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CONTROL THEORY

Aircraft Control with Anti-Windup Compensation

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Abstract—We consider an anti-windup compensation method ensuring the convergence of the closed-loop system for a class of reference signals. An application of the method to an aircraft flight control problem is shown.

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1. INTRODUCTION

Under external disturbances, the aircraft control system may, in addition to the desired stable solution corresponding to the desired flight, produce other stable and unstable solutions corresponding to undesired dangerous behavior of the aircraft. In addition, the desired solution may lose its stability for large amplitudes of the input signal, which may lead to catastrophic consequences [1].

There were a number of aircraft crashes caused by incorrect control algorithm synthesis, including the crash of the American advanced fighter *YF*-22 Raptor (manufactured by Lockheed Martin/Boeing), which crashed when landing at the Edwards air base in April 1992 [2], and the Swedish fighter *JAS*39 Gripen (manufactured by SAAB) [3]. These catastrophes were caused by incorrect control algorithm synthesis, which was carried out without concerning saturation type nonlinearities, whose influence can result in so-called *pilot induced oscillations* deranging the pilotage [4]. In these crashes, the *pitch flatter* effect was observed during landing (i.e., there occurred pitching oscillations with increasing amplitude).

Note that so-called *hidden oscillations* (whose attraction domain does not intersect with small neighborhoods of equilibria) [5–9], which arise in such systems, dramatically complicate numerical analysis and can lead to erroneous conclusions: "*Since stability in simulations does not imply stability of the physical control system* (*an example is the crash of the YF22*) *stronger theoretical understanding is required*" [10].

There are also well-known cases in which spacecraft entered uncontrolled rotation [11, 12]. The study of transient modes for such damping necessitates developing a mathematical theory of global analysis of attitude systems. The demand for such a theory was indicated by Academician B.V. Raushenbakh, who noted that it is difficult to control a spacecraft during rapid turns.

Undesired situations can be depicted most visually for the case in which a system describes a plant in the form of a "pure" integrator with input saturation closed with a PID negative feedback. Here the control error is integrated by the controller, but for large mismatches, it cannot be counteracted because of saturation. This leads to onset of oscillation processes in the system, which correspond to maximum possible input amplitudes for the plant (integrator). In the literature, this phenomenon has been dubbed *windup*. Accordingly, measures for counteracting this phenomenon by introducing additional feedbacks and/or compensators are known as *anti-windup*.

Recall that Keldysh [13] developed mathematical methods for the analysis of various flatter damping systems used in aircraft in the 1940. In the present paper, we develop and modify Keldysh's methods for anti-windup compensation problems.

The present paper is organized as follows. A brief survey of publications on anti-windup compensation methods is given in Section 2. In Section 3, we present general information on convergent systems and describe the possibility of application of the harmonic balance method for their investigation. An anti-windup compensation method based on the convergence property for neutrally stable plants is described in Section 4. Section 5 deals with its application to the control of the aircraft yaw angle. Concluding remarks are given in Section 6.

2. ANTI-WINDUP COMPENSATION METHODS

Earlier methods for preventing integrator excitation (*anti-windup* compensation) were mainly heuristic and lacked mathematical rigor. Surveys of these methods can be found in [14, 15], and the references are given in [16]. The modern state of anti-windup compensation methods is reflected in the monographs [17, 18] and the survey [19].

It was noted in [20] that controller synthesis under control constraints can be carried out on the basis of optimal (for example, time- or energy-optimal) control methods [21, 22]. However, even if such solutions, which lead to a bang-bang (discontinuous) control, can sometimes be specified in a feedback form in principle, the implementation of these methods encounters substantial computational difficulties even for the simplest systems. Therefore, optimal solutions of this kind are not used in most applications; instead, a "nominal" linear controller is synthesized under the no-saturation assumption, and some compensation signal is introduced in it as the saturation becomes "active."

