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Convergence-based Analysis of Robustness to Delay in Anti-windup Loop of Aircraft Autopilot ⋆

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Abstract: The windup phenomenon is interpreted as a consequence of the convergent property absence for system with a saturation. This makes it possible to use the frequency-domain criterion for analysis of anti-windup augmentation in the case of stable and marginally stable plants. Based on this approach, robustness of the systems with respect to time delay in the anti-windup loop is examined and the approach for an optimal choice of the static anti-windup gain is proposed. An application of the convergence-based anti-windup control strategy to aircraft flight control for the case of time-delay in the anti-windup loop is described and studied by simulations.

Keywords: integrator windup, flight control, anti-windup correction, convergent systems

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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. The windup phenomenon is described, and the state-of-an-art of the AW design methods are comprehensively reported in (Glattfelder and Schaufelberger, 2003; Hippe, 2006; Tarbouriech and Turner, 2009; Galeani et al., 2009; Tarbouriech et al., 2011). Let us briefly outline the latest results in the field of AW methods and their applications to control of aircrafts.

The closed-loop quadratic stability and L_2 performance properties of linear control systems subject to input saturation is considered by Grimm et al. (2003). These properties are examined within the context of the linear AW augmentation paradigm, which refers to designing a linear filter to augment a linear control system subject to a local specification, called the "unconstrained closed-loop behavior". It is shown that, iff the plant is asymptotically stable, plant-order linear AW compensation is always feasible for large enough $\mathcal{L}_2$ gain and that there exists static AW compensation provided a quasi-common Lyapunov function between the open-loop and unconstrained closed-loop.

Zaccarian and Teel (2004) give a linear matrix ineqaulity (LMI) formulation of high-performance AW design for control systems with linear asymptotically stable plants. Sofrony et al. (2006) demonstrated the application of an AW technique for systems with rate-saturated actuators to a realistic flight control example.

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 flight testing results are also presented in (Menon et al., 2013), where a nonlinear AW compensation scheme by Herrmann et al. (2010) is implemented and tested on a 1/16 scaled *BAE Hawk* jet trainer wind-tunnel model. Two types of nonlinear antiwindup schemes were applyied: a nonlinear variant of the internal model control scheme and a suboptimal L_2 norm-based AW compensator.

The problem of static AW strategy for flight control system of linear unstable aircraft with saturated actuator was considered in (Queinnec et al., 2006). The 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. Multivariable nonlinear systems subject to actuator saturation are considered by da Silva et al. (2014), who proposed a method to compute a static AW gain which ensures regional stability for the closed-loop system assuming that a dynamic output feedback controller is previously designed to stabilize the nonlinear system. The control saturation effects are taken into account by the

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application of a generalized sector bound condition. The LMI-based conditions are found to compute an AW gain to enlarge the closed-loop region of attraction.

Herrmann et al. (2006) formulated the AW problem in discrete time using a configuration which effectively decouples the nominal linear and nonlinear parts of a closed loop system with constrained plant inputs. An example of control of the unstable aircraft along the longitudinal axis is demonstrated. In the recent work, Turner and Herrmann (2014) have found a more general set of sector-like matrix inequalities by introducing an additional non-square operator which exploits connectivity of two connected deadzone nonlinearities.

AW compensation in the framework of the adaptive control problem is considered by Kahveci and Ioannou (2013), where an adaptive steering control design for uncertain ship dynamics subject to input constraints is presented. An adaptation law is combined in (Kahveci and Ioannou, 2013) with a Linear Quadratic (LQ) controller and a Riccati based AW compensator using Certainty Equivalence Principle for asymptotically stable plants with saturation limits imposed on the control input.

An uncommon approach for AW design, based on the theory of Quasi-linear Control (QLC), is presented by Kabamba et al. (2013). Their development includes introducing a precompensator, which observes given step tracking specifications, and recasting the output of the precompensator into a random reference bandwidth requirement. Unlike commonly used techniques, this approach supposes taking the saturation into account directly at the initial stage of the design and does not require AW augmentations.

