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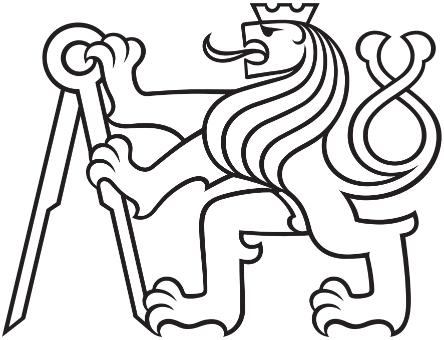

DOCTORAL
THESIS
STATEMENT

Czech Technical University in Prague
Faculty of Mechanical Engineering
Department of Instrumentation and Control Engineering

Summary of Dissertation thesis

Saturation effect and anti-windup schemes for time-delay systems

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schémata pro systémy s dopravním zpožděním

This doctoral thesis is an outcome of a part-time doctoral study programme at the Department of Instrumentation and Control Engineering, Faculty of Mechanical Engineering, Czech Technical University in Prague.

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Abstrakt

Název: Saturace a anti-windup opatření pro systémy s dopravním zpožděním

V předkládané disertační práci je nejdříve provedena analýza třídy časově zpožděných regulátorů podléhajících astatickému chování, které je spojené s tzv. windup efektem v regulačních smyčkách se saturujícími akčními členy. Analýza je realizována jak pomocí analytických nástrojů, tak i nástrojů spektrální analýzy. S důrazem na následné jednoduché ladění je navrženo tzv. anti-windup schéma založené na nelineárním pozorovateli pro skupinu regulátorů se zpožděními ve stavech. Snaha o zjednodušení ladění vede na pozorovatele s funkcionální zpětnou vazbou, která může obsahovat časového zpoždění. Tento přístup vhodně snižuje náročnost ladění tím, že redukuje návrh na metodu předepsání konečného počtu kořenů charakteristické rovnice saturovaného regulátoru. Následné ladění navrhovaného anti-windup schématu je založeno na minimalizaci integrálního kritéria aplikovaného na regulační odchylku v okamžiku saturace akční veličiny, přičemž hledání minima zvoleného kritéria je prováděno s ohledem na jediný ladicí parametr. Popisovaný přístup je nejdříve aplikován na třídu základních modelů se zpožděním. Následně je schéma zobecněno s využitím Ackermannova vztahu aplikovaného na neisochronního pozorovatele a nasazeno na zpožděný model přenosu tepla. Jako doplňující téma je zkoumán vliv saturace na chování uzavřené regulační smyčky s inverzí tvarovače signálu ve zpětné vazbě, což je technika používaná pro kompenzaci kmitavých módů flexibilní části. Studie vlivu saturace na kompenzační schéma je zakončena experimentálním ověřením pomocí laboratorní soustavy a simulačního modelu.

Abstract

Title: Saturation effect and anti-windup schemes for time-delay systems

In the present dissertation thesis, an analysis of a class of time-delay controllers subject to astatic behaviour associated with the so-called wind-up effect in control loops with saturating actuators is conducted using both analytical and spectral approach. An observer-like anti-windup scheme for the class of controllers is proposed with an emphasis on easy subsequent tuning. The effort to simplification leads to a functional feedback deployment which may involve time-delay elements in it. This approach beneficially reduces the anti-windup tuning task to a finite-spectrum assignment. The tuning of the proposed anti-windup scheme is done by minimization of the control error integral criterion with respect to a single tuning parameter. At first, the proposed approach is applied to low-order models. Then, a generalized state feedback parametrization based on Ackermann formula applied to anisochronic observer design is deployed to a high-order heat-transfer model. As a complementary topic, the saturation effect to the performance of the closed loop with the feedback inverse shaper as a oscillatory modes compensator is studied. The study concludes with experimental validation using a laboratory set-up and a simulation model.

List of Acronyms

AWC	anti-windup compensator
DCD	direct control design
DZV	distributed-delay zero-vibration
EI	extra-insensitive
FOPTD	first orded plus time delay
FSA	finite spectrum assignment
IAE	integral absolute error
IMC	internal model control
ISE	integral square error
LMI	linear matrix inequality
PD	proportional-derivative
PI	proportional-integral
PID	proportional-integral-derivative
SISO	single-input single-output
SOPTD	second orded plus time delay
UAV	unmanned aerial vehicle
ZV	zero-vibration
ZVD	zero-vibration-derivative

Contents

1 Introduction

The control loop design and tuning based on linear dynamical models may exhibit a strikingly different behaviour at its implementation as soon as the always existing *actuator saturation* affects the operation. Primarily the actuating variable of the digital controller is to be artificially prevented from any possibility to exceed the saturation boundaries and particularly from any undue getting stuck at these boundaries. This faulty effect is referred to as *windup* and the schemes getting the controller saturation rid of this fault are considered as *anti-windup* schemes. The control action saturation is currently an integral part of the control design, since the designers are overall forced to design energy-optimized devices. Therefore, actuators are typically selected to meet the requirements for their function at the minimum possible weight leading to involvement of their entire working range.

The anti-windup strategies and conditioning techniques are well elaborated for the control loops with processes and controllers considered as rational transfer functions. On the other hand, as to the controllers involving the delay operation a number of issues remain still open. The thesis aims at analysis and design of anti-windup schemes for controllers of time-delay systems. Both finite and infinite order controllers are considered, utilizing both static gain and functional feedback in the anti-windup schemes. Besides, saturation effect on the controllers and compensators with time delays are studied.

2 State of the art

In the most control systems nonlinear actuators are encountered, and one of the common nonlinearities, resulting from "real-world" limitations, is the actuator saturation. The saturation nonlinearity is the ubiquitous part of the actual control systems and it is caused by limited capabilities of the actuator given by its physical realization. Therefore, the actuator saturation is closely related to a connection between the real system and the practical implementation of the designed controller. Account must be taken of the significant fact that in the case when the control system was designed to be stable without considering the saturation, it cannot be guaranteed, in general, the stability of the closed-loop system with saturation included [22].

2.1 Time-delay systems

Delays, in general, are an essential feature of controlled process dynamics. Especially nowadays, when high-speed control systems being used, communication delays in the loop have to be taken into account in the control design. As a rule, such delay has been neglected due to their short duration in comparison with reachable dynamics of control loops until recently. The delays can be in complex processes effective not only in inputs of the system but also in its internal feedbacks which is, for example, a typical property of complex heat transfer systems. An overview of some recent advances and open problems in time-delay systems have been presented by Richard in [26] with extensive list of monographs devoted to this field of active research.

2.1.1 Control of time-delay systems

Time-delay system control design forms a special group of control system theory demanding specific requirements arising from inherent infinite-dimensionality of a controlled system. The following control strategies belong to basic methods possibly leading to feedback controllers with time delays in internal states and exhibiting astatic property not obvious at first sight.

The Smith predictor [32] and its modifications towards unstable time-delay systems control (e.g. [47]) are well-known schemes to control community. An alternative control scheme for time delay compensation is a method known as a finite spectrum assignment (FSA), which has been pronounced as an effective control strategy for poorly-damped or even unstable time-delay systems, e.g. see [21, 45]. One of the first attempts in the direction of the method development can be found already in [9], followed by work of Manitius and Olbrot [20] and comprehensively compared in [46]. An undeniable advantage of FSA controller design strategy is that it can address delays not only in the input/output channel, but also in the states. Another control design strategy for a class of time-delay systems is internal model control (IMC) [8]. Currently, the IMC scheme gains attention especially in the areas of practical applications, e.g. see [35], based on previous works towards implementation incorporating also the saturation phenomenon [50, 10, 1]. However, as Hlava in [17] referred, IMC applications to time-delay systems are rare and limited to the simplest ones with exception of a paucity of works, where, for example, the work of Zítek presented in [54] belongs.

