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A FUZZY LOGIC CONTROL SYNTHESIS FOR AN AIRPLANE ANTILOCK-BRAKING SYSTEM

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In memoriam Vasile Andrei

In this paper, an airplane fuzzy logic control synthesis for an antilock-braking system (ABS) is proposed. The slip ratios of rear 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 airplane speed during the landing brake process. The simulation results, performed on the mathematical model of a military jet braking, show that proposed ABS algorithm ensures the avoiding of wheel's blockage, even in the worst road conditions, with adding 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.

Key words: antilock-braking system, wheel slip, road label, road condition, fuzzy control, Mamdani fuzzy controller, airplane braking.

1. INTRODUCTION

In principle, in the ABS brake, the control is considered from a "panic stop" viewpoint [1]: the ABS is designed to stop the vehicle as safely and quickly as possible. This means first of all the avoiding of the vehicle lateral instability as a result of wheel slip increasing beyond a critical point, where the ability to steer the vehicle will be compromised. The cause is not the loss of longitudinal friction coefficient, but the lateral friction coefficient, which decreases proportional to the slip. Given the ABS's main purpose, the controller releases or applies the brakes, aiming to achieve a tradeoff between braking effectiveness and lateral stability.

Many successful proprietary algorithms exist for ABS control logic, see, e.g., [2]. In addition, several conventional control approaches have been reported in the open literature [3–5], and even intelligent control approaches has been investigated [6, 7].

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 [8–10] (see, also, [11–13]). 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 [14], which is free of a few fundamental limitations, such as linearity, time invariance, accurate mathematical representation of plant etc.

In the present paper, a fuzzy controller is proposed for an airplane ABS. The numerical illustration of

Recommended by Horia-Nicolai TEODORESCU, member of the Romanian Academy

ABS algorithm working is given using the data concerning the Romanian military jet IAR 99. The organization of the paper is as follows. Below, the airplane brake mathematical model is described, with a view to obtain a framework of ABS fuzzy logic controller validation. Then, the ABS fuzzy logic controller is developed, having as starting point the Mauer's paradigm [6]. The next section provides the ideas of bringing into accord the derived fuzzy control with the strong changes in vehicle speed during the brake process. Finally, numerical simulations and some concluding remarks are reported.

2. AIRPLANE BRAKE MATHEMATICAL MODEL

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: $F_f = \varphi Z_1$, $F_{rl} = \varphi_l Z_2$, $F_{rr} = \varphi_r Z_2$. In the above, by F_f, F_{rl}, F_{rr} were denoted the front, the left rear and the right rear tractive forces; φ 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_r 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, $\varphi_l := \varphi_l(\alpha; v, c)$, $\varphi_r := \varphi_r(\alpha; v, c)$.