One of the first attempts at the theoretical justification of existing methods for damping the integrator excitation in the controller in the case of control saturation was suggested in [23], where the abbreviation ARW (*antireset-windup*) was used, because the integral component in PI- and PID-controllers is sometimes referred to as the *reset component* in engineering publications. It was noted in that paper that, by then, the main idea of how to suppress the integrator excitation was to constrain the output signal of the linear controller by using additional feedbacks so as to ensure that the constrained variable (for example, the actuator rod displacement signal) stays within a given range. Nonlinear adders, multipliers, or selectors of minimum and maximum values were used for this purpose in early papers. Despite the broad and fruitful use of such structures in practice, the analysis of properties of the closed-loop system was clearly insufficient from the theoretical viewpoint, leaving space for intuition, designers' experience, modeling, and tweaking adjustment methods. The following problem was aimed at in [23] : use methods of the theory of nonlinear systems to prove the robustness of the system with antireset-windup suggested in [24] in comparison with a nominal linear system in the case of a scalar control.

Anti-windup compensation was studied in [25] for systems with a cascade (two-loop) discrete controller in which constraints are imposed on the magnitude of the control signal produced by the external loop PI-controller (for example, a constraint on the current in the winding of a motor in a velocity control system). It was noted that, as a result of discretization, large values of the compensating feedback factor leads to stability loss. The stability analysis carried out in [25] is based on the Popov criterion for discrete systems [26–28]. A numerical example of a control system with a first-order inertial plant was considered there.

It was suggested in [29] to use an antireset-windup method for systems with several actuators that have saturation, and with a vector control formed by a control law with an integral component. The nonlinear blocks in actuators are assumed to be described by memoryless (static) nonlinearities with upper and lower boundary values that define the saturation levels. Within this range, the outputs of the nonlinear blocks coincide with the input signals. In this antireset-windup scheme, the integrators in the controller are embraced by simple nonlinear insensitivity feedbacks: if the output signal of some integrator lies in the admissible range, then the compensating feedback signal is zero; if the output signal is outside this range, then there appears a negative feedback signal proportional to the output of the integrator. Therefore, for each component of the control, the system acquires the Lur'e form with two nonlinear blocks that have a common input. (The output of the linear part of the system is the output of the integrator unit of the controller.) The linear part of the system has two inputs; one is the control itself (the output of the unit with saturation), and the other is the output of the nonlinear compensating feedback unit. In addition, the system is subjected to a reference signal formed outside the feedback.

A systematic technique for synthesizing cross-coupled (multi-inputs–multi-output) systems for asymptotically stable plants (if the integral occurs in the control law, then the asymptotic stability means that the linear part of the system is neutrally stable) was presented in [20] in the case of several saturation units. It was noted in this paper that, for the case of a vector control, saturation may lead not only to integrator windup but also to a change in the direction of the vector control signal, which also results in a system operation failure. The method suggested in [20] is based on the introduction of a supervising feedback such that if the reference signal and the disturbance are sufficiently small, then the control system operates as a “nominal” linear system (synthesized without regard of saturation). In the case of relatively large inputs leading to saturation, the control law is modified so as to ensure stability and, if possible, preserve the characteristics of the nominal linear system. To solve the posed problem, it was suggested in [20] to augment the error signal loop with an *Error Governor* ensuring that, as far as possible, the control signal does not reach saturation for any reference signals and disturbances. One example considered in [20] is the control of longitudinal motion of the *F8* aircraft.

Apparently, the paper [30] was the first to study the combined influence of control signal magnitude and rate saturations. Just as in [20], a systematic technique for synthesizing controllers ensuring the stability and admissible behavior of the closed-loop system was suggested in [30] for cross-coupled linear systems neutrally stable as open-loop systems.

Anti-windup compensation methods with *anti-windup bumpless transfer* were suggested in [31, 32]; in these methods, the nonlinearities in the input signal are taken into account by implementing the following two-step synthesis procedure: first, one designs a linear controller without concerning the nonlinearities at the input of the plant, and then one introduces an anti-windup bumpless transfer correction so as to minimize the harmful influence of the input nonlinearities to the behavior of the closed-loop system. Thus, standard controllers developed for constraint-free systems are adjusted to the constraints. Controller synthesis is based on the *passivity* conception [33] and the *multiplier theory* [34, 35]. For an appropriate choice of multipliers, sufficient stability conditions are reduced to equivalent linear matrix inequalities (LMI). Sector nonlinearities, especially *saturation type nonlinearities*, are considered in the paper. It is noted that if there is a known bound for the signal fed to the input of the nonlinearity, then one can obtain less conservative conditions by shrinking the sector considered.