An approach to use delaying the activation of the AW mechanism, until the saturation reaches a certain level of severity, as a way for enhancement performance of the closed-loop system is considered by Lin and Wu (2011); Wu and Lin (2014). The authors stated that further improvements can be obtained by activating a static anti-windup mechanism in anticipation of actuator saturation, instead of immediate or delayed activation. Delay-dependent stability of reset control systems is considered by Banos and Barreiro (2007). Using a set of LMIs and passivity properties the authors obtained the stability conditions, which guarantee that the reset action does not destabilize the base LTI system. Stability analysis of linear systems with state delay and input saturation is also given by Cao et al. (2002). The domain of attraction resulting from an a priori designed state feedback law is analyzed in (Cao et al., 2002) using Lyapunov-Razumikhin and Lyapunov-Krasovskii functional approach. Both delay-independent and delay-dependent estimation of the domain of attraction are presented using the linear matrix inequality technique.

A method for enlargement of domain of stability of an actuator constrained state time-delay system with a dynamic two controller AW-design is proposed by Ahmed et al. (2013). The design is based on a controller-modeled actuator saturation-controller-plant topology. Anti-windup gains for two separate controllers are computed by LMIs through delay independent and delay dependant Lyapunov-Krasovskii functionals, ensuring closed-loop asymptotic stability. Anti-windup augmentation for systems with delays is also discussed in monograph (Tarbouriech et al., 2011).

In the majority of papers solution to the AW problem is understood as achievement of global asymptotic stability of the origin for autonomous saturated system and bounddness of closed-loop trajectories and "smallness" of the $\mathcal{L}_2$ gain between input and output for the non-autonomous case (Grimm et al., 2003; da Silva and Tarbouriech, 2005; Tarbouriech et al., 2011).

The less commonly used approach, adopted in the present work, is based on the concept of the *convergence* property, given by Demidovich (1961). For asymptotically stable linear systems excited by inputs, convergence is a natural property. Indeed, due to linearity of the system, every solution is globally asymptotically stable and, therefore, all solutions of such a system forget their initial conditions and converge to each other. After transients, the dynamics of the system are determined only by the input. For nonlinear systems, in general, global asymptotic stability of a system with the zero input does not guarantee that all solutions of this system with a non-zero input "forget" their initial conditions and converge to each other, see (Pavlov et al., 2007) for details. An application of this approach to the windup analysis and AW augmentation technique was proposed by Pogromsky and van den Berg, see (van den Berg, 2008; van den Berg et al., 2006; van den Bremer et al., 2008). The example, demonstrated insufficiency of the global asymptotical stability of the system free motion to stability of its forced motion is presented in (van den Berg et al., 2006), where the second order system with a saturation nonlinearity is examined. This system satisfies the Popov criterion and, therefore, its free motion is globally asymptotically stable. At the same time, if the system is subjected to the harmonic excitation with a sufficiently large amplitude, the forced oscillations stability may depend on the reference input and, also, different periodic solutions may co-exist for the same reference input. The similar results are provided in (Pogromsky et al., 2009; Leonov et al., 2012; Andrievsky et al., 2012) for an aircraft control problem. It should be noticed that for all the mentioned systems, absence of the convergency is a result of the integrator windup in the PI- PID-controller of the feedback loop of the marginally stable plant with saturated input. This gives birth to an idea suppressing the windup effect by means of ensuring the closed-loop system convergency. The last property, in its turn, may be verified with the help of the frequency-domain condition by Pavlov et al. (2004).

The present paper gives the application example of this approach to robustness analysis of the aircraft control with respect to the time delay in the AW loop, cf. (Biannic and Tarbouriech, 2009).

The rest of paper is organized as follows. Convergence-based AW control strategy of (Pavlov et al., 2004; van den Berg et al., 2006; Pavlov et al., 2006; van den Bremer et al., 2008) is briefly recalled in Section 2. An application example for aircraft yaw control with time delay in the AW loop is presented in Section 3. Concluding remarks and the future works intensions are given in 4.