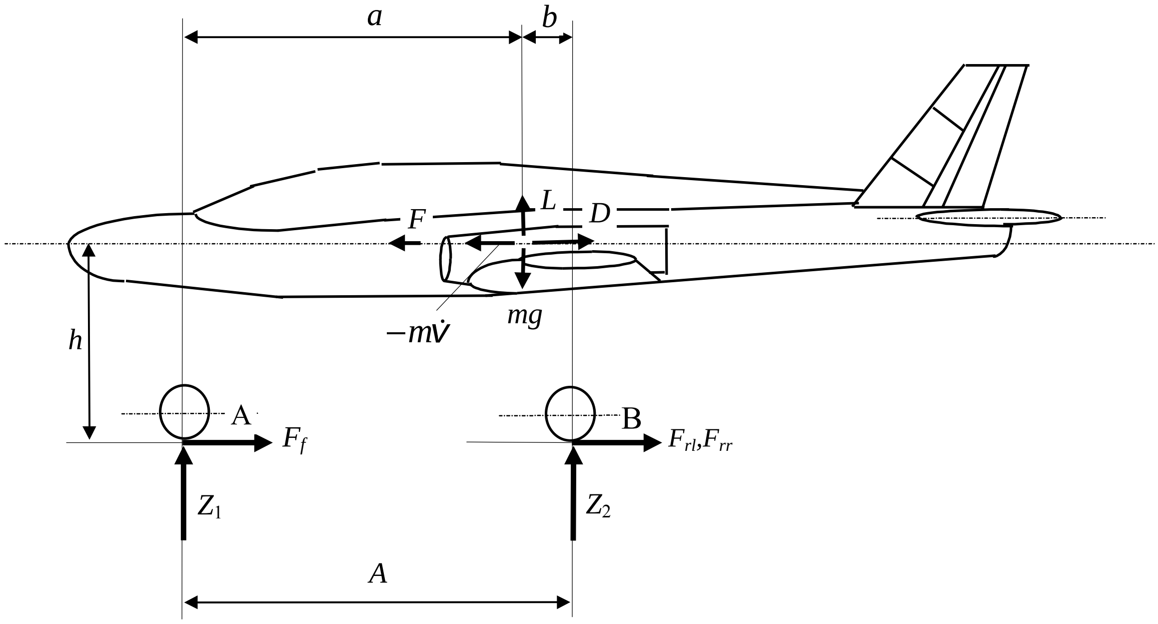

Fig. 1 – Sketch of the forces developed during the airplane braking.

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; ρ − 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.

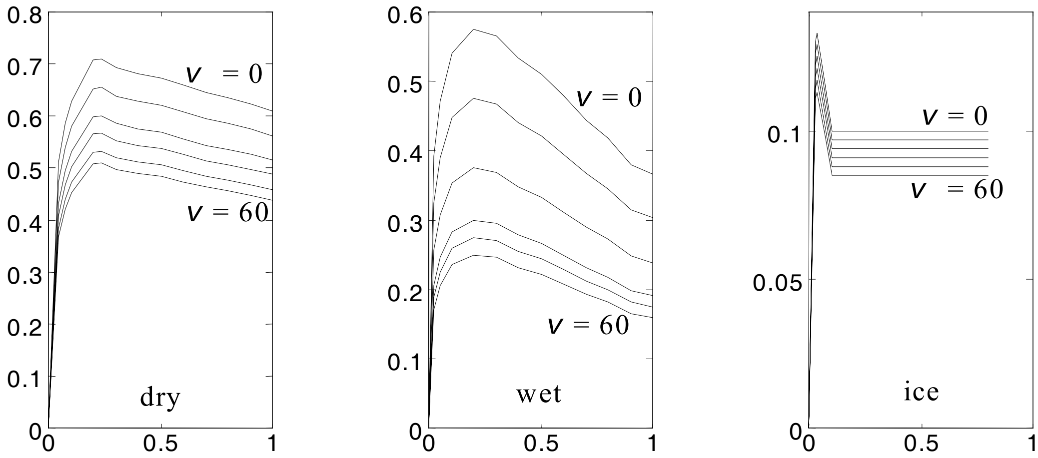

Fig. 2 – Parametric dependencies of road adhesion coefficients: $\varphi_l\,(\alpha;\, v,\, c)$, $\varphi_r\,(\alpha;\, v,\, c)$.

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

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

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

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

$$\alpha_l = \frac{v - \omega_l R}{v}, \quad \alpha_r = \frac{v - \omega_r R}{v}. \tag{3}$$

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

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

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)

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

Index w marks the $l$eft or $r$ight wheel. Initial control values $u_{w,\,0} = u^*$, $w = l, r$, are given on $0 \le t \le T$; also, the initial pressures $P_{w,0} = 0$, $w = l, r$ 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 the road conditions: dry, wet and ice. The graphic functions $\varphi_l\,(\alpha;\, V, c)$, $\varphi_r\,(\alpha;\, V, c)$ were assumed from table representations given in reference [15] and are shown as interpolated versions in Fig. 2. These functions represent an extended Pacejka model [6] 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. A crucial point in development of wheel slip control systems is the determination of the vehicle speed.

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: $u_{\rm b} = 0$, if the "blockage" label is decided, and $u_{\rm d}$, $u_{\rm w}$, $u_{\rm i}$, if the "dry", "wet", or, respectively "ice" label is decided. This is the basis of a phenomenological scenario conceived to on line decide – via fuzzy logic reasoning – upon the most suitable 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 value 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 (see Fig. 4).