The windup problem, which arises for manual piloting of an open-loop unstable aircraft if there are constraints on the control surface deflection and slew rate, was considered in [36], where one solution was suggested and compared with the optimal solution. A short-periodic longitudinal motion of a tailless aircraft was considered in [37] for arbitrary trim flying conditions. It was shown that the suggested anti-windup compensator admits more aggressively maneuvering than the one provided by the standard *command limiting*. The suggested compensation mechanism guarantees the stability of the piloted aircraft for arbitrary control commands of the pilot and ensures the desired flight performance characteristics to the extent to which they are possible under the given control constraints.

In [38], the authors considered an anti-windup compensation mechanism for linear time-invariant systems in the case of nonlinear constraints on the control surface deflection and slew rate. A procedure for synthesizing a convex anti-windup control was developed on the basis of an extended version of the circle criterion for linear fractional transformation (LFT) systems, that is, the class of linear time-dependent systems with *fractional* dependence of the parameters. The compensator equations were obtained in closed form, which simplified the implementation. The efficiency of the suggested control method was demonstrated for the linearized model of the aircraft *F*-8 in [20]. An anti-windup compensation method was suggested in [39] for the case of actuator rate limitation, and a compensator adjustment algorithm was developed to achieve a trade-off between the control performance and the size of the estimated attraction domain of the stable mode. The application of the method was demonstrated for a realistic example of a flight control system for a nonlinear model of a longitudinal and transverse motion of the experimental aircraft *ATTAS* (Advanced Technology Testing Aircraft) used by the German Aerospace Center (Deutsche Zentrum für Luft und Raumfahrt, DLR). The possibility of the use of anti-windup compensation to diminish the sensitivity of aircraft to pilot-induced oscillations (PIO) was illustrated. The results of the research were later justified in a number of test flights. The synthesis and analysis were performed in [40], and the results of test flights for the experimental aircraft *ATTAS* obtained by the German Aerospace Center were represented. Further results can be found in [41], where a comparative analysis of dynamic anti-windup compensators of diminished order was performed to estimate the value of various design parameters. The static anti-windup compensation problem for linear unstable aircraft in the case of saturation in the control loop was considered in [42]. Standard approaches based on Lyapunov functions, the *S*-procedure, and nonlinearities with sector constraints were used. The suggested approach was analyzed from the viewpoint of enlarging the domain of safe initial conditions for which the stability of the closed-loop system can be guaranteed.

A robust anti-windup compensation scheme was suggested in [43] to improve the aircraft lateral control performance, and its efficiency was demonstrated. The problem of the synthesis of an anti-windup controller that takes into account the trade-off between the control performance in the presence and absence of an the actuator saturation nonlinearity was considered in [44]. The results were used for the bank control for the *F*8 aircraft. The case of large parametric uncertainty in an aircraft model with actuator saturation was analyzed in [45, 46]. The authors suggested a robust adaptive linear-quadratic synthesis of a control law with adaptive anti-windup compensation for counteracting the changes in the aircraft parameters in the course of time. It was shown that the airframe follows the trajectory formed by the navigation algorithm despite the presence of large parametric uncertainties. The anti-windup compensation problem was considered in [47] in discrete time. These results were used for a model control problem for a promising fighter in [48]. A procedure for synthesizing anti-windup compensation for linear systems described by regular transfer functions was suggested in [49] for magnitude and rate constraints in the actuators. Using generalized sector conditions and *linear matrix inequalities* (LMI), the authors suggested a procedure for finding the anti-windup compensator gain ensuring stability for given initial conditions. This approach was illustrated by an example of control of the longitudinal motion of the *F*8 fighter in the longitudinal channel. An anti-windup compensation procedure was suggested in [50] on the basis of the response of a nonlinear system with saturation type nonlinearity to a step input. This procedure was used in the control problem for the longitudinal motion of the *M*-2000 aircraft. The approach was further developed in [51, 52] to ensure the fastest offset-free tracking of the desired angle of attack with high control performance. For dead-band nonlinearities, the papers [53, 54] suggest a solution of the anti-windup compensation problem with the use of a modified sector condition on the basis of LMI for constructing dynamic compensators of full and reduced order.

