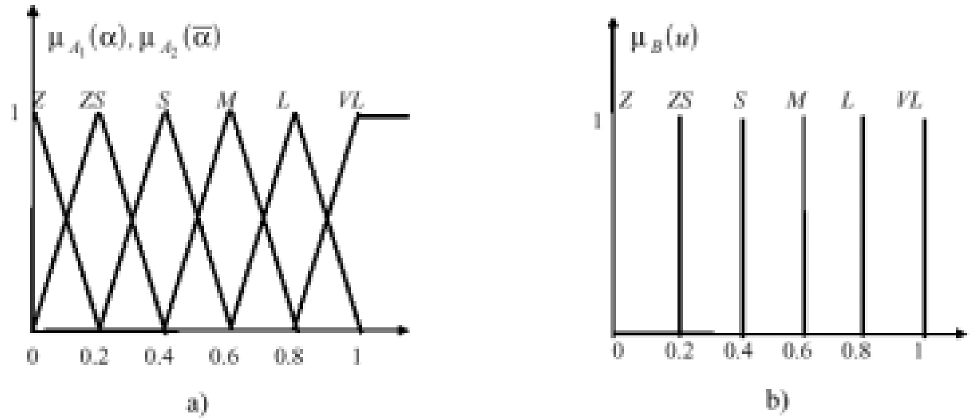

Fig. 5 – Membership functions: a) triangular, for scaled input variables $\alpha, \overline{\alpha}$ and b) singleton, for control variable u.

The fuzzyfier concerns the transforming of fuzzy IF... THEN... rules into a mathematical formula giving the output control variable u. To be more specific, if the pair $(\alpha, \overline{\alpha})$ is measured (or calculated) at the time step k as (scaled) $\left(\alpha_k^0, \overline{\alpha}_k^0\right)$, the control u follows as a consequence of Mamdani fuzzy machinery inference. Having in mind the fuzzyfier stage (Fig. 5) and rules base described, a number of I (dependent on *"l"* and time step k) IF... THEN... rules will operate. A such rule may be, for instance, the following rule derived from the validated rule 4 "dry" :

$$\text{IF } \alpha_k^0 \text{ is } m \text{ and } \overline{\alpha}_k^0 = L, \text{ THEN } u_k \text{ is } L. \tag{9}$$

As matters stand, the rule (9) defines a fuzzy set $A_1^i \times A_2^i \times B^i \equiv m \times L \times L$ in the input-output Cartesian product space R_+^3 , whose membership function can be defined in the manner

$$\mu_{u_i} = \min\left[\mu_{A_1^i}\left(\alpha_k^0\right), \mu_{A_2^i}\left(\overline{\alpha}_k^0\right), \mu_{B^i}\left(u_k\right)\right] \tag{10}$$

(other variants, e.g. product instead of min, can be chosen). For simplicity, the singleton-type membership function $\mu_B(u)$ of control variable has been preferred here. In this case, $\mu_B^i(u_k)$ will be replaced by u_i^0 the singleton abscissa corresponding to the fuzzy set B^i . Therefore, using: 1) the singleton fuzzyfier for u;

2) the center-average type defuzzyfier; and 3) the min inference, these *I* IF... THEN... rules can be transformed, at each time step kT, into the following formula giving the crisp control *u* (Wang and Kong, 1994)

$$u = u_k = \sum_i \mu_{u_i} u_i^0 \bigg/ \left(\sum_i \mu_{u_i} \right), \quad i = 1, 2, \ldots, I. \tag{11}$$

This value will be rounded off to the nearest singleton abscissa (see Fig. 5b).

