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Vibration control subjected to windup problem: An applied view on analysis and synthesis with convex formulation

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ABSTRACT

In this paper, the windup problem in active vibration control (AVC) is studied systematically. Instead of evaluating the performance of several anti-windup compensators implemented on independent abstract simulation problems, a unified benchmark setup in active-damping control (ADC) is used. The investigated anti-windup schemes (analysis and synthesis) are adapted to the disturbance rejection control. Large attention is given to capture the similarities and differences of the methods in dealing with the windup event in a practical context. Therefore, instead of categorizing the methods into static and non-static methods or model recovery and direct linear anti-windup schemes, a logical route is followed to highlight the significance of each method. The mathematical interpretations of the methods are provided for the vibration engineer while delivering forthright implementation algorithms for AVC. The tackled methods are unified on a state space model obtained from the frequency-domain subspace system identification approach. Practical issues that may raise for each technique are mentioned, and detained guidelines are provided for tuning each algorithm. Finally, in order to compare the compensated system's performance, comprehensive time-domain studies are carried out by separating the transient response of the compensated systems to three modes: linear mode, where the actuation nonlinearity is inactive; the nonlinear mode, where the windup event is in progress, and finally, the output mismatch rejection mode, where the windup incident is over, but performance degradation is still present.

1. Introduction

In the recent years, due to increasing prominences of the flexible manipulators over the bulky rigid ones in terms of less material usage, cost-effectiveness, lightweightedness, and small actuators requirements, they have been employed in the industrial setups such as microsurgical robots, decontamination manipulators in nuclear sites, and aerospace applications (Buckingham, 2006; Pereira, Becedas, Payo, Ramos, & Feliu, 2010). The International Space Station (ISS) and German Aerospace Center (DLR) have both launched some projects in dealing with dynamic analysis and control of these structures such as Canadarm2, European Robotic Arm (Hirano et al., 2013). Although, mostly the manipulators in these case studies are manufactured from carbon fiber composite materials, because of their beam-like geometries resultant vibrations in the arm-tip are unavoidable. Therefore, such modern structural configurations demand features such as self-adaptation in various dynamical maneuvers that may add to the robustness of their behavior. In this perspective, this paper deals with end-effector regulation problem with constraint-time rest-to-rest motion performance index (Benosman & Le Vey, 2004). It should be noted that the simplistic geometry of these structures should not overshadow the intrinsic practical issues of control design such as non-minimum phase problem of non-collocated configuration and geometrically nonlinear dynamics (Kerschen, Lenaerts, & Golinval, 2003; Qiu, Han, Zhang, Wang, & Wu, 2009). Due to the flexibility of these manipulators, sensitive multi-domain transducers are essential especially if they can be bonded to the host structure (Hasheminejad & Oveisi, 2016; Oveisi & Nestorović, 2016b). Such composite mechanical systems, also referred to as smart structures, became active to reject the environmental stimuli that may affect their performance. For this purpose, piezoelectric patches are the primary transducers which couple the deformation and the electric charge (Nezami & Gholami, 2015; Omidi, Mahmoodi, & Shepard, 2015).

In the context of smart structures, it may often occur that the difference between the designed controller's output signal and actual implemented control signal on the system is nonzero. Other than the fragility of the control system due to the finite-word-length in the digital system and round-off errors in binary arithmetics (Oveisi & Nestorovic, 2016), which are mostly permanent, two foremost temporary sources of such imperfections are actuation constraints and control law substitutions. Calamitous influence of substitution appears when in a multi-mode controller each of the modes is responsible for a neighborhood around a distinct linear operating point and repetitive changes between