In numerous publications, the anti-windup compensation problem is stated as the problem of providing the global asymptotic stability of the equilibrium of a system in the absence of external disturbances. This approach is fundamentally wrong and dangerous in applications. The paper [55] provides an example of a second-order system with a saturation type nonlinearity that satisfies the critical case of the Popov criterion and hence is globally asymptotically stable in the absence of external disturbances. The same system subjected to an external (periodic) disturbance may have a multitude of periodic modes, while the desired low-amplitude mode may lose stability. Similar results for an aircraft course control system can be found in [56]. This observation shows that one needs a sound and rigorous mathematical definition of the anti-windup compensation synthesis problem.

3. CONVERGENT SYSTEMS AND THE HARMONIC BALANCE METHOD

3.1. Statement of the Problem of Anti-Windup Compensation

As is seen from the survey part of the present paper, nowadays there is no unified generally accepted approach to the description of the problem; numerous authors suggest their own definitions and the corresponding solution methods. Let us use a simplified example to outline an alternative approach to the description of the problem.

Let us consider a control system in which the loop error signal is formed as the difference between the reference signal and the plant (integrator) output. The loop error signal is fed to the input of a linear PI (proportionally integrating) controller and then to the plant input via a saturation type nonlinearity. By using the Popov criterion, one can readily show that, for zero reference signal, the closed-loop system is globally asymptotically stable if the coefficients of the PI-controller are positive. At the same time, for a harmonic reference signal, one can use the harmonic linearization

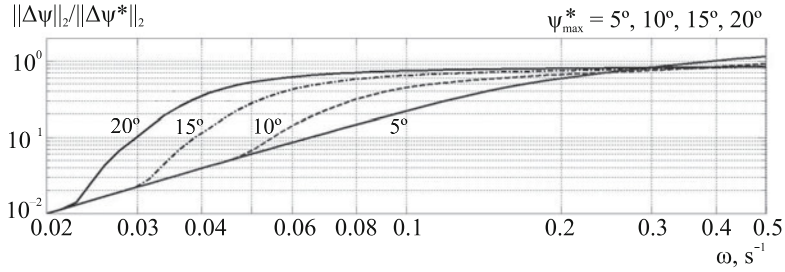

Fig. 12. The sensitivity function $\mathcal{S}(\psi^*_{\max}, \omega) = \|\Delta\psi\|_2/\|\psi^*\|_2$ for the control law (21), (26) with $k_A = 2$ and with $\psi^*_{\max} = 5° \div 25°$.

(see Fig. 5), there is no hysteresis, and, in addition, the amplitudes of the control signals and the tracking error in yawing lie in the range of practical requirements.

The graphs of the functions $\psi(t)$ and $u(t)$ obtained for $\psi^*(t) = \psi^*_0 + \psi^*_{\max}\sin(\Omega t)$, $\psi^*_0 = 11°$, $\psi^*_{\max} = 25°$, and $\Omega = 0.01$ s^{-1} and for the initial values $\psi(0) \in [-40°, 40°]$ are shown in Fig. 11. The figures demonstrate the coincidence of the steady-state processes in the aircraft control system for a given command input.

Since the aircraft control system with the anti-windup compensation (21), (26) is convergent for $k_A = 2$, it follows from Section 3.2 that one can compute the sensitivity function $\mathcal{S}(\psi^*_{\max}, \omega)$, which specifies the accuracy of tracking of the harmonic input depending on its frequency and amplitude. The graph of $\mathcal{S}(\psi^*_{\max}, \omega)$ for the considered system is shown in Fig. 12.

6. CONCLUSION

The present paper dealt with control problems in the case of a nonlinear effect of saturation of the control signal, which leads to the appearance of undesired oscillatory modes in systems with isodromic governor. We have reviewed publications on anti-windup compensation methods. We have suggested an anti-windup compensation method ensuring the convergence of the closed-loop system for reference signals of a specific class in the case of neutrally stable plants.

We illustrate the application of the method to the control problem for the flight of an aircraft. The results of modeling of aircraft control systems have been represented for various forms of controllers, and the accuracy of the suggested algorithms has been analyzed on the basis of the harmonic balance method for conservative systems. We have demonstrated the application of the developed analytic-numerical methods to the analysis of undesired oscillatory modes in control systems with saturation. We have modelled aircraft control systems for large amplitudes of the reference signal and the effect of saturation of nonlinear control elements.

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