4. Fuzzy control value moderating and a sui generis optimal braking search

Due to the lift force, the tractive forces F_f, F_{rl}, F_{rr} developed by the tire strongly change with vehicle speed. To counteract this effect on braking process, the obtained fuzzy control *u* given in (11) is tuned, taking into account just the vehicle speed

$$u := u u_c(v), \; 0 < u_c \le 1. \tag{13}$$

The correction value u_c is thought as a strictly monotone increasing function

$$u_c = \frac{\beta_1 + \beta_2 v^2}{u_{max}} \tag{14}$$

and parameters β_1, β_2, will be derived from the equations

$$\beta_1 + \beta_2 v_0^2 = \theta u_{max}, \; \beta_1 + \beta_2 v_f^2 = u_{max}, \; 0 < \theta < 1 \tag{15}$$

where v_0 and v_f are, respectively, the initial and final values considered in the braking process.
Thus

$$u_c = \frac{\theta v_f^2 - v_0^2 + (1-\theta) v^2}{v_f^2 - v_0^2}. \tag{16}$$

The coefficient θ can be considered as connected with that value of control variable, which, initialized as constant in system, does not causes the wheels blocking on a given road condition, say dry.

Another observation can improve the ABS fuzzy logic algorithm. By inspecting the given also in (1) equations

$$I\dot{\omega}_w + k_b P_w = R\varphi_w Z_2,\ w = l \text{ or } r \qquad (17)$$

one infers that a value indicator of the current road adhesion coefficient φ_w is at hand: the left-hand side of equation (17). To have this opportunity, the mathematical model must be simplified by introducing the hypothesis $\varphi_l = \varphi_r := \varphi_w$ concerning the road adhesion coefficients at rear wheels. Indeed, in this condition the right-hand side of the equation (17) is increasing with φ_w and, by measuring the variables $\dot{\omega}_k$ and P_w, one obtains a sign on the variation of φ_w. Preserving a mathematical model with distinct left and right road adhesion coefficients, the clamed opportunity doesn't holds, because in this situation the right-hand side of the equation (17) should be increasing with respect to, say φ_r, and decreasing with respect to the other coefficient φ_l. Thus, in the case of simplified mathematical model, an heuristic procedure of optimal braking searching can be conceived. Namely, the control (13) will be applied at system input so long as the latest three indirectly measured values of φ_w, at sampling times $i\tau$, do not fulfill the inequalities

$$\varphi_{w,i-2} \geq \varphi_{w,i-1} \geq \varphi_{w,i} \qquad (18)$$

If the above inequalities hold, the control $u_{w,k} = 0$ is decided to system input, until the inequality

$$\varphi_{w,i-1} \leq \varphi_{w,i} \qquad (19)$$

holds, when the control (13) is again applied at system input, and so on.

5. Numerical simulations and concluding remarks

Numerical simulation of the mathematical model (2) is enabling engineer to evaluate thoroughly: 1) the ABS fuzzy logic control working; 2) a first guess of algorithm's threshold $\alpha_b, \alpha_{bd}, \alpha_{bw}, \alpha_{bi}, \overline{\alpha_i}, \alpha_w, u_w^*, \alpha_d, u_d^*$. The system parameters, concerning the Romanian military jet IAR 99, were as follows: *m* = 3850 kg, *A* = 4.235 m, *a* = 3.772 m, *h* = 1.092 m, *R* = 0.263 m, *I* = 0.615 kgm^2 , *F* = 95 X 9.8 N, $k_p = P_{\max} / u_{\max}, \varphi = 0.02, L = 1.25 \times 18.71 \times 0.618 \times v^2 / 2N, \tau_{bc} = 0.03s$.

$D = 1.25 \times 18.71 \times 0.1088 \times v^2 / 2N$ (with v given in m/s), $1/k_b = 0.4135 \times 0.98$ daN/cm^2/daNm, $v_0 = 50$ m/s, $v_0 = 10$ m/s, P_{max} = 1250 N/m^2 , u_{max} = 10 mA. State variables *v, ω_l, ω_r*, with initial conditions *v*(0) = ω_l(0)R = ω_r(0)R = 50 m/s, are obtained by integrating of the system (2).