2.2 Actuator saturation and anti-windup

The actuator saturation acts in control loop so that values outside the actuator's amplitude limits are mapped into the range of capabilities to the nonlinear saturation function described mathematically by the following equation

$$u_{\mathrm{s}}(t) = \mathrm{sat}(u(t)) := \begin{cases} u_{\max}, & \text{if } u(t) > u_{\max} \\ u(t), & \text{if } u_{\min} \le u(t) \le u_{\max} \\ u_{\min}, & \text{if } u(t) < u_{\min} \end{cases} \tag{2.1}$$

where $u_{\min}$ and $u_{\max}$ correspond to the minimal and maximal attainable actuator limits.

The intended windup problem in the controller is closely related to the control input saturation. In general, it can be described as a lack of consistency in the internal states of the controller in the presence of a nonlinearity defined by the inequalities (2.1). As soon as any of the saturation boundaries is reached during controller operation the saturated variable cannot follow desired value of the controller output anymore and becomes stuck at the appropriate boundary value. Then the controller internal states no longer correspond to the effective output actually acting to a controlled plant. In that case, the feedback control loop is broken and the astatic (or unstable) modes of the controller may drift to undesirable values causing a prolongation of a settling time after an upset or even instability of an entire closed-loop system. The main task of the anti-windup compensator is then to restore this consistency of the controller states. The restoration effect basically depends on a structure and parameters of the anti-windup compensator.

There are two general commonly proposed solutions how to deal with the control input saturation, declared in [36]—so called anti-windup compensator (AWC) and direct control design (DCD). The first *"a posteriori"* approach consists of two following separated steps

1. designing a controller for a process that ensures a satisfactory control performance in the absence of actuator saturation
2. then, a static or dynamic (anti-windup) compensator with a various architecture is designed to minimize the impact of actuator saturation on the closed-loop performance.

In contrast to AWC approach, the DCD method refers to as the one step approach. The control input constraints are taken into account *"a priori"* immediately at a controller design phase. While this approach is satisfactory in a principle, and it has a significant portion of the literature devoted to it (see e.g. [27, 11, 6, 40]), it has been often criticised (e.g. in [38]) because of its conservatism, lack of intuition (in terms of tuning rules etc.) and lack of applicability to some practical problems.

With respect to a structure of AWC, the resulting compensation part of a controller can be either *static*, or *dynamic*, depending on a dynamical behaviour prescribed to the AWC. The static AWC implies only static behaviour without any dynamic elements. The most of original AWC approaches are inseparably linked with the static structure [7, 2]. Nevertheless, even recent works (e.g. [39, 28]) try to deal with windup problem using just a static approach incorporating linear matrix inequality (LMI) tools, in most cases. The reason for a static AWC deployment is that it offers reasonable satisfactory performance (very effective on some systems) with considerable simplicity. On the contrary, the dynamic AWC, in general, contains a more complicated dynamics resulting from various parameterizations approaches which allows to treat the performance degradation of complex controllers in more optimal manner. For example, the dynamic anti-windup synthesis for state-delayed systems using the LMI procedure has been recently addressed in [12, 37]. An other dynamic, observer-based, AWC has been proposed in [23, 48].

2.2.1 Anti-windup for time-delay systems

The anti-windup strategies and conditioning techniques are well-elaborated for the control loops with plants and controllers considered as rational transfer functions. On the other hand, as to the controllers involving the delay operation some issues remain still open. The anti-windup compensation for time-delay systems has been recently addressed, for instance, in [23, 37, 49, 14, 4]. As it is clear from a number of recent works, the interest in AWC schemes for time-delay systems (both controllers and controlled processes) has raised recently, and it continues to persist. The AWC methods differs from each other in intended time-delay systems and, of course, in chosen approaches to design the optimal solution. The most common connecting element of the recent works is the state-space representation of a system, giving the ability to describe more complex systems, and LMI approach, offering a powerful tool for designing the AWC schemes with strong computer support.

2.3 Signal shapers

Input shaping is a well known technique for compensating undesirable oscillatory modes of mechanical systems, see [33], [30, 31] for zero-vibration (ZV), zero-vibration-derivative (ZVD) and extra-insensitive (EI) shaper design, or for example [24] for more recent techniques. Next to the classical feed-forward arrangement of the input shapers which can only handle the effect of reference command, there was an impulse to place shapers in a feedback interconnection in order to eliminate the effect of unmeasurable disturbances on the excitation of the flexible modes. In order to handle this task, Smith [34] developed a basic scheme with a compensator and a shaper in the feedback. However, it was shown in [43] that the scheme can be applied if and only if both the controller and the system are bi-proper as their inversion is needed in the compensator design.

Recently, it was revealed in [43] that the given task of compensating the oscillations by both the set-point changes and disturbances acting on the system main body can be performed if and only if the input shaper is applied in the inverse form and placed within the feedback path of the closed loop. As it was identified in [43], the classical ZV shaper with lumped delays is not applicable in the inverse implementation due to neutral distribution of its infinite chain of zeros, which imposes neutral character to the closed-loop system. In order to mitigate this inefficiency, the distributed-delay zero-vibration (DZV) was introduced in [44, 42] having a retarded spectrum of zeros. The transfer function of the equally distributed delay shaper is given by

$$S(s) = A + (1 - A)\frac{1 - \exp(-sT)}{Ts}\exp(-s\tau), \tag{2.2}$$

where T represents the distributed delay length, and τ is the lumped delay value. The parameters A, T, τ of the shaper are tuned in order to compensate the target oscillatory mode of the flexible system. As demonstrated in [18] in the coupled case, however, the mode to be targeted by the inverse shaper needs to be isolated, as it is neither the oscillatory mode of the flexible part, nor the mode of the coupled system. The algorithm for assessment of the target mode for the inverse feedback shaper was presented in [18].

The described methodology to suppress oscillatory mode of the flexible part brings an additional time-delay term into a control loop which is beneficial in ideal (i.e. linear) case. However, the algorithm efficiency for saturated (i.e. nonlinear) control appearing in real-life implementation has not been studied yet.

3 Problem statement

In the mainstream of time-delay system theory, the controller saturation and related anti-windup issues are not systematically taken into account in the controller design. Compared to delay-free systems, this fact can bring even more dramatic consequences to the closed-loop performance and stability. This is given by the distributed nature of the system state (an internal memory) which can even be transferred to the controller structure, e.g. within IMC design, in case the delays are dominant and need to be compensated via including them into the controller structure.

Despite the fact that considerably more attention has been paid to solving anti-windup for delay-free systems, recently, solving this task for time-delay systems has received an enhanced attention, as outlined in the state of the art chapter 2.2.1. The proposed methods predominantly aim at stability analysis under the introduced nonlinearity by saturation, which leads to application of *Lyapunov methods* [3, 51], known for their conservatism and standard solution by LMI methods of enhanced complexity [36, 12, 16].

A general aim of the dissertation is to investigate a possibility of reducing a negative effect of the control signal saturation on the performance of a control loop with time delays by a modification of an anti-windup compensation included in the controller. As a rule, the saturation causes that an actual control process behaviour fails to achieve a quality of process considered in a theoretical design, i.e. it is worse than a modelled (linear) solution. Due to the fact that a control variable cannot exceed its saturation limits a certain lack of action is caused, which usually results in a longer settling time with greater fluctuations in control error variable.

As demonstrated in literature mainly in the subject of delay-free systems [19, 41], the performance of the closed loop with saturated control can be tuned by proper parametrization of the anti-windup scheme. Instead of vigorously stopping and triggering integration during the saturation, it is possible to improve the closed loop behavior by intentional prolonging the time at the saturation, even after the control error indicates by its sign change that the control action should decrease below the limit. For this purpose, the observer based anti-windup techniques proved efficient. The extension of these techniques towards time-delay control schemes form the second and third objectives of the thesis.