The following nine threshold-values concerning input variables in the road label "l" inferring diagram mean: $\alpha_{\rm b}$ – blockage threshold slip at the braking start point; $\alpha_{\rm bd}$ – blockage threshold slip in the case "l" = "dry"; $\alpha_{\rm bw}$ – blockage threshold slip in the case "l" = "wet"; $\alpha_{\rm bi}$ – blockage threshold slip in the case "l" = "ice"; $\overline{\alpha}_{\rm i}$ – predicted slip for "ice" road label setting; $\alpha_{\rm w}$ – threshold slip for "wet" road label setting in logical conjunction ("and") with threshold control $u^*_{\rm w}$; $u^*_{\rm w}$ – threshold control for "wet" road label setting in logical conjunction with threshold slip $\alpha_{\rm w}$; $\alpha_{\rm d}$ – threshold slip for "dry" road label setting in logical conjunction with threshold control $u^*_{\rm d}$; $u^*_{\rm d}$ – threshold-control for "dry" road label setting in logical conjunction with threshold-slip $\alpha_{\rm d}$.

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 present paper.

Generally, a fuzzy logic controller consists of three main components: a fuzzyfier, a fuzzy reasoning or inference engine, and a defuzzyfier [16].

The fuzzyfier component converts 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 linguistic degrees 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, when applied to variables α, $\overline{\alpha}$ and *u*, whose domain is the closed interval [0, 1]. 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 in [6]: "*l* " = "**dry**": 1) IF $\overline{\alpha} \neq VL$ THEN $u = L$; 2) IF $\alpha = L$ and $u = L$ THEN $u = m$; 3) IF $\alpha = s$ and $u = L$ and $\overline{\alpha} \neq VL$ THEN $u = L$; 4) IF $\alpha = m$ and $\overline{\alpha} \neq VL$ THEN $u = L$; "*l* "= "**ice**": 1) IF $\alpha = Zs$ and $u = Zs$ THEN $u = Zs$; 2) IF $\alpha = Z$ THEN $u = s$; 3) IF $\alpha = s$ THEN $u = Z$; "*l* " = "**wet**": 1) IF $\alpha = Zs$ and $\overline{\alpha} \neq L$ THEN $u = s$; 2) IF $\alpha = s$ THEN $u = Zs$; 3) IF $\alpha = Z$ and $\overline{\alpha} \neq L$ THEN $u = s$; "*l* " = "**blockage**" : $u = 0$ (in fact, $u_{w,k} = 0$, see (6)).