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the modes are needed. The offline behavior of switching while the controller is in an online loop introduces overshoot and eventually windup. Although, in the case of substitution, a smooth transition between the controller modes may compensate for the mismatch control law, detailed mathematical treatment of this problem is not discussed in this paper. This is justified by considering the application of smart structures in active vibration control (AVC) where the system model is mostly linearized around a single operating point. However, the actuator nonlinearities such as saturation and hysteresis may play key roles in driving the system states to non-ideal trajectories. Saturation, as a constraint on the amplitude of the control signal, is defined by a particular limit that is eligible to be applied to the active elements. This limit includes the output voltage and electrical current range of a piezo-amplifier, the maximum achievable displacement of a shaker's baffle, and the depolarization voltage of the piezo-actuator patches. A good deal of control systems in vibrating smart structures use an oversimplified linear model neglecting these nonlinearities. In addition, it is well-established that controllers with sluggish or unstable dynamics eventually suffer from the windup. A bumpless transition in such a case is realizable by compensating the controller input, states, and outputs by means of various anti-windup strategies. In this regards, we intentionally employ a standard approach for the nominal control design so that the main goal, namely unification and comparison of the second step in the decoupled *anti-windup compensator technology* is not overshadowed by the nominal controller. A typical windup scenario in active vibration control appears when the observer-based controller experiences actuator saturation in which the integrated linear state observer is unaware of the actuator nonlinearity chopping off the control signal. A windup in linear controller's output may happen in this case leading to diverging system output which is catastrophic in the range of space applications.

The subject of decoupled anti-windup analysis and synthesis has reached to a mature level. As a result, this paper by no means is aimed at summarizing the vast well-documented methods on anti-windup compensation. Such an attempt for an applied problem is critical since it may leave out some valuable contributions from the leading scholars on the topic. Instead, the paper is intended to establish a connection between a handful of reliable compensator methods available in the literature and the practical implementation of these methods for the end-effector regulation problem of manipulators with saturated actuators. It should be pointed out that the selected application may be replaced by other plants that are vulnerable w.r.t. actuation nonlinearities such as controlling the flow of gas by positioning of electromechanical actuators on engine throttle which saturates after a certain angle (Thiel, Schwarzmann, Schultalbers, & Jeinsch, 2016). Especial effort is given for formulating the analysis and synthesis of 'posteriori' algorithms based on convex optimization such as linear matrix inequality (LMI) eigenvalue problem which is a convex minimization subjected to LMI constraints. Additionally, the selected algorithms are mostly based on the stability analysis of Lyapunov-type. The reason behind this perception is that the absolute stability schemes e.g. Circle criterion and Popov stability theorem are mostly limited to single loop systems (Wu & Jayasuriya, 2001).

It should be noted that the well-known 'priory' strategies based on model predictive control (MPC) that incorporate the hard constraints such as limitations on control effort (amplitude and rate) in synthesis procedure are not studied in this paper. Such methods in contrast to the two-step paradigm of this paper are computationally expensive due to the online optimization and are less flexible in terms of linear unconstrained controller synthesis (Oveisi, Hosseini-Pishrobat, Nestorović, & Keighobadi, 2018). The latter is because of often conflicting conditions imposed on control system even before the actuation nonlinearity event. Therefore, knowing that the actuator nonlinearities in real industrial applications are presumed to be seldom to happen in the nominal operational range and fast to be over, the two-step anti-windup paradigm seems to be more suitable in comparison to MPC. In other words, the two-step anti-windup paradigm preserves the ideal controller's performance and only compensates the actual control law during (and shortly after) the actuator nonlinearity event. Accordingly, in this paper, the methods for analysis and synthesis of anti-windup mechanisms in the modern sense are briefly overviewed in a relatively broad manner to provide constructive tools developed as the typical embodiment of anti-windup augmentation. Instead of extensive literature review, the authors summarized their observations in accordance with implementing different anti-windup scenarios in a practical manner while directing the interested reader to the relevant fundamental approaches. Authors are well-aware of the extended strategies published in recent years that may serve as attractive frameworks for saturated delayed systems, systems with sampled output, systems with matched and mismatched uncertainties, systems with non-exponentially stable plants, and their discrete counterparts. However, due to the nature of discussed application, these methods are mostly out of the scope of this paper. Additionally, methods that are tailored particularly for PID controllers or for single-input-single-output (SISO) systems are not covered in the more general scope of this paper. However, the main thrust of this research is to unify the available tools in the literature together with highlighting the practical tuning considerations.