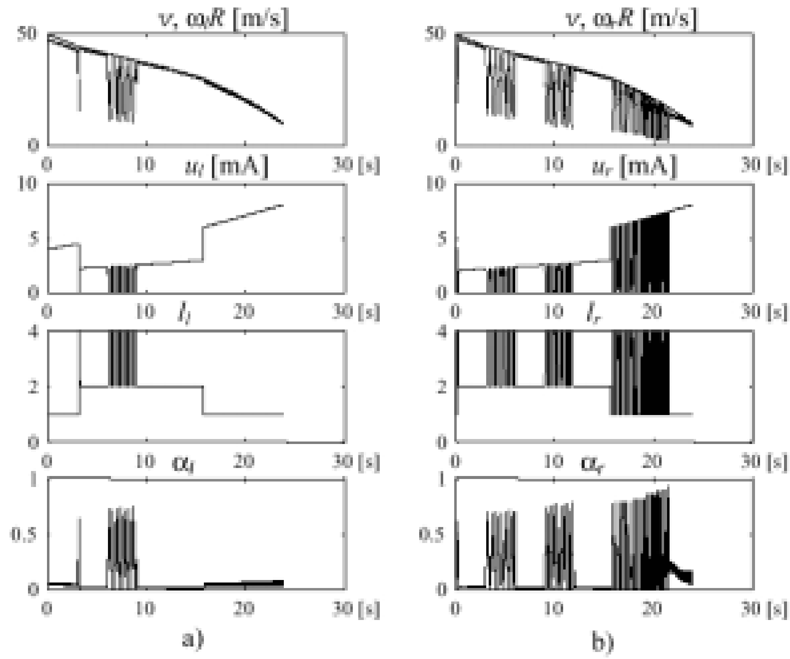

Fig. 6 – Braking evolution, various road conditions; fuzzy control moderating parameters: θ = 1/0.5, φ = 1. a) left wheel: dry-wet-ice-wet-dry; b) right wheel: wet-ice-dry-ice-wet.

Many numerical explorations were performed. As representative for simulation, Fig. 6 shows the fuzzy controller's response to following inserted in system road conditions (for each wheel, the first four sequences, each of 3 s length, are followed by a fifth, variable as time, sequence). The succession of the road conditions sequences are: *dr*y, *we*t, *ic*e, *we*t, *and dry* – for the left wheel and *we*t, *ic*e, *dr*y, *ic*e, *wet* – for the right wheel. The main issue concerns a remarkable fac*t: fuzzy logic control algorithm ensures wheel's blockage avoiding, inclusively in the worst road conditio*n, defined by the adhesion coefficients on ice: see Fig. 7; choosing θ = ½ φ = 1/0.6, the wheels roll is spectacular as concerning the maintenance of a very little slip, and concomitantly preserving an acceptable stopping time. As speaking of this dynamical feature of the system, it is to emphasize that the stopping time is not the main purpose of ABS control. It is a system mainly designed to maintain control of the vehicle during emergency braking situations, not necessarily make the vehicle stop more quickly. On very soft surfaces, such as gravel or unpacked snow, it is accepted that ABS may actually lengthen stopping distances.

