Aircraft flight control with convergence-based anti-windup strategy

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Abstract: A convergence-based anti-windup control strategy is presented and demonstrated by the example of aircraft yaw control problem.

Keywords: Flight Control; Anti-windup; Nonlinear control

1. INTRODUCTION

The *anti-windup* (AW) control problem is a challenging one during the several last decades and a great number of works is devoted to it, e.g. see (Hippe, 2006) and the references therein. Let us briefly recall the existing results in the field of AW control of aircrafts.

The windup problem arising from actuator rate and magnitude limits in the context of manual flight control for an open loop unstable aircraft was addressed in (Barbu et al., 1999). An AW solution tailored for this problem is presented and the result is compared with an optimal solution. Barbu et al. (2005) considered longitudinal short-period dynamics of a tailless aircraft model around any trim flight condition. The proposed AW scheme allows for more aggressive maneuvers than the standard "command limiting" approach. The compensation law guarantees stability of the controlled aircraft for any pilot command and enforces flight quality specifications whenever they are achievable within the given control constraints.

Wu and Soto (2004) extended the AW control scheme to control of LTI systems subject to actuators with both magnitude and rate constraints and LFT systems with input saturations. Based on the extended Circle criterion, convex AW control synthesis was developed. The explicit AW controller formula were provided to facilitate compensator construction. The effectiveness of AW control schemes was demonstrated using an F-8 aircraft model.

Sofrony et al. (2006) demonstrated the application of a recently developed anti-windup technique for systems with rate-saturated actuators, to a realistic flight control example. An approach to tuning the anti-windup compensator was devised, allowing a transparent trade-off between performance and the size of an estimate of the region of attraction. The AW algorithm was applied to a nonlinear simulation model of the longitudinal and lateral dynamics of an experimental aircraft showing the potential of AW to lessen an aircraft's susceptibility to pilot-induced-oscillations. Design, flight testing and accompanying analysis of two AW compensators for an experimental aircraft – the German Aerospace Center's (DLR) advanced technologies testing aircraft (ATTAS) have been presented in (Brieger et al., 2007). The AW compensators are aimed to reduce the deleterious effects of rate-saturation of the aircraft's actuators on handling qualities. The further results were presented in (Brieger et al., 2008), where a variety of low-order AW compensators were compared to determine the importance of different design parameters.

The problem of static AW strategy for linear unstable aircraft flight control systems with saturated dynamics was considered in (Queinnec et al., 2006). The quadratic Lyapunov functions, *S*-procedure and a sector nonlinearity description were used. AW design was investigated to increase both a domain of admissible references to track and a safety region over which the stability of the resulting closed-loop saturated system was ensured.

Roos and Biannic (2006) using a simplified LFT model of an aircraft-on-ground, applied a robust AW control technique to improve lateral control laws, demonstrating advantage of a simplified representation of the nonlinear lateral ground forces which were reduced to saturation-type nonlinearities.

The problem of multivariable AW controller synthesis that incorporates trade-offs between unconstrained linear performance and constrained AW performance was studied by Tiwari et al. (2007). Results were applied to the multivariable model for the longitudinal dynamics of an F8 aircraft.

The case of large parametric uncertainties in the dynamics of the glider as well as actuator saturation limits was considered in (Kahveci et al., 2007, 2008). The authors proposed a robust adaptive linear quadratic (LQ) control design with an adaptive AW compensator to handle both the unknown time varying parameters and the saturation nonlinearities. The glider tracks the optimal soaring trajectory generated by the decision algorithm despite the parametric uncertainties and the control input constraints.

In (Herrmann et al., 2006) the AW problem was formulated in discrete time using a configuration which effectively decouples the nominal linear and nonlinear parts of a closed loop system with constrained plant inputs. The results were applied to control of a high-performance fighter aircraft model, presented in (Yee et al., 2001).