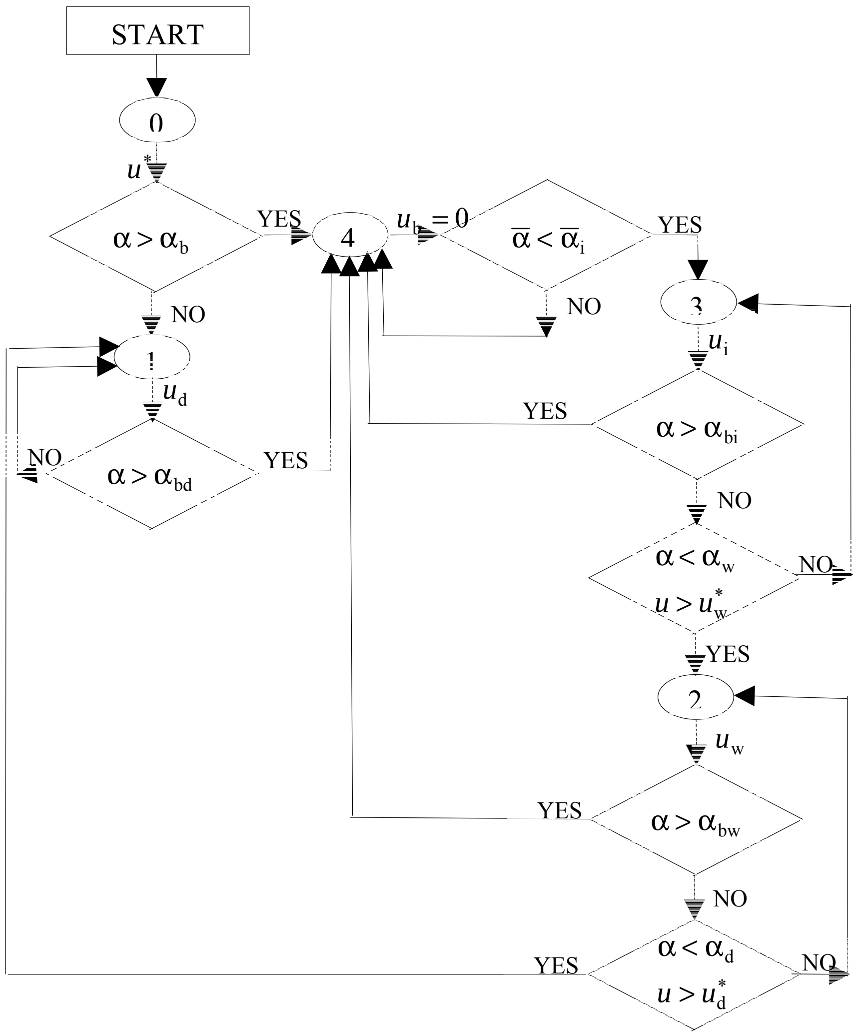

Fig. 3 – Phenomenological algorithm for road label decision diagram.
Legend: 1 – "dry"; 2 – "wet"; 3 – "ice"; 4 – "blockage".

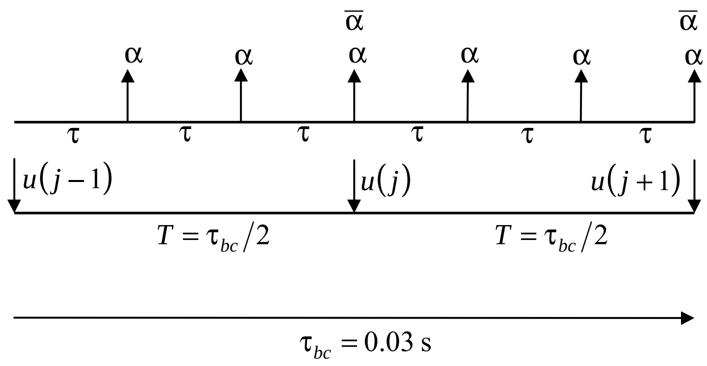

Fig. 4 – Frequencies of data acquisition and processing and control insertion.

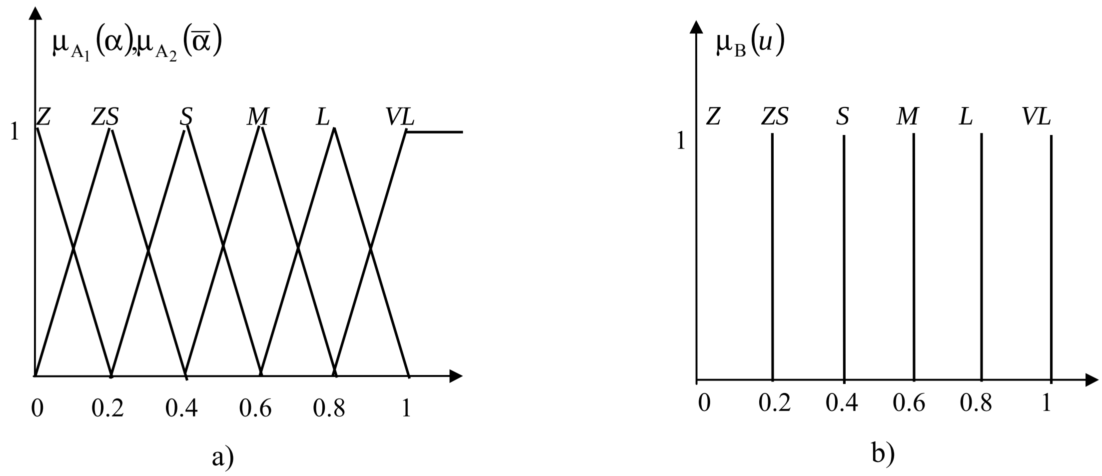

Fig. 5 – Membership functions:
a) triangular, for scaled input variables $\alpha, \overline{\alpha}$; b) singleton, for control variable *u*.

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 (α , $\overline{\alpha}$) is measured (or calculated) at the time step *k* as (scaled) ($\alpha_k^0, \overline{\alpha}_k^0$), the control *u* follows as a consequence of Mamdani fuzzy machinery inference. Having in mind the fuzzyfier stage (Fig. 5) and the described rules base, a number of *I* (dependent on "*l*" and time step *k*) IF... THEN... rules will operate. A 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 *minimum*, can be chosen. For simplicity, the singleton-type membership function $\mu_B(u)$ of control variable has been preferred here; thus, $\mu_B{}^i(u_k)$ can 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 [17]

$$u_f := u_{fk} = \sum_i \mu_{u_i} u_i^0 \Big/ \left(\sum_i \mu_{u_i} \right), \quad i = 1, 2, ..., I, \quad k = 1, 2, ... \tag{11}$$