Next to the above defined main and general topic of the anti-windup, an attention is also paid to analysis of time-delay system controllers. In particular, the astatism (integration) nature brought by applying the IMC method is studied. This so-far unsolved task is crucial for understanding the windup effect nature under the projection of time distributed state of the controller. Analysis of this problem forms the first, preliminary objective of the thesis.

The last task and open problem to be solved arises from the work on the projects GAČR (16-17398S): *Time delay compensators for flexible systems* (performed under the leadership by prof. V. Kučera, CTU in Prague) and INTER-ACTION (LTAUSA17103): *Time-delay control laws for innovative transportation UAV systems* (performed under collaboration with prof. W. Singhose, Georgia Tech., Atlanta), which are focused on design and application of time-delay compensators. The problem is related to the general topic of the thesis via studying the effect of controller saturation on the performance of time-delay compensator—an inverse shaper recently proposed and analyzed in [43] and [18] for compensating the oscillatory modes of the attached flexible subsystem. In particular, the representation of the saturation as a system input disturbance and its impact on the performance of the closed loop to the flexible mode compensation forms the last objective, together with the validation of theoretical findings on case study examples.

4 Thesis objectives

Based on the state of the art analysis and the above defined problem statements, the thesis objectives have been stated as follows:

Objective 1

The first objective, which can be considered as preliminary, is to analyze the astatism of controllers arising from application of the IMC control design method to time-delay systems. Their characteristic equation is typically in the form

$$m(s) = sq(s) + 1 - \exp(-s\tau) = 0$$

where $q(s)$ can be either polynomial or quasi-polynomial. The controller astatism brought by the above equation is not obvious and its nature is to be analyzed by time domain and spectral methods. The understanding of this phenomenon is essential towards studying the windup nature for time-delay controllers.

Objective 2

The second objective aims at analysis and design of anti-windup schemes of low-order systems with input time delay often used in process control for approximating wide range of systems. Applying the dimensionless model forms, the objective is to propose general procedures for parametrization of anti-windup schemes for both finite and infinite-order (time-delay) controllers with the task to minimize the negative effect of control input saturation on the closed-loop responses.

Objective 3

The subsequent objective is to generalize the anti-windup design task solved within Objective 2 towards internal model controllers of higher order time-delay systems. The subsequent task is to validate and demonstrate the results on a complex case study application example.

Objective 4

Aside to anti-windup schemes for time-delay systems targeted in Objectives 2 and 3, the last objective of this thesis aims at studying effects of saturation to the performance of the closed loop with deployed inverse shaper—a time-delay compensator of oscillatory modes of flexible subsystems. The particular tasks are to

(i) study the saturation and its impact on the flexible mode compensation from the perspective of system input disturbance

(ii) study the effect on simulation and experimental case studies.

5 Results

Objective 1, addressed in section 5.1, reveals astatic effect of time-delay feedback with support of a simple example completed with analytical solution. Objective 2, addressed in section 5.2, focuses on IAE based tuning of the anti-windup feedback in a controller of a first orded plus time delay (FOPTD) and a second orded plus time delay (SOPTD) models which are basic models commonly used for approximating higher order systems. Objective 3, addressed in section 5.3, describes proposed observer-based AWC technique in combination with the anisochronic state observer for dealing with control input saturation for a controller of a retarded type. Objective 4, addressed in section 5.4, presents an idea to treat the saturation effect as a disturbance on the control input of the actuator which can be canceled by a shaper in the feedback control loop.

5.1 Astatic effect of time-delay feedback

Time-delay control systems also reveal some problems commonly found in other control strategies like the proportional-integral-derivative (PID) control in the presence of the so-called *hard nonlinearity* such as saturation or even static friction as it was shortly pointed out by Chang and Park in [5]. A large overshoot, limit cycles, or even unstable responses have been observed when the saturation limits are reached by control variable in time-delay control systems. The effort is to show that time delays must be seriously taken into account if saturation occurs in the control loop because of not obvious astatic property possible occurring in some time delay control strategies.

Lets suppose a controller given by transfer function $K(s)$ with strictly proper fraction $(m < n)$ of quasi-polynomials of the retarded type

$$K(s) = \frac{q(s)}{p(s)} \tag{5.1}$$

as stated in [55], with retarded quasi-polynomials of the generic form

$$p(s) = s^n + \sum_{i=0}^{n-1} \sum_{j=1}^{N_{\bar{\vartheta}}} p_{i,j} s^i \exp(-s\bar{\vartheta}_{i,j}), \tag{5.2}$$

which is also characteristic (quasi-)polynomial of $K(s)$, and

$$q(s) = \sum_{i=0}^{m} \sum_{j=1}^{N_{\bar{\tau}}} q_{i,j} s^i \exp(-s\bar{\tau}_{i,j}), \tag{5.3}$$

where the highest power term s^n of $p(s)$ is free of delay. For the time delay values the inequalities $\bar{\vartheta}_{i,j}, \bar{\tau}_{i,j} \in \mathbb{R}, \bar{\vartheta}_{i,j} \geq 0$ and $\bar{\tau}_{i,j} \geq 0$ apply.

A classical feedback controller $K(s)$ based on the IMC controller design with the artificial process model $\tilde{P}(s) = \exp(-s\tau)$ has the following form with respect to the structure of IMC control loop

$$K(s) = \frac{1}{1 - \exp(-s\tau)} \tag{5.4}$$

with a simple quasi-polynomial in the denominator with the time delay τ. Using *generalized final value theorem* [13], it has been shown that step response $h_K(t)$ of (5.4) can be obtained by integrating the impulse function $g_K(t)$ and so in Laplace transform it gives

$$H(s) = \frac{1}{s}K(s) = \frac{1}{s\tau} \tag{5.5}$$

which is a simple integrator with an integral time constant given by the time delay τ. Therefore, the input time delay τ of the process model $\tilde{P}(s)$ determines the time constant of the equivalent integration.

The integral nature of a controller $K(s)$ is also preserved if there is a quasi-polynomial of higher degree in characteristic equation of controller $K(s)$ or even if there are multiple time delays in characteristic equation of a controller provided that there is a zero pole $s = 0$. The presence of zero pole is caused by the quasi-polynomial (5.2) coefficients in the denominator of (5.1) fulfilling

$$\sum_{j=1}^{N_{\bar{\vartheta}}} p_{0,j} = 0 \tag{5.6}$$

where $N_{\bar{\vartheta}}$ is a number of different time delays and $p_{0,j} \in \mathbb{R}, \forall j = 1, \dots, N_{\bar{\vartheta}}$ are the coefficients of zeroth s-powers.

The astatic behaviour of time delay can be also observed if *Maclaurin series* or the method called *Padé approximation* is used for approximating the time delay term in (5.4) as illustrated in Fig. 5.1. Next to the preserved astatic behaviour and different initial jump the *Padé approximation* has also undamped oscillations as shown in the same figure.

Complex roots (i.e. *characteristic roots*) of the characteristic equation of the controller (5.4) including the zero one giving astatic property can be found analytically using the well-known *Euler's formula* applied in a complex number theory in this simple case. The characteristic roots are given as follows

$$s_k = j\frac{2k\pi}{\tau}, k \in \mathbb{Z} \tag{5.7}$$

which all lie on the imaginary axis equally spaced and all separated by the exact distance of $\frac{2\pi}{\tau}j$ with one single root $s_0 = 0$ for $k = 0$. Suppose $\tau = 1\,\mathrm{s}$, then the characteristic roots are $s_k = 2k\pi, k \in \mathbb{Z}$ and their place-

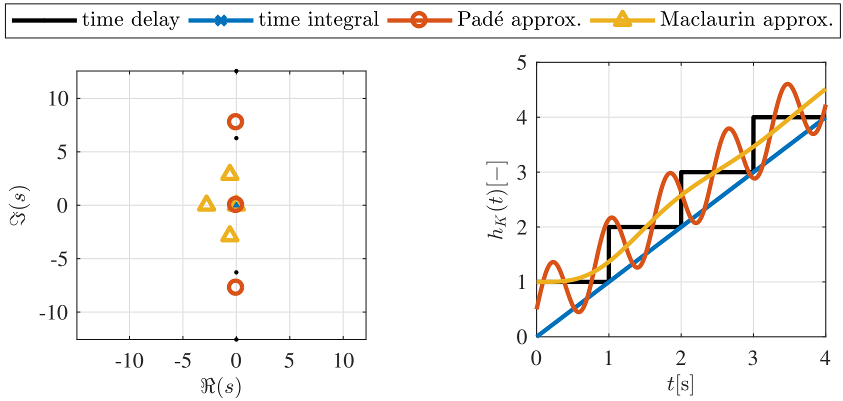

Figure 5.1: Comparison of time delay approximations applied to the transfer function (5.4) for $\tau = 1\,\mathrm{s}$: system poles (left); step responses (right)

ment in the complex plane is outlined in Fig. 5.1. A distance between the characteristic roots increases for $\tau \to 0$, causing the characteristic roots moving far away from the origin of the complex plane. Only the root $s_0 = 0$ with its integrating character stays at the origin for an arbitrary time delay τ. This root is responsible for astatic nature of the controller (5.4).