Galeani et al. (2008) addressed the AW design problem for linear control systems with strictly proper controllers in the presence of input magnitude and rate saturation. Using generalized sector condition, an LMI-based procedure for the construction of a linear AW gain acting was provided, ensuring regional closed-loop stability. The approach was illustrated by the example of F-8 aircraft longitudinal flight control. In (Biannic et al., 2006), the AW design based on nonlinear performance characterization of saturated systems step responses is performed for control of M-2000 aircraft along the longitudinal axis. The method is further developed in (Biannic and Tarbouriech, 2007), where the problem is considered to ensure tracking the angle-of-attack as fast as possible, without any steady-state error and with a high robustness level. In Biannic et al. (2007) using a description of deadzone-type nonlinearities via modified sector conditions, a new LMI characterization of full-order continuous-time AW controllers was proposed and the reduced-order case was considered. A two-step design procedure is then implemented. This methodology is evaluated on a real-world application. Roos and Biannic (2008) used this approach to compute full-order continuous-time AW controllers with pole constraints and presented an example of PID AW control of longitudinal behavior of an aeronautical vehicle.

In the context of a closed-loop LFT model, Ferreres and Biannic (2007) proposed an LMI technique for the synthesis of a static or dynamic AW controller, which extends existing LMI methods for designing a robust filter or feedforward controller. A missile example was given to illustrate the feasibility of the technique.

The paper is organized as follows. Convergence-based AW control strategy based on the results of Pavlov et al. (2004); van den Berg et al. (2006); Pavlov et al. (2006); van den Bremer et al. (2008) is briefly described in Sec. 2. An application example of aircraft yaw control is presented in Sec. 3. Concluding remarks and the future works intensions are given in Conclusions.

2. CONVERGENCE-BASED AW CONTROL STRATEGY

Following (van den Berg et al., 2009), let us present some basic results on the convergence-based AW control strategy.

2.1 Uniformly Convergent Systems

In this section a basic definition and some properties of uniformly convergent systems are given that will be used in the remainder of this paper. For definitions and properties of quadratic or exponential convergency, the interested reader is referred to e.g. (Pavlov et al., 2006).

Consider the following class of systems,

$$\dot{x}(t) = f(x, w(t)) \tag{1}$$

with state $x \in \mathbb{R}^n$ and input $w \in \overline{\mathbb{PC}}_m$. Here, $\overline{\mathbb{PC}}_m$ is the class of bounded piecewise continuous inputs $w(t) : \mathbb{R} \to \mathbb{R}^m$. Furthermore, assume that $f(x,w)$ satisfies some regularity conditions to guarantee the existence of local solutions $x(t,t_0,x_0)$ of system (1) for any input $w \in \overline{\mathbb{PC}}_m$.

Definition 1. System (1) is said to be *uniformly convergent* for a class of inputs $\mathscr{W} \subset \overline{\mathbb{PC}}_m$ if for every input $w(t) \in \mathscr{W}$ there is a solution $\bar{x}(t) = x(t,t_0,\bar{x}_0)$ satisfying the following conditions:

(1) $\bar{x}(t)$ is defined and bounded for all $t \in (-\infty, +\infty)$,
(2) $\bar{x}(t)$ is globally uniformly asymptotically stable for every input $w(t) \in \mathscr{W}$.

Note that *uniformly* in the above definition, refers to uniformity with respect to time, i.e. if a system is uniformly convergent for a class of inputs $\mathscr{W} \subset \overline{\mathbb{PC}}_m$, this implies that for each arbitrary input $w(t) \in \mathscr{W}$ there exists a unique solution $\bar{x}(t)$ which is globally uniformly asymptotically stable (uniformly with respect to time).

The solution $\bar{x}(t)$ is called a *limit solution*. As follows from the above definition, any solution of an uniformly convergent system "forgets" its initial condition and converges to a limit solution which is independent of the initial conditions.

An important advantage of convergent nonlinear systems over general nonlinear system is that for convergent systems performance can be evaluated in almost the same way as for linear systems. Whereas performance evaluation for general nonlinear systems can be difficult due to the possibility of multiple steady-state solutions, convergent systems have a unique limit solution and therefore performance can also be defined in a unique way.