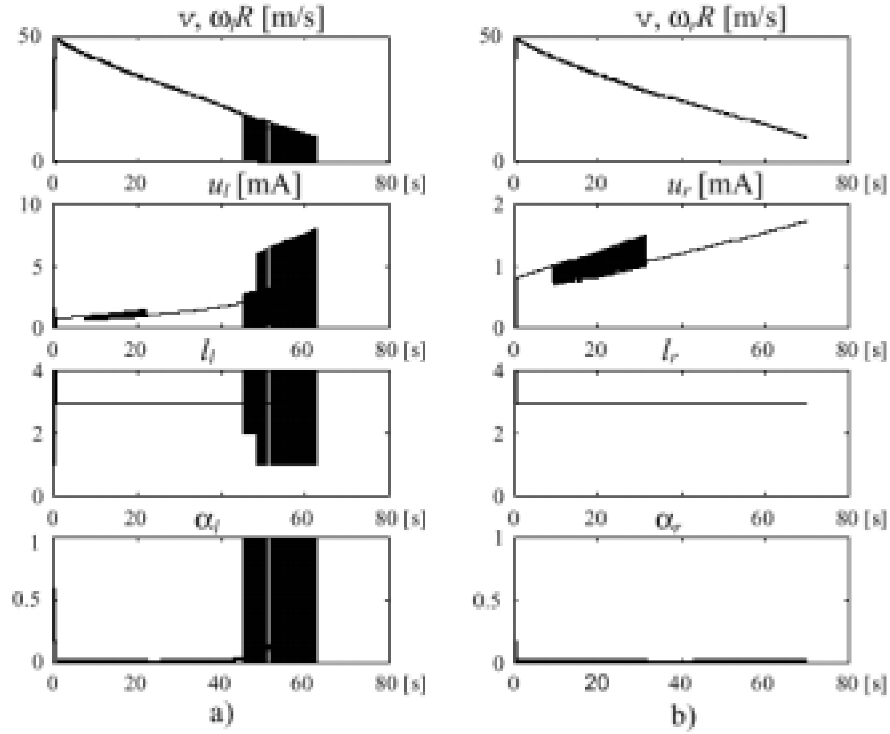

Fig. 7 – Braking evolution on ice; fuzzy control moderating parameters: a) $\theta = 1/0.2$, $\varphi = 1.$; b) $\theta = 1/0.2$, $\varphi = 1/0.6$.

Figures 8 and 9 show samples of tuning fuzzy control moderating parameters on dry road: the values $\theta = 1/0.5$ and $\varphi = 1/1.5$ seem to be the most suitable from stopping time viewpoint.

Note again that the failing of real road conditions guess, in fact the failing of occurring adhesion coefficients guess, means no algorithm failing; due to the rigor of road label "blockage" specification $u_{w,k} = 0$, the occurrence of a real wheel blockage, when the brake is supervised by the proposed algorithm, is entirely improbable. To make more efficacious the decision $u_{w,k} = 0$, a switching valve is designed: when the control value $u_{w,k} = 0$ is settled, the valve switches on the time constant $\tau_{bc}/10$, hastening so the pressure discharge from the brake cylinder. Thus, the infallible road condition guess is not an important purpose in our control problem.

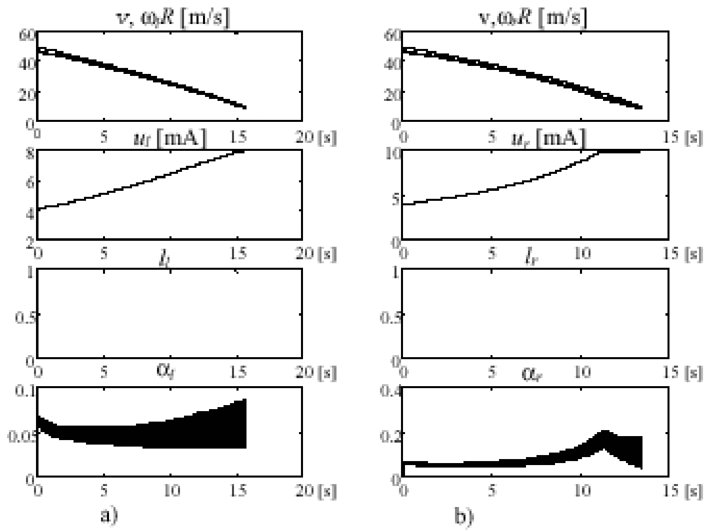

Fig. 8 – Tuning of the fuzzy control moderating parameters on dry road:
a) θ = 1/0.5, φ = 1.; b) θ = 1/0.5, φ = 1/1.5.