The inherent astatic effect of time delay feedback, possibly appearing in some class of time delay compensating controllers, has been described with support of a simple example completed with analytical solution. The condition for astatism of time-delay controllers with characteristic equation in a quasi-polynomial form has been pronounced. Because time delay approximations are commonly used in various control system design techniques some of them have been shown to have quite similar integral nature if they are applied to substitute pure time delay terms.

5.2 IAE optimum AWC tuning for low-order time-delay system controllers

The schemes of anti-windup and conditioning are well developed for the controllers with the rational transfer function structure as it is briefly summarized in section 2.2. However, the specific design methods for the time-delay processes also lead to controllers whose transfer functions may become meromorphic, i.e. involving time delays in their structure. As a particular case of Youla affine parameterization the most specific method in this area is the well-known IMC [15].

Two basic time delay plant models are stated concisely to introduce a class of systems for subsequently presented case study dealing with AWC design and its tuning with respect to a chosen criterion. Dimensionless approach is appropriately used to generalize a validity of the presented results. Following the approach proposed by Zítek et al. in [53] for the second order model with time delay, the plant models are reformulated using *dimensionless description* in order to determine the set of dynamically similar plants, i.e. the plants with different parameters but the same so-called similarity numbers.

As the first representative the fundamental FOPTD stable plant model is considered due to its simple dynamics offering easy comprehension of the proposed method. It can be considered in the universal dimensionless form

$$P_1(\bar{s}) = \frac{y(\bar{s})}{\bar{u}(\bar{s})} = \frac{\exp(-\bar{s}\bar{\tau})}{\bar{s}+1} \tag{5.8}$$

where the single parameter is the scaled time delay $\bar{\tau} = \tau/T$ and $\bar{s} = sT$ is the dimensionless Laplace transform operator.

For a more general investigation of the efficiency of the observer-based anti-windup scheme a sufficiently generic model of the plant has been chosen. The SOPTD model is able to describe a wider class of plants than the model (5.8) thanks to more optional parameters. However, this complexity has to be naturally reflected in a controller design and a related anti-windup scheme. A stable linear time delay plant given by second order differential equation can be described by the following transfer function

$$P_2(\bar{\bar{s}}) = \frac{k\exp(-\bar{\bar{s}})}{\bar{\bar{s}}^2(\lambda\vartheta^2)^{-1} + \bar{\bar{s}}(\lambda\vartheta)^{-1} + 1} \tag{5.9}$$

considering dimensionless approach with respect to the proposed Laplace transform operator substitution $\bar{\bar{s}} = s\tau$ and so-called *swingability* λ and *laggardness* ϑ similarity numbers respectively.

The original aim of tuning an anti-windup scheme is to minimize the time intervals when saturation affects the actuating variable, i.e. to minimize the saturation error $u_\mathrm{s}(t) - \hat{u}(t)$, which means to keep the *actuating variable* as much as possible close to its ideal predetermined action. This requirement is reformulated for higher order controllers in the sense of trying to keep internal states of the controller to the ones corresponding to saturated control output [23, 48]. But anti-windup as deployed in this chapter is an inherent part of a controller and therefore the minimization of *control error* $e(t) = r(t) - y(t)$ is to be preferred to a strict minimization of the *saturation error*, $u_\mathrm{s}(t) - \hat{u}(t)$. Therefore the optimization of

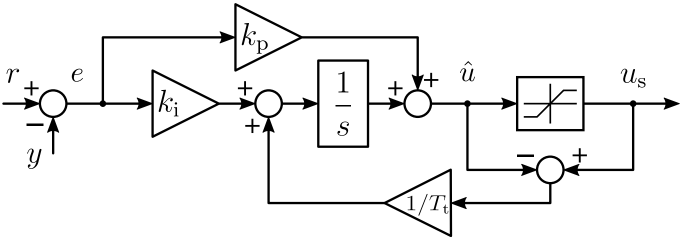

Figure 5.2: PI controller with back calculation anti-windup

anti-windup parameters is made from the aspect that not an optimization of the *saturation error* $u_\mathrm{s}(t) - \hat{u}(t)$ but the best attainable performance of *control error* $e(t)$ is searched in the anti-windup tuning.

The performance of the control loop is analyzed with the objective to determine the optimum value of anti-windup parameters in the sense of minimizing the IAE criterion

$$I_\mathrm{IAE} = \int_0^\infty |e(t)|\,\mathrm{d}t \tag{5.10}$$

in the cases when the control action, induced by either set-point or input disturbance, is saturated.

5.2.1 Static AWC tuning

A classical finite order (static) anti-windup feedback known as *back-calculation method* (Fig. 5.2) is utilized as a preliminary study. The technique is applied first to a simple proportional-integral (PI) controller with the FOPTD model. Then, an extension to observer-based anti-windup is deployed to meromorphic IMC controller designed for the SOPTD model to show a satisfactory closed-loop performance preservation even for a static feedback.

In order to find an optimal value of $\bar{T}_\mathrm{t} \in \mathbb{R}; \bar{T}_\mathrm{t} > 0$ that minimizes the IAE criterion, the brute-force method has been applied based on sweeping the parameter $\frac{1}{\bar{T}_\mathrm{t}}$ over the interval $[0, 10]$ and evaluating the criterion (5.10) for every grid point. This procedure has been applied to classes of systems given by combination of the chosen dimensionless parameters and various values of the saturation levels.

As the result, for the system classes with larger values of $\bar{\tau} = \tau/T$, the optimum is reached for $1/\bar{T}_\mathrm{t} < 1$, i.e. for $T_\mathrm{t} > T$. More specifically, for $\bar{\tau} = 0.5$ the optimum is still fairly close to $T_\mathrm{t} = T$, but it is not the case for $\bar{\tau} = 1$ where T_t should be considerably larger as can be seen in Fig. 5.3.