Furthermore, due to the fact that the limit solution of a convergent system only depends on the input and is independent of the initial conditions, *simulation* can be used to determine the limit solution of the system. That is, evaluation of one solution (one arbitrary initial state) suffices, whereas for general nonlinear systems all (i.e. an infinite number of) initial conditions need to be evaluated to obtain a reliable analysis. This means that for convergent systems simulation is a reliable analysis tool.

In Section 3 by the example of yaw aircraft control, it is shown that this approach is also applicable to a class of AW systems with a marginally stable plant.

2.2 Uniform Convergency for Marginally Stable Lur'e Systems with Saturation Nonlinearity

Consider a Lur'e system with saturation nonlinearity as given by the following equations

$$\begin{aligned} \dot{x} &= Ax + B\mathrm{sat}(u) + Fw \\ u &= Cx + Dw \\ y &= Hx \end{aligned} \tag{2}$$

where $x \in \mathbb{R}^n$ is the state, $u \in \mathbb{R}$ is the control input, $w \in \mathbb{R}^m$ is the external input (e.g. reference, disturbance), $y \in \mathbb{R}^p$ is the output, and the saturation function is defined as $\mathrm{sat}(u) = \mathrm{sign}(u)\min(1,|u|)$. Matrix A is marginally stable, i.e. there exists a $P = P^{\mathrm{T}} > 0$ such that $PA + A^{\mathrm{T}}P \leq 0$.

Definition 2. A continuous function $t \mapsto w(t)$, $w(t) \in \mathbb{R}^m$ is said to belong to the class $\mathscr{W}$ if $w(t)$ is bounded and if it satisfies the following conditions

1. $\forall t \in \mathbb{R}$, $Dw(t)$ is uniformly continuous,
2. $\forall t \in \mathbb{R}$, $|F_1 w(t)| \leq \alpha_1 |B_1|$ for some constant $\alpha_1 < 1$.

Theorem 3. ((van den Berg et al., 2009)). If there exists a Lyapunov matrix $P = P^{\mathrm{T}} > 0$ such that

$$PA + A^{\mathrm{T}}P \leq 0 \tag{3}$$

and

$$P(A+BC) + (A+BC)^{\mathrm{T}}P < 0, \tag{4}$$

then for all $w \in \mathscr{W}$ system (2) is uniformly convergent.

Note that if there is a Lyapunov matrix $P = P^{\mathrm{T}} > 0$ such that $PA + A^{\mathrm{T}}P < 0$ (instead of condition (3)) and $P(A+BC) + (A+BC)^{\mathrm{T}}P < 0$ hold, then the corresponding system can be proven to be quadratically convergent. However, the system we consider is marginally stable thus $PA + A^{\mathrm{T}}P < 0$ can not be satisfied.

Remark As follows from the Kalman-Yakubovich-Popov lemma (Brogliato et al., 2007), there exists a positive definite P that satisfies conditions (3), (4) if the following frequency domain inequality

$$\mathrm{Re}\, W(i\omega) < 1 \tag{5}$$

holds for all $\omega \neq 0$ with $W(s) = C(sI - A)^{-1}B$.

2.3 Uniform convergency for anti-windup systems with a marginally stable plant

Consider the system with plant dynamics

$$\begin{aligned} \dot{x}_p &= A_p x_p + B_p(\mathrm{sat}(u) + w_1) \\ y_p &= C_p x_p \end{aligned} \tag{6}$$

where A_p is marginally stable. The controller dynamics are given by

$$\begin{aligned} \dot{x}_c &= A_c x_c + B_c(w_2 - y_p) + k_A(\mathrm{sat}(u) - u) \\ u &= C_c x_c + D_c(w_2 - y_p) \end{aligned} \tag{7}$$

in which k_A is a *static* AW gain.