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

4. FUZZY CONTROL VALUE MODERATING

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

$$u := u u_c(v). \tag{13}$$

The correction value $u_c(v)$ is thought as a strictly monotone decreasing function

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

The parameters β_1, β_2 will be derived from the equations

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

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

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

5. NUMERICAL SIMULATIONS

Numerical simulation of the mathematical model (2) is enabling engineer to evaluate thoroughly: 1) a first guess of algorithm's thresholds $\alpha_b, \alpha_{bd}, \alpha_{bw}, \alpha_{bi}, \overline{\alpha}_i, \alpha_w, u_w^*, \alpha_d, u_d^*$; 2) the ABS fuzzy logic control working. 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, $I = 0.615\ \mathrm{kgm}^2$, $F = 95 \times 9.8$ N, $k_P = P_{\max}/u_{\max}$, $\varphi = 0.02$, $L = 1.25 \times 18.71 \times 0.618 \times v^2/2$ N, $D = 1.25 \times 18.71 \times 0.1088 \times v^2/2$ N (with v given in m/s), $1/k_b = 0.4135 \times 0.98\ \mathrm{daN/cm^2/daNm}$, $\tau_{bc} = 0.03$ s, $v_0 = 50$ m/s, $v_f = 10$ m/s, $P_{\max} = 1250$ N/m^2, $u_{\max} = 10$ mA. State variables v, ω_l, ω_r, with initial conditions $v(0) = \omega_l(0)R = \omega_r(0)R = 50$ m/s, are obtained by integrating of the system (2).

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 was: *dry*, *wet*, *ice*, *wet*, *dry* – for the left wheel and *wet*, *ice*, *dry*, *ice*, *wet* – for the right wheel. Other many numerical explorations were performed. The main issue concerns a remarkable fact: fuzzy logic control algorithm ensures wheel's blockage avoiding, inclusively in the worst road condition, defined by the adhesion coefficients on ice: see Fig. 7. Choosing $\theta = 1/2$ and $\varphi = 1/0.6$, 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.

Note 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.

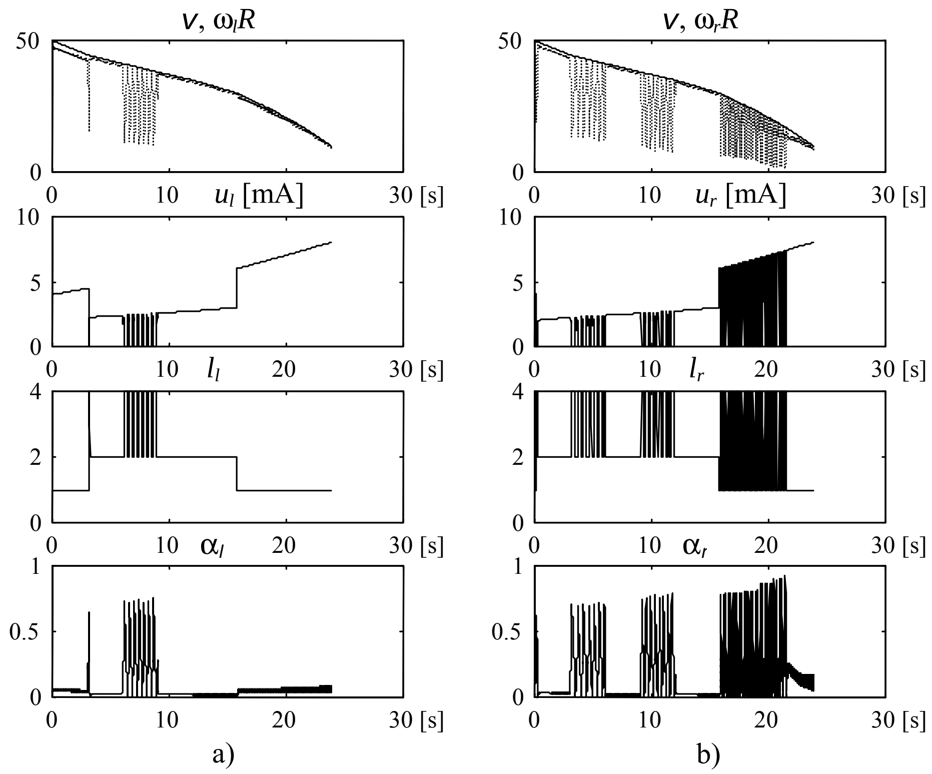

Fig. 6 – Braking evolution, various road conditions; fuzzy control moderating parameters: θ = 1/0.5, φ = 1. a) left wheel: dry-wet-ice-wet-dry; b) right wheel: wet-ice-dry-ice-wet.