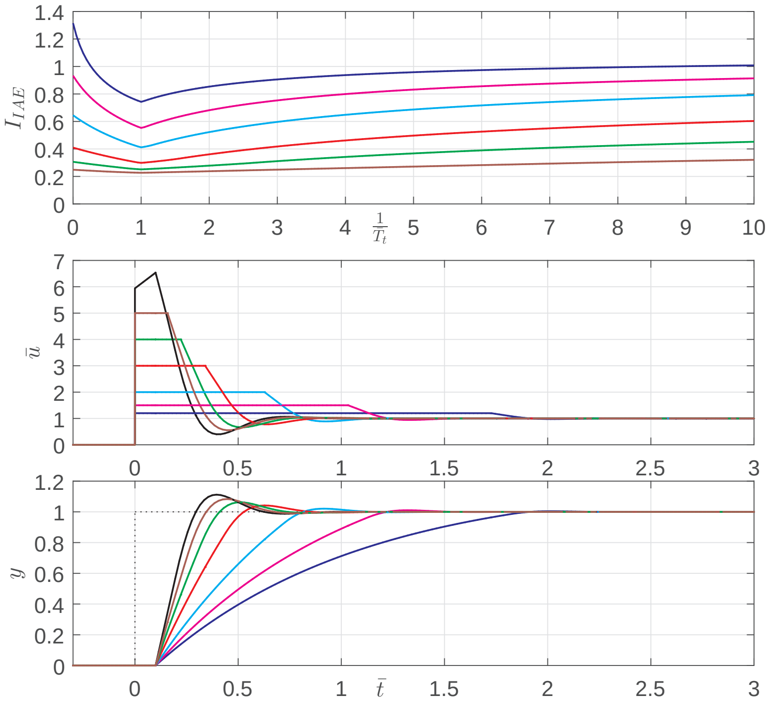

Figure 5.3: Results of optimizing the IAE criterion for the system class (5.8) with $\bar{\tau} = 0.1$, PI controller with the anti-windup feedback (up-most figure), and the optimal responses for the considered values of the control signal saturation

In order to extend the class of involved plant models the SOPTD model is considered in combination with IMC controller. The aim of this extension is to define a similar (static) anti-windup scheme tuning presented above for FOPTD model and PI controller. Compared to the PI controller an increase of tuning parameters occurs due to higher complexity of IMC scheme and resulting controller. Despite that, the effort of the following optimization task is to obtain a simple anti-windup tuning rule.

The classical closed-loop controller transfer function for system model (5.9) is not simply rational—it involves a delay operation in controller structure and its meromorphic nature has to be considered in the design of anti-windup scheme too. Then from the IMC parameterization the following meromorphic controller is obtained

$$K_{2,\mathrm{IMC}}(\bar{\bar{s}}) = \frac{(\bar{\bar{s}}^2 + \vartheta\bar{\bar{s}} + \vartheta^2\lambda)(\delta^2+1)\Phi^2}{k\vartheta^2\lambda\left[\bar{\bar{s}}^2 + 2\delta\Phi\,\bar{\bar{s}} + (1+\delta^2)\Phi^2(1-\exp(-\bar{\bar{s}}))\right]} \tag{5.11}$$

which is converted into state-space representation (given by matrices $\mathbf{F}$, $\mathbf{G}$, $\mathbf{H}$ and gain L) in order to apply observer-based AWC. Then, the controller operating according to the following equations

$$\begin{aligned} \bar{\bar{s}}\hat{\mathbf{x}}(\bar{\bar{s}}) &= \mathbf{F}(\bar{\bar{s}})\hat{\mathbf{x}}(\bar{\bar{s}}) + \mathbf{G}(\bar{\bar{s}})e(\bar{\bar{s}}) + \mathbf{W}[u_s(\bar{\bar{s}}) - \mathbf{H}\hat{\mathbf{x}}(\bar{\bar{s}}) - Le(\bar{\bar{s}})] = \\ &= [\mathbf{F}(\bar{s}) - \mathbf{WH}]\hat{x}(\bar{\bar{s}}) + [\mathbf{G}(\bar{s}) - \mathbf{W}L]e(\bar{\bar{s}}) + \mathbf{W}u_{\mathrm{s}}(\bar{\bar{s}}) \end{aligned} \tag{5.12}$$

with an ordinary gain matrix $\mathbf{W} = [w_1, w_2]^T$ is introduced as the *windup observer* where $\mathbf{W}$ is to be set by an anti-windup tuning procedure. The observer-like feedback characterized by $\mathbf{W}$ in equation (5.12) acts intermittently, being *switched on* and *off* in the instants of saturation. Using the dimensionless model (5.9) and the controller (5.11) in state-space representation (5.12) the gains w_1, w_2 have been found by minimization of the following ratio

$$R_{\mathrm{AE}} = \frac{I_{\mathrm{AS}}}{\hat{I}_{\mathrm{A}}}$$

where $\hat{I}_{\mathrm{A}} = \int_0^{\bar{t}} |\hat{e}(\sigma)|\,\mathrm{d}\sigma$ and $I_{\mathrm{AS}} = \int_0^{\bar{t}} |e_{\mathrm{s}}(\sigma)|\,\mathrm{d}\sigma$ expressing the saturation-free performance and the performance degradation due to the saturation respectively. A novelty of the presented approach consists in considering the plant model properties in the tuning of AWC.

5.2.2 Dynamic AWC tuning

Analogously to the PI controller presented in previous section, the IMC controller for the system (5.8) can be extended by a general anti-windup *back-calculation* feedback

$$\hat{K}_{\mathrm{IMC}} : \begin{cases} \dfrac{\mathrm{d}x(t)}{\mathrm{d}t} = \dfrac{1}{T_{\mathrm{f}}}(x(t-\tau) - x(t)) + \dfrac{T}{T_{\mathrm{f}}}(e(t-\tau) - e(t)) \\ \qquad\qquad + e(t) + w\left(u_{\mathrm{s}}(t) - \dfrac{1}{kT_{\mathrm{f}}}(Te(t) + x(t))\right) \\ u(t) = \dfrac{1}{kT_{\mathrm{f}}}(Te(t) + x(t)) \\ u_{\mathrm{s}}(t) = \mathrm{sat}(u(t)) \end{cases} \tag{5.13}$$

where $w \in \mathbb{R}$ is the anti-windup single tuning parameter and u_{s} is the plant real control input limited by saturation. The characteristic equation of (5.13) then reads

$$T_{\mathrm{f}}s + 1 + \frac{w}{k} - \exp(-s\tau) = 0. \tag{5.14}$$

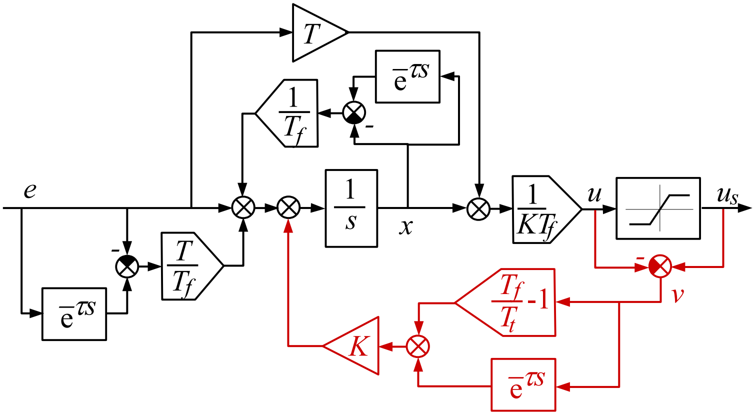

Figure 5.4: IMC controller scheme with functional anti-windup feedback given by term $w(s)$ in (5.15)

Due to its quasi-polynomial nature, the anti-windup feedback system has infinitely many roots. This fact makes the tuning of the parameter w considerably more difficult compared to the tuning of T_t in the PI controller case. Even though design and spectral analysis tools are available to handle such a design task, the fact that only one of the infinitely many poles can be assigned by a single parameter is likely to bring considerable constraints concerning the stability perspective. In order to avoid this issue, a functional anti-windup feedback instead of a static gain w is introduced which simplifies noticeably the anti-windup design task. Then, the functional feedback term for controller (5.13) is determined as

$$w(\bar{\bar{s}}) = k\left(\frac{T_\mathrm{f}}{T_\mathrm{t}} - 1 + \exp(-\bar{\bar{s}}\tau)\right) \tag{5.15}$$

giving the opportunity to tune AWC using just one tuning parameter T_t. The functional feedback structure is illustrated in the Fig. 5.4. Analogously to the PI controller, the parameter T_t was optimized with respect to the IAE criterion applied to the dimensionless model of the controlled system leading to the choice $T_\mathrm{t} = T$ is a reasonable choice as it guarantees close to optimum responses when the saturation limit cuts considerably the non-saturated control action peak value.