For the given system the closed-loop dynamics can be written in Lur'e form (2) with $x = [\,x_p,\, x_c\,]^{\mathrm{T}} \in \mathbb{R}^n$, $w = [\,w_1,\, w_2\,]^{\mathrm{T}} \in \mathbb{R}^m$, and

$$A = \begin{bmatrix} A_p & 0 \\ k_A D_c C_p - B_c C_p & A_c - k_A C_c \end{bmatrix},$$

$$B = \begin{bmatrix} B_p \\ k_A \end{bmatrix}, \quad F = \begin{bmatrix} B_p & 0 \\ 0 & B_c - k_A D_c \end{bmatrix},$$

$$C = [-D_c C_p \;\; C_c], \quad D = [0 \;\; D_c], \quad H = [C_p \;\; 0].$$

Theorem 3 can be applied to establish uniform convergency of this system. In Section 3 it is demonstrated for aircraft yaw control problem how the static AW gain k_A can be chosen in such a way that the system is convergent.

3. APPLICATION EXAMPLE. AIRCRAFT YAW CONTROL

Let us apply the convergence-based AW control strategy of Sec. 2 to aircraft yaw control problem.

3.1 Aircraft yaw angle PID-control law with anti-windup

Assume that the high-accuracy azimuth guidance for the time-varying yaw reference signal $\psi^*(t)$ is demanded. To eliminate the steady-state error caused by linearly changing part of $\psi^*(t)$, introduce the integral component in the control signal. This leads to the following PID-control law

$$u(t) = k_D r(t) - k_P \Delta\psi(t) - k_I \int_0^t \Delta\psi(t)\, dt, \tag{8}$$

where $u(t)$ is the control action, $\Delta\psi = \psi^*(t) - \psi(t)$ is the tracking error, $r(t)$, $\psi(t)$ denote the yaw angular rate and the yaw angle, respectively, $\psi^*(t)$ is a yaw reference signal. Parameters k_D, k_P and k_I are, respectively *derivative*, *proportional* and *integral* gains (design parameters). Let the rudder servosystem command signal $u_r(t)$ be bounded due to slideslip and lateral acceleration limitations and mechanical rudder angle restrictions by a certain threshold $\bar{u}_r$, i.e. the following inequality should be fulfilled:

$$-\bar{u}_r \leq u(t) \leq \bar{u}_r \quad \text{for all } t. \tag{9}$$

Inequality (9) introduces a *saturation* in the control loop, which makes system design and analysis more complex and may lead to degradation of the system performance.

The most commonly used and the simplest way to ensure fulfillment of (9), is an implementation of the *saturation* nonlinearity in producing the rudder servosystem command signal δ_r^* as follows:

$$\delta_r^* = \mathrm{sat}_{\bar{u}}(u), \tag{10}$$

where $\mathrm{sat}_{\bar{u}}(u)$ denotes the following saturation function:

$$\mathrm{sat}_{\bar{u}}(u) = \begin{cases} \bar{u} & \text{if } u > \bar{u}, \\ -\bar{u} & \text{if } u < -\bar{u}, \\ u & \text{otherwise.} \end{cases} \tag{11}$$

Equations (8), (10) describe the PID-control law with saturated actuator input (to simplify the exposition we assume that a static gain of the rudder servosystem is equal to one).

The control law (8), (10) does not employ any AW control strategy, which may lead to serious reduce the system performance quality or even to loss of stability due to the windup effect. Let us modify the control law, introducing the AW loop as follows:

$$\begin{aligned} u(t) = k_D r(t) - k_P \Delta\psi(t) - k_I \int_0^t \Delta\psi(t)\, dt \\ - k_A \int_0^t \big(u(t) - \delta_r^*(t)\big)\, dt, \end{aligned} \tag{12}$$

where the AW-gain k_A is a design parameter.

3.2 Model of the aircraft yaw motion dynamics

For a numerical example let us take a linearized model of interrelated lateral (roll-yaw) motion dynamics of the hypothetical aircraft, presented by Bukov and Ryabchenko (2001). Assuming that the roll angle ϕ is stabilized by means of the fast autopilot channel (i.e. that the lateral maneuvering is made in skid-to-turn fashion) consider the isolated yaw motion. Describing the rudder servosystem by the first-order lag model with the time constant $T_r = 0.122$ s, we obtain the following yaw dynamics equations in the state-space form:

$$\dot{x}(t) = Ax(t) + B\delta_r(t) + f(t), \tag{13}$$

where $x(t) = \big[\beta(t), r(t), \psi(t), \delta_r(t)\big]^{\mathrm{T}} \in \mathbb{R}^4$ is the plant state vector, where β denotes the side-slip angle; $r(t)$ is the yaw angular rate, $\psi(t)$ is the yaw angle; $f(t) \in \mathbb{R}^4$ stands for the disturbance vector. The matrices A, B in (13) are following: (Bukov and Ryabchenko, 2001):

$$A = \begin{bmatrix} -0.152 & 0.906 & 0 & -0.032 \\ -1.46 & -0.136 & 0 & -1.76 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & -8.20 \end{bmatrix} \quad B = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 8.20 \end{bmatrix} \tag{14}$$

The corresponding transfer function from the yaw control signal δ_r^* and the yaw angle ψ is as follows:

$$W_{\delta_r^*}^{\psi}(s) = \frac{\psi(s)}{\delta_r^*(s)} = \frac{-12.0(s+0.113)}{s(s+8.2)(s^2+0.288s+1.61)}, \tag{15}$$

where $s \in \mathbb{C}$ denotes the Laplace transform variable.

3.3 Numerical results

Let us consider now the "nominal" (unsaturated) mode, when $\delta_r^*(t) \equiv u(t)$ and the closed-loop system is described by linear equations (8), (13) **(**note that at this mode the anti-windup term $u(t) - \delta_r^*(t)$ in (12) is equal to zero, therefore the output signals of (8) and (12) are equal**)**. Based in the frequency-domain stability criterion for linear system (8), (13) and Nelder-Mead optimization method (Venkataraman, 2001), the following controller (8) gains are obtained: $k_I = 0.56$ s^{-1}, $k_P = 1.0$, $k_D = 2.85$ s. With these gains, the open-loop system transfer function from the input signal of the rudder servosystem δ_r^* to the output signal u of the PID-controller (8) is as follows:

$$W^u_{\delta_r^*}(s) = \frac{u(s)}{\delta_r^*(s)} = \frac{-34.1(s+0.113)(s^2+0.35s+0.20)}{s^2(s+8.2)(s^2+0.288s+1.61)}, \quad (16)$$

the gain margin G_m is infinitely large, the phase margin $\varphi_m = 61$ deg and the H_∞-gain $M = 1.2$.

Let us take into account an effect of saturation in the control loop. The plant is boundary stable and then, the open-loop system with PID-controller is unstable due to presence of zero poles of multiplicity two in (16). Therefore, the frequency domain inequality (5) can not be satisfied and system (8), (10), (13) convergence can not be proved based on Theorem 3. Violation of (5) is demonstrated by the Nyquist plot of $-W(i\omega)$, shown in Fig. (1) (the sign of the transfer function $W(s)$ has been changed to an opposite one since the high frequency gain of (16) is negative). For chosen parameters, (5) is not satisfied for $\omega \in [0, 0.17]$ s^{-1}.

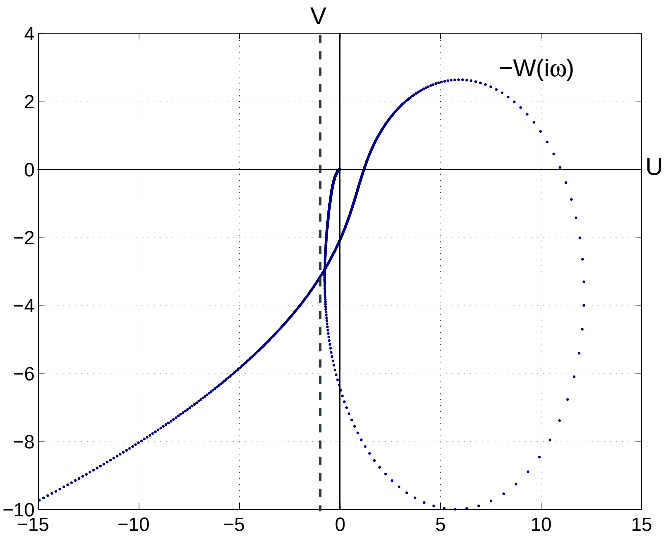

Fig. 1. Nyquist plot for aircraft control system. Control law (8), (10) (no anti-windup).