In the rest of the paper, the script symbol $\mathcal{I}_n$ stands for identity matrix such that $\mathcal{I}_n \in \mathbb{R}^{n\times n}$ with $\mathbb{R}$ being the set of real-valued numbers. When n is not given, it is intended that identity matrix has an appropriate dimension in relation to the multiplied and added matrices in the related equations. A similar definition applies for $0_n \in \mathbb{R}^{n\times n}$ and 0, respectively. Additionally, $\mathbb{R}^{n}_{\geq 0}$, $\mathbb{R}^{n\times n}_{\geq 0}$, and ${}^{+}\mathbb{R}^{n\times n}_{\geq 0}$ represent the space of time-dependent vectors, matrices, and positive definite matrices with dimensions of $n \times 1$, $n \times n$, and $n \times n$ for $t \geq 0$, respectively. Superscript T on vectors and matrices denotes the transpose operator while A^{-1} represents the inverse of a nonsingular matrix A. The system in state-space form is represented by $ss(A, B, C, D)$ following the conventional form of definition for state matrix A, input matrix B, output matrix C, and feedthrough term D. In the context of linear matrix inequalities, for two square Hermitian matrices with the same dimensions, $A > B$ $(A \geq B)$ means that $A - B$ is positive (semi-) definite. The symbols $\prec, \preccurlyeq$ and $\succ, \succcurlyeq$ are element-wise inequality operators. $\mathbb{L}_2$ is Hilbert space of m-vector-valued arrays such as x and y on $\left(-\infty \quad \infty\right)$ with scalar product $\langle x|y\rangle = \int_{-\infty}^{\infty} x^{cc} y \mathrm{d}t$ (x^{cc} is the complex conjugate of x). $x \in \mathbb{L}_2$ if $\|x\|_2 \overset{\text{def}}{=} \langle x|x\rangle^{1/2}$ is bounded. $\mathbb{L}_{2e}$ is assumed as an extension of $\mathbb{L}_2$ that for any $x \in \mathbb{L}_{2e}$, we also have $x \in \mathbb{L}_2$ and $\forall t > \mathrm{T}$: $x = 0$. $\mathbb{H}_\infty$ is the Hardy space of bounded analytical functions with $\mathbb{H}_\infty$-norm defined as $\|x\|_\infty \overset{\text{def}}{=} \sup_{\omega\in\mathbb{R}} \bar{\sigma}\left(G\left(j\omega\right)\right)$ with $\bar{\sigma}\left(.\right)$ signifying the maximum singular value of the system over frequency ω. A dead zone is defined as $\mathrm{dz}\left(u\right) = u - \mathrm{sat}\left(u\right)$ for saturation function $\mathrm{sat}\left(u\right)$ defined as

$$\mathrm{sat}\left(u_i\right) = \begin{cases} u_{i,\min} & \text{if} \quad u_i < u_{i,\min}, \\ u_i & \text{if} \quad u_{i,\max} \geq u_i \geq u_{i,\min}, \\ u_{i,\max} & \text{if} \quad u_i > u_{i,\max}, \end{cases}$$

The rest of the paper is organized in the following logical order: First, a benchmark problem for active damping control (ADC) purposes is introduced, and the modeling of the structure is referred to Appendix D. Accordingly, the system model is constructed based on the combination of modal analysis (non-parametric modeling) and the frequency-domain subspace system identification. Next, the problem formulation is presented in standard state space representation while stating the preliminary definitions and common forms of treating actuation nonlinearities in mathematical forms. In Section 4, the algorithms are introduced in a sequential form. It should be noted that due to the close connection of the interpretations of different methods, categorizing the discussed methods seems unnecessary and therefore is neglected. Some tools for assessing the stability and performance of the augmented closed-loop system with anti-windup compensator are given in Section 5. Next, in Section 6, the implementation setup for real-time investigation of the algorithms from Section 4 is introduced, and the behavior of the system in time-domain and frequency-domain is analyzed.