The key contribution of the study is in a simulation based tuning of the anti-windup feedback with respect to the IAE criterion for low-order time-delay models. Unlike the commonly used approach to the windup problem the actuator saturation is not regarded as a separate nonlinearity but as an inseparable property of the controller. From this point of view the *control error* rather than *saturation error* is preferred in tuning the anti-windup scheme parameters. Next ot that, a novel structural solution of the anti-windup feedback scheme is proposed for an IMC controller, also considered and tuned for the FOPTD model. Due to the time delay that is projected to the structure of the IMC controller, the anti-windup feedback system is of infinite order. This problem is handled by a functional feedback that turns the dynamics of saturated controller to the equivalent finite-order form of the PI case.

5.3 Observer-based anti-windup compensator with anisochronic feedback

The task of the objective is to design AWC for single-input single-output (SISO) controller of retarded type burdened by saturation with the aim of achieving the least possible closed-loop deterioration caused by the present saturation. A general observer-based AWC has been chosen for this task thanks to the ability to directly influence the internal states of controller. Using the state feedback $\mathbf{W}$ from saturation error $u_\mathrm{s} - \hat{u}$, it is possible to prescribe the dynamic behaviour of the controller when the saturation occurs. A two-step approach has been chosen for the proposed AWC design:

1. the AWC state-feedback form is determined (i.e. elements of the feedback matrix $\mathbf{W}$)
2. then, the available parameters are optimized with respect to a chosen criterion.

The controller involving such functional AWC feedback (see Fig. 5.5) is given by the following state-space representation in Laplace transform

$$\hat{K}(s): \begin{cases} s\mathbf{x}_{\hat{K}}(s) = \mathbf{F}(s)\mathbf{x}_{\hat{K}}(s) + \mathbf{G}(s)e(s) + \mathbf{W}(s)(u_\mathrm{s} - \hat{u}(s)) \\ \qquad\quad = \bar{\mathbf{F}}(s)\mathbf{x}_{\hat{K}}(s) + \bar{\mathbf{G}}(s)e(s) + \mathbf{W}(s)u_\mathrm{s} \\ \hat{u}(s) = \mathbf{H}\mathbf{x}_{\hat{K}}(s) + Le(s) \\ u_\mathrm{s} = \mathrm{sat}(\hat{u}(s)) \\ e(s) = r(s) - y(s), \end{cases} \tag{5.16}$$

where $\bar{\mathbf{F}}(s) = (\mathbf{F}(s) - \mathbf{W}(s)\mathbf{H})$ and $\bar{\mathbf{G}}(s) = (\mathbf{G}(s) - \mathbf{W}(s)L)$ are state and input matrix, respectively. In order to simplify the follow-up optimization task, only one parameter is determined for tuning in the first step determining the form of the AWC feedback. With this aim the prescribed

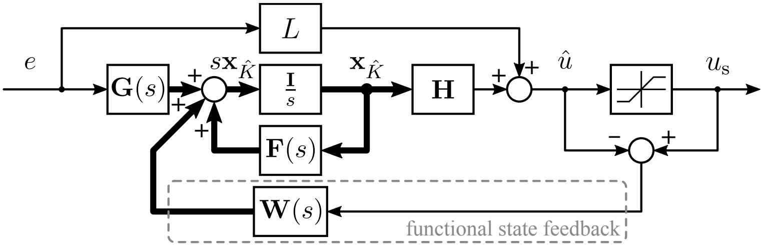

Figure 5.5: Block diagram of the proposed observer-based AWC with the functional state feedback matrix $\mathbf{W}(s)$

characteristic polynomial $m_{\hat{K}}(s)$ of the saturated controller is chosen in the following form

$$m_{\hat{K}}(s) = (s+\sigma)^n = \sum_{k=0}^{n} \binom{n}{k} s^{n-k}\sigma^k, \tag{5.17}$$

where n is the number of state variables and also the multiplicity of $\sigma \in \mathbb{R}; \sigma > 0$. The requirement on the finite spectrum (5.17) yields the following condition

$$m_{\hat{K}}(s) = \det(s\mathbf{I} - \mathbf{F}(s) + \mathbf{W}(s)\mathbf{H}) \overset{!}{=} (s+\sigma)^n. \tag{5.18}$$

This imply that the elements of $\mathbf{W}(s)$ may not be constant but functions of s, i.e. functional. An approach involving *anisochronic state observer* with *Ackermann formula* is chosen to deal with determining functional elements of $\mathbf{W}(s)$ in order to meet the condition (5.18). The feedback matrix $\mathbf{W}(s)$ is obtained in the form

$$\mathbf{W}(s) = m_{\hat{K}}(\mathbf{F}(s))\,\boldsymbol{\mathcal{O}}^{-1}(s)\begin{bmatrix}0 & 0 & \dots & 1\end{bmatrix}^T, \tag{5.19}$$

where $\boldsymbol{\mathcal{O}}(s)$ is observability matrix of the controller. The tuning of the AWC scheme characterized by the functional state feedback $\mathbf{W}(s)$ (5.19) is then limited to finding an optimal setting with the single tuning parameter σ subject to a chosen criterion. The chosen criterion is integral square error (ISE) given by the following time integral over infinite time

$$J_{\text{ISE}} = \int_0^\infty e^2(t)\,\mathrm{d}t \tag{5.20}$$

where $e(t) = r(t) - y(t)$ is an error variable expressing a difference between a set-point and a controlled variable. The chosen criterion J_{ISE} is slightly different in a comparison with the generally used observer-based approaches (for example [23, 48]) that attempts to minimize controller internal states error instead of entire closed-loop optimization.

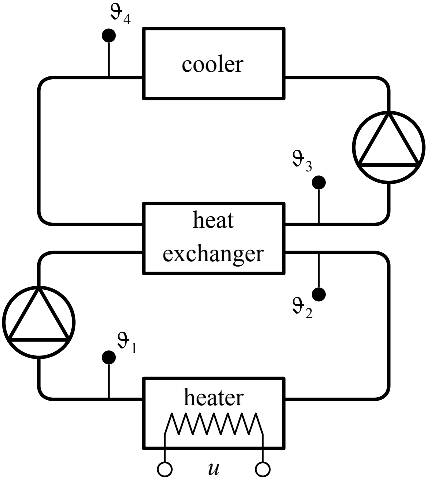

Figure 5.6: Scheme of the laboratory heat transfer set-up model (scheme taken from [29])

A higher order SISO model of a simple heat transfer process with significant time delays illustrated in Fig. 5.6 combined with IMC design of a controller demonstrates a parametrization of the proposed observer-based AWC for a controller of a retarded type.

The AWC feedback matrix $\mathbf{W}(s)$ for the heat transfer example is obtained in the following form

$$\mathbf{W}(s) = \begin{bmatrix} T_{\mathrm{f}}^3 b_1 \sigma^4 - b_0 + b_0 \exp(-s\tau_b) \\ 4T_{\mathrm{f}}^3 b_1 \sigma^3 - 3T_{\mathrm{f}} b_0 - b_1 + b_1 \exp(-s\tau_b) \\ 6T_{\mathrm{f}}^3 b_1 \sigma^2 - 3T_{\mathrm{f}}^2 b_0 - 3T_{\mathrm{f}} b_1 \\ 4T_{\mathrm{f}}^3 b_1 \sigma - T_{\mathrm{f}}^3 b_0 - 3T_{\mathrm{f}}^2 b_1 \end{bmatrix} = \begin{bmatrix} w_0(s) \\ w_1(s) \\ w_2 \\ w_3 \end{bmatrix}. \tag{5.21}$$

Regarding to feasibility of the proposed result, the feedback matrix (5.21) has a delay term in two elements, namely $w_0(s)$ and $w_1(s)$, remaining elements are constant. The delays are positive so there is no obstacle to implement such a feedback with the matrix $\mathbf{W}(s)$ because there are no unfeasible anticipative delays involved.