Consider the system behavior for the case of time-varying reference signal $\psi^*(t)$. Assume that $\psi^*(t)$ is a piecewise linear function (a "triangular waveform"). Such a shape of the reference signal may appear in some surveillance missions of UAVs (Siu et al., 2007). Let δ_r^* be bounded by $\bar{u} = 5$ deg **(**see (10)**)**. The time histories of yaw angle $\psi(t)$, sideslip angle $\beta(t)$ and the yaw reference error $\Delta\psi(t)$ for control law (8), (10) are shown by dash-dot lines in Figs. 3 — 5, demonstrating divergence of system trajectories for some conditions.

Let us apply now the AW control law (12) instead of (8). It was found numerically that (5) is satisfied for $k_A = 1.5$ (and in a

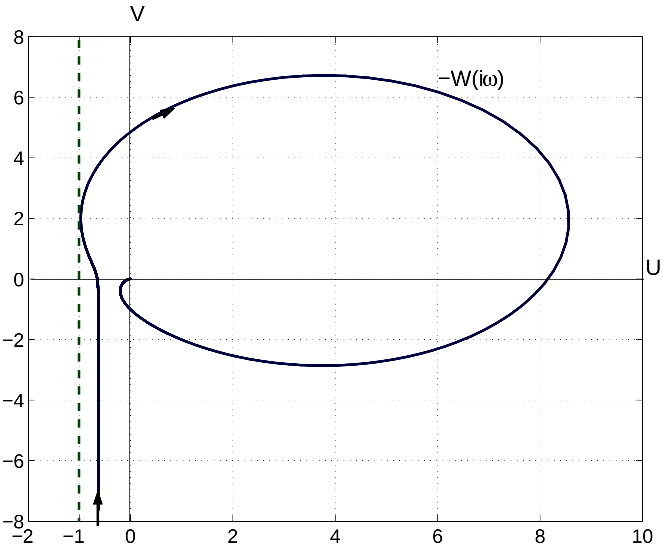

Fig. 2. Nyquist plot for aircraft control system with anti-windup; $k_A = 1.5$.

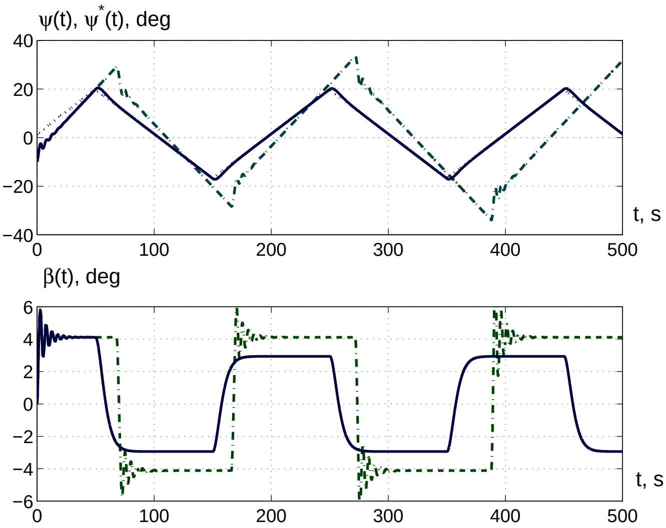

Fig. 3. Yaw angle $\psi(t)$ and sideslip angle $\beta(t)$ time histories. Reference signal $\psi^*(t)$ – dotted line; no anti-windup – dash-dot line; AW control – solid line ($k_A = 1.5$).