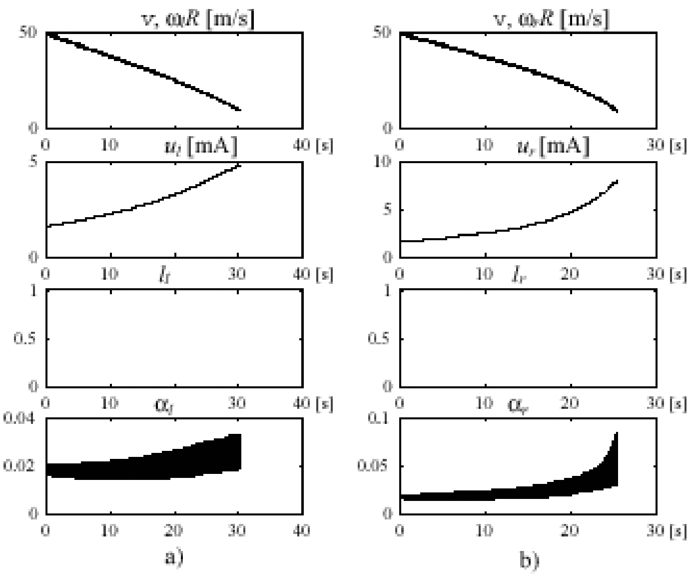

Fig. 9 – Tuning of the fuzzy control moderating parameters on dry road:
a) θ = 1/0.2, φ = 1/0.6; b) θ = 1/0.2, φ = 1.

Let finally note the most meaningful feature of the proposed ABS fuzzy logic controller: because is in fact a free model strategy, this methodology ensures a reduced complexity and provides antisaturating and antichattering properties to the controlled system, thus favourising its robustness (see, also, I. Ursu and F. Ursu, 2002).

Such a control synthesis in the case of airplane landing is not available in a current literature of the field, to the best of author's knowledge.

References

[1].Alexandru, D., F. Popescu, V. Andrei (2000). Requirements concerning an IAR 99 optimized braking system. *INCAS* ("Elie Carafoli" National Institute of Aerospace Research) *Internal Report* 2503.

[2].Ghazi Zadeh, A., A. Fahim, M. El-Gindy (1997). Neural network and fuzzy logic applications to vehicle systems: literature survey. *International Journal of Vehicle Design*, **18**, 2, 132-193.

[3].Han, J. (1989). Control theory: it is a theory of model or control? *Systems Science and Mathematical Sciences*, **9**, 4, 328–335.

[4].Mauer, G. F. (1995). A fuzzy logic control for an ABS braking system. *IEEE Transaction on Fuzzy Systems*, **3**, 4, 381-388.

[5].Passino, K. M., S. Yurkovich (1998). *Fuzzy control*. Addison Wesley Longman, Menlo Park, CA (later published by Prentice Hall).

[6].Ursu, I., F. Ursu, T. Sireteanu, C. W. Stammers (2000). Artificial intelligence based synthesis of semiactive suspension systems. *The Shock and Vibration Digest*, Sage Publications, **32**, 1, 3–10.

[7].Ursu, I., F. Ursu, L. Iorga (2001). Neuro-fuzzy synthesis of flight control electrohydraulic servo. *Aircraft Engineering and Aerospace Technology*, MCB University Press, **73**, 5, 465–471.

[8].Ursu, I., F. Ursu (2002). *Active and semiactive control* (in Romanian), Romanian Academy Publishing House, Bucharest.

[9].Wang, L.-X., H. Kong (1994). Combining mathematical model and heuristics into controllers: an adaptive fuzzy control approach. *Proceedings of the 33 rd IEEE Conference on Decision and Control*, Buena Vista, Florida, USA, **4**, 1994, 4122–4127.

[10].Wang, L. (1994). *Adaptive fuzzy systems and control˜design and stability analysis*. Englewood Cliffs, New Jersey, Prentice Hall.

[11].Yen, J., R. Langari, L. A. Zadeh Eds. (1995). *Industrial applications of fuzzy control and intelligent systems.* New York, IEEE Press.

Authors: Ioan Ursu, Felicia Ursu,
"Elie Carafoli" National Institute for Aerospace Research, Bdul Iuliu Maniu 220, sector 6, Bucharest 06 1099, e-mail: iursu@aero.incas.ro