The resulting tuned AWC causes that the control action continue to stay at the saturation boundary for a “little” longer in the sense of the chosen optimality. This continuance may be regarded to an additional supply of missing energy which has not been delivered to a controlled process due to the saturation. The described prolongation is highlighted in the Fig. 5.7 where an example of the optimized control action behaviour

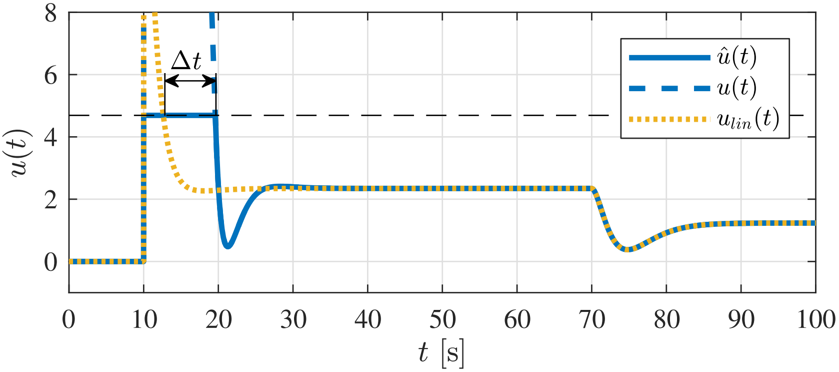

Figure 5.7: Optimal nonlinear $\hat{u}(t)$ and (ideal) linear $u(t)$ control action for the controller $\hat{K}$ ($T_\mathrm{f} = 2\,\mathrm{s}$) with annotated time prolongation Δt

is shown next to the ideal case free of any saturation. The slow response of AWC for strong limitations of the control variable causes that the control input $\hat{u}(t)$ to the process remains stuck at the saturation limit too long leading to an undesirably small but long-lasting overshoot of the controlled variable $y(t)$, an unsatisfactory time response or even unstable closed-loop time response for $\sigma \to 0^+$. On the other hand, too aggressive dynamics caused by the AWC generates hectic reactions to the exceeding the saturation limits. In such a case, the AWC tries to recklessly reach the state $u(t) = \hat{u}(t)$ again regardless of the control process negatively influencing a linear behaviour of the controller.

Observer-based AWC design using anisochronic observer feedback for the controller of the retarded type with delays in internal states has been proposed and applied. The anisochronic observer is beneficial because it assures that there is only one tuning parameter in the AWC tuning procedure although the original (linear) controller dynamics is of infinite dimension. The value of the AWC parameter is determined with respect to ISE criterion optimizing the performance of entire closed loop subject to the present control action saturation. Rather heuristic tuning of the parameter is adopted but it does not undermine in any way the nature of the proposed AWC method.

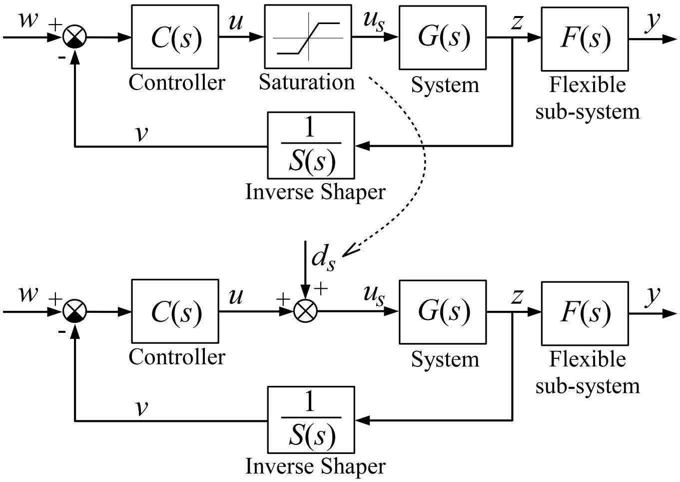

Figure 5.8: Interpretation of the saturation nonlinear function as a disturbance at the system input in the flexible mode compensation loop

5.4 Saturation effect in flexible mode compensation systems with inverse shaper

An input shaping architecture for vibration suppression of flexible systems controlled with magnitude saturated actuators is considered. It is shown that the distributed-delay shaper with the inverse form in the feedback path has the capability of canceling the undesired vibration caused by the actuator saturation. The main idea is to treat the saturation effect as a disturbance (see Fig. 5.8) on the control input of the actuator which can be canceled by the shaper in the feedback control loop. A laboratory set-up [B1] has been designed within this project and measurements were made during which real limitations occurred in the form of actuator saturation.

5.4.1 Experimental validation using a benchmark system: a cart with suspended pendulum

The first example illustrating the approach to a control action saturation in a control loop with inverse feedback DZV shaper is a pendulum attached to a controlled cart which can be considered as a gantry crane simplified demonstrator. Because the weight of the pendulum is noticeably smaller than the weight of the cart and the stiffness of a belt actuator is not negligible the laboratory set-up is considered as uncoupled.

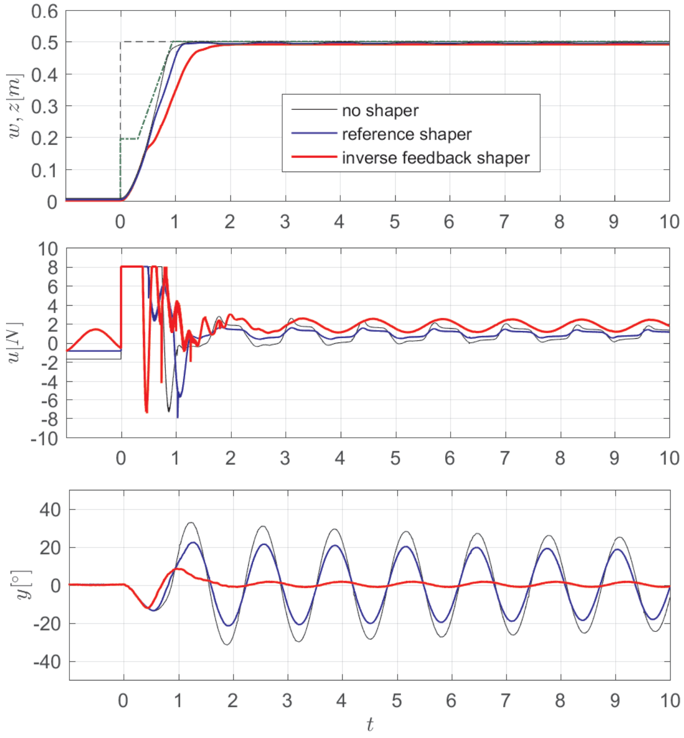

Figure 5.9: Experimental measurements with saturation for the experimental set-up when reference and inverse feedback shaper are applied (dashed - the reference w change; dash dotted - the reference shaped by the shaper $S(s)$)

It has been shown by the experiment (as illustrated in Fig. 5.9) with the laboratory cart with pendulum set-up that the recently proposed control architecture with an inverse feedback DZV shaper (2.2) can also successfully handle with actuator saturation. Although a simple uncoupled model not describing all dynamic properties of the cart (i.e. cart-rails friction) has been used, the control scheme gives very good results pursuant the flexible mode compensation.