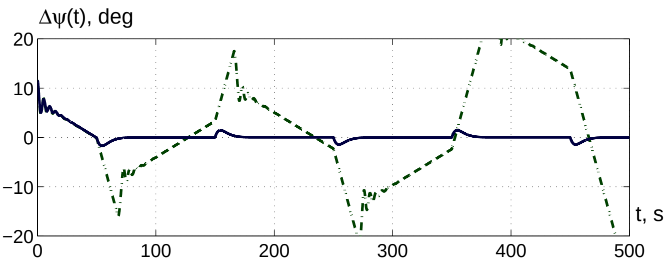

Fig. 4. Yaw reference error $\Delta\psi(t)$ time histories. No anti-windup – dash-dot line; AW control – solid line ($k_A = 1.5$).

certain region about this value), see the Nyquist curve, plotted in Fig. (2). Therefore, based on Theorem 3, the system (12), (10), (13) is convergent. The corresponding time histories are depicted in Figs. 3 — 5 by solid lines.

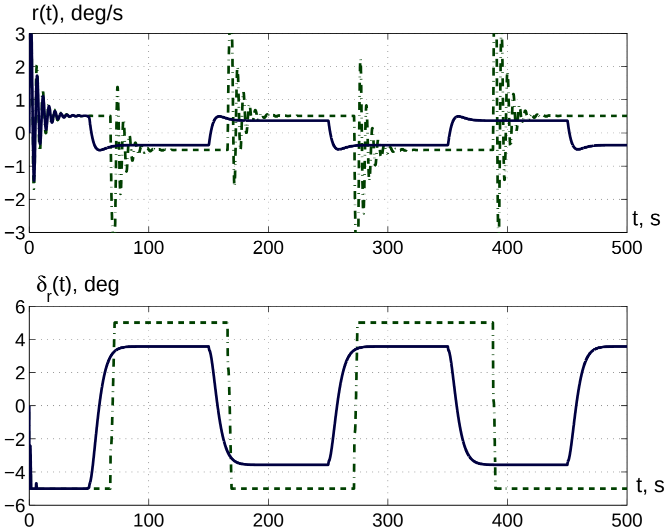

Fig. 5. Yaw angular rate $r(t)$ and rudder angle $\delta_r(t)$ time histories. No anti-windup – dash-dot line; AW control – solid line ($k_A = 1.5$).

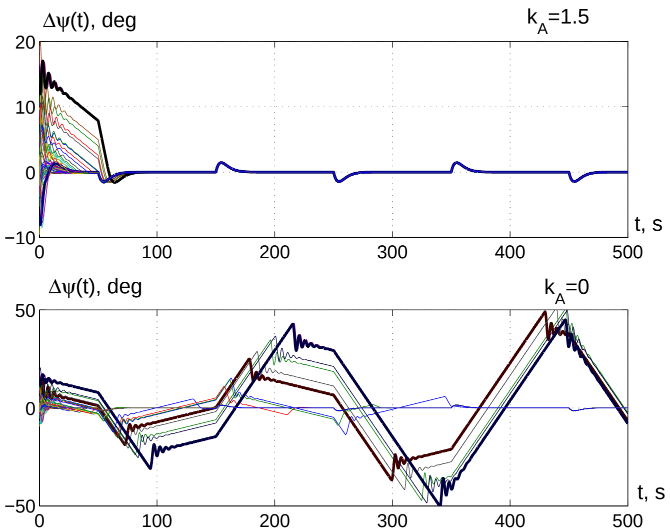

Fig. 6. Yaw reference error $\Delta\psi(t)$ time histories for random initial conditions; $N = 50$.

To illustrate the closed-loop system performance for different initial conditions, the number of $N = 50$ simulation runs for random values of the initial state vector $x(0)$ have been made. The $\Delta\psi$ time histories for (12) and (8) control laws are plotted in Fig. 6. It is demonstrated that AW-controller (12) for a given class of input (reference) signal ψ^*, ensures independence of the system asymptotic trajectories of the initial conditions, whereas non-anti-windup control (8) leads to tracking error divergence for some initial conditions.

4. CONCLUSIONS

In this paper we presented a convergence based anti-windup control of linear marginally stable plants with saturation in control loop. An LMI-based condition for convergency is derived and applied for an example of aircraft yaw control. The performance of the anti-windup controller was analyzed via computer simulation. It follows from the computer simulation that without AW compensation the performance of the closed loop system can be unsatisfactory, while the system with AW compensation performs reasonably well.

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