6. CONCLUDING REMARKS

While most of reported results in the literature of the field are categorically favorable to the fuzzy viewpoint, we do not evade that there are many opponents of the fuzzy control; see, for example, the recent tempestuous and radical challenge of Michael Athans, a great name of the classical control. In his exposition titled "Crisp control is always better than fuzzy control" (see the site `fuzzy.iau.dtu.dk`), Athans concludes sententiously: "fuzzy control is a parasitic technology". On the contrary, our conclusion is that, in various approaches, regarding as applications active and semiactive suspensions and electrohydraulic servo actuating primary flight controls [11–13], the fuzzy control worked very well, much better than classical methodologies. However, facing with assertions as that of Athans, we consider in principle that even the subjective considerations are necessary and beneficent.

Now, this paper proposes an ABS fuzzy logic control for an airplane. Such a control synthesis is not available in a current literature of the field, to the best of the author's knowledge. Thus, a connection of our results with similar other results is not at hand. But in the literature many approaches are presented involving ABS control for the modern car [1−7], mainly consisting in the following applied control tools: heuristic viewpoint, as that used in some older Bosch projects, Kalman filter synthesis [2], [18], sliding mode synthesis [3, 5], fuzzy logic synthesis [6, 7]. Considering previous researches of the authors [19, 20], the main conclusion of the paper concerns the remarkable fact that fuzzy logic control algorithm ensured wheel's blockage avoiding, inclusively in the worst road condition, defined by the adhesion coefficients on ice.

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 design complexity and provides antisaturating and antichattering properties of the controlling system [13], thus favourising its robustness.

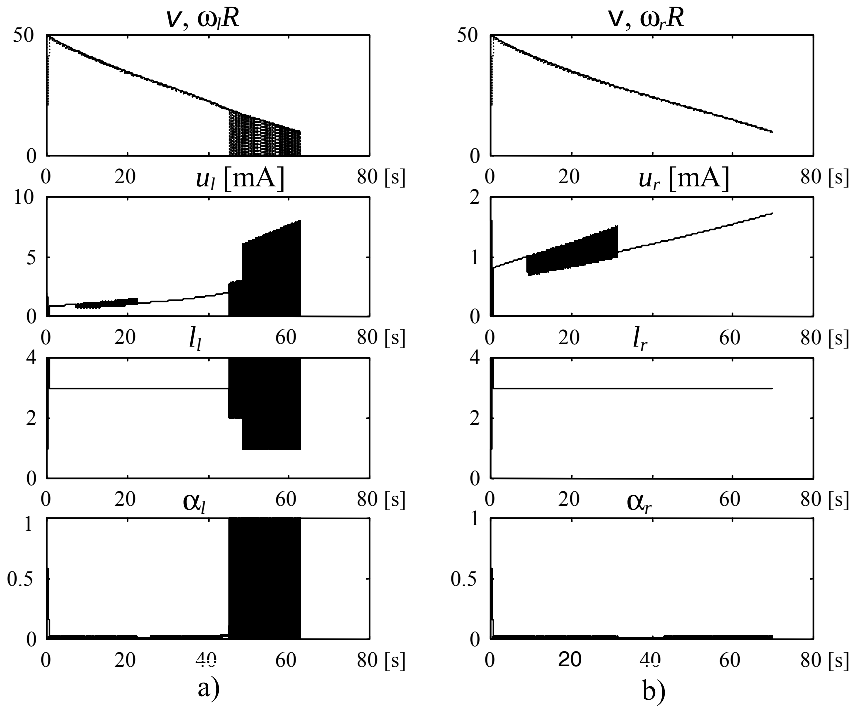

Fig. 7 – Braking evolution on ice; fuzzy control moderating parameters:
a) θ = 1/0.2, φ = 1. ; b) θ = 1/0.2, φ = 1/0.6.

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