5.4.2 Simulation validation using a benchmark system: a quadcopter with suspended pendulum

The objective of this section is to propose a scheme for controlling a quadcopter planar model as illustrated in Fig. 5.10 with a control sig-

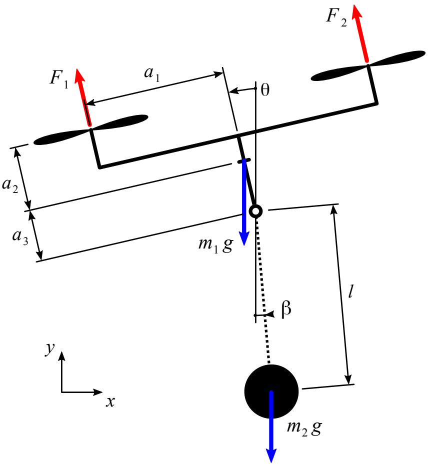

Figure 5.10: Quadcopter planar model with suspended load geometry

nal saturation considered which possibly requires an anti-windup scheme deployment. A classical cascade scheme will be applied, usual in UAV applications, see e.g. [25]. In order to prevent the payload swing during the maneuvers, an inverse input shaper is to be placed to a low-level (slave) feedback loop causing a presence of an artificial time delay in the entire closed-loop system. Despite the present saturation it will be shown that the control scheme with inverse feedback DZV shaper preserves good performance. Compared to the previous cart-pendulum experiment the following simulation-based example exhibits coupling between the masses demanding preliminary decoupling procedure deployment.

Using a simulation-based example, a beneficial saturation-tolerant behaviour of the inverse DZV shaper (2.2) placed in the feedback path has been illustrated. It has been shown that despite the fact that inclusion of the inverse shaper with delays to the feedback loop causes infinite dimensionality of the entire closed-loop system dynamics, it has positive impact on the overall control system with master PID and slave proportional-derivative (PD) controller both burdened by control action saturation.

6 Conclusion

Design and optimization of the anti-windup schemes for time-delay controllers is solved as the core topic of the thesis. As soon as time delays are involved in the controller structure, the controller forms an infinite dimensional system and its state is of functional nature. This makes the design of the anti-windup scheme a considerably more difficult task, compared to the delay-free controllers. Starting from the controllers of simple structure systems with input time delay, which are often used for approximation of higher order distributed parameter systems within process control field, anti-windup of both static and functional (dynamic) feedback are proposed and validated. Note that the latter allows to compensate the internal time delays in the anti-windup feedback scheme. By this, the infinite dimensional design task can be turned to finite dimensional one. Consequently, the functional character of the anti-windup scheme is extended to handle time delay controllers of enhanced structure, arising from application of the internal model principle, in particular. For designing the functional feedback, the Ackermann method modified for designing the time-delay system is applied.

Throughout the thesis, the objective is to tune the anti-windup scheme in order to compensate, at least partly, the loss in actuation due to the controller saturation. As a rule, it leads to considerably milder gains in the anti-windup feedback allowing a certain level of the control signal windup. This prolongs the time during which the control signal is stuck at the saturation level. Consequently, the entire power transferred to the system by the saturated actuation is enhanced by this setting, which can bring the saturated closed loop responses closer to the nominal closed loop responses without saturation. As the last topic of the thesis, the effect of saturation to the closed loop systems with applied time delay compensator, an inverse input shaper, is studied. Via interpreting the saturation effect as a disturbance at the system input, it is shown that the compensation performance is preserved under the saturation. Validation of this concept is performed on two case study examples. In what follows, the particular objectives are outlined:

Objective 1

This objective targets the character of the astatism of the so-called time delay feedback. The astatic nature of the controllers with feedback time delays, arising e.g. from application of IMC scheme, does not need to be visible at first sight, as it is the case for the astatic finite dimensional controllers with the polynomial characteristic equation. Besides, the functional nature of the controller state may bring different nature of the astatism, typically of staircase nature. These aspects have been studied by applying both analytical approach, and spectral tools. It has been shown that the feedback (state) delays, forming quasi-polynomials in a characteristic equation of a controller in a general, have potential to bring astatic behaviour when combined properly with the static gain. This needs to be taken into account while AWC is designed for such a controller. The feedback time delay has the same tendency to the windup effect as the pure integration. Moreover, the pronounced behaviour is even preserved for time-delay approximations commonly used for substituting pure time delays in order to obtain a delay-free (rational) transfer function. All pronounced statements are completed with some demonstration examples. The time delay astatism survey has been accepted as a preliminary study and presented in [B10]. Last but not least, another possible effects of time delay terms have been briefly introduced to clarify a diversity of time delay utilization.

Objective 2

Using beneficial dimensionless model forms, a general procedure for parameterization of observer-like AWC for low-order process models (FOPTD and SOPTD) controlled by both finite and infinite-order (time-delay) controllers have been proposed. Thus, the results derived on a relatively low set of simulations can be generalized to a broad class of systems. At first, the parametrization for a static AWC is studied giving a suggestion how to choose static parameters of AWC. Then, a novel functional AWC feedback is proposed in order to decrease the number of tuning parameters. Moreover, the functional feedback turns the dynamics of saturated controller to the equivalent finite order form of original *back-calculation technique* for PI controller. The tuning of the proposed AWC has been performed using IAE criterion applied to the control error in contrast with a general approach trying to minimize the saturation error. Thanks to that, the negative effect of control input saturation to the closed loop responses is minimized. The presented results are an extension of the original publications [B2] and [B6] with an emphasis on the systematic description of the solved problems and their results.

Objective 3

Based on the results obtained by the study of AWC for low-order controllers in Objective 2, the observer-like AWC scheme involving a functional state feedback has been generalized using anisochronic observer design. The deployment of the anisochronic observer facilitates the subsequent tuning, because it turns the procedure into finite-order pole assignment although the original dynamics of a controller may be of an infinite order. The parametrization of functional feedback is utilized by *Ackermann formula* extended for anisochronic systems. As a result, a single tuning parameter is determined to optimize the behaviour of the closed loop when the saturation vanishes. The subsequent tuning is performed with respect to ISE criterion applied to the control error. An example consisting of high-order time-delay model controlled by IMC controller with application of the proposed AWC concludes the chapter. The proposed method has been submitted in [B11].

Objective 4

As an outcome of participation in the related research subject, a study of the saturation effect to the performance of the closed loop with the feedback inverse shaper as an oscillatory mode compensator has been conducted. It has been shown, that the inverse DZV placed in the feedback path has a saturation-tolerant behaviour in combination with a stable controller. This behaviour is attributed to the disturbance rejection of such an arrangement with regard to the fact that the control input saturation is also pronounced as the artificial disturbance. Further, the mentioned saturation-tolerant behaviour has been verified using the experiment executed on set-up of a cart with a suspended pendulum and completed with simulation based case study of UAV planar motion cascade control. The core results were included in the publications [B3, B5] and [B7] (previously briefly presented in [B8]) as a contribution of author. The research continues with recent work [B12] which deals with oscillation damping using up and down movement with focus on UAV application in limited available space. The motivation for further research came from the partial work [B4] successfully treating oscillations using nonlinear time-delay feedback.

From the above outline of the results presented in the thesis, it can be concluded, that all the stated objectives have been fulfilled.

List of publications

[B1] D. Pilbauer, J. Bušek, V. Kučera, and T. Vyhlídal. “Laboratory set-up design for testing vibration suppression algorithms with time delays”. In: *Transactions of the VŠB - Technical University of Ostrava, Mechanical Series* 60.1 (June 2014), pp. 87–95. doi: `10.22223/tr.2014-1/1982`.

[B2] P. Zítek, J. Bušek, and T. Vyhlídal. “Anti-windup conditioning for actuator saturation in internal model control with delays”. In: *Low-Complexity Controllers for Time-Delay Systems*. Ed. by Alexandre Seuret, Hitay Özbay, Catherine Bonnet, and Hugues Mounier. Vol. 2. Advances in Delays and Dynamics. Springer International Publishing, 2014, pp. 31–45. isbn: 978-3-319-05575-6. doi: `10.1007/978-3-319-05576-3_3`.

[B3] B. Alikoç, J. Bušek, T. Vyhlídal, M. Hromčík, and A. F. Ergenç. “Flexible mode compensation by inverse shaper in the loop with magnitude saturated actuators”. In: *IFAC-PapersOnLine* 50.1 (2017). 20th IFAC World Congress, pp. 1251–1256. issn: 2405-8963. doi: `10.1016/j.ifacol.2017.08.350`.

[B5] J. Bušek, B. Alikoç, T. Vyhlídal, and P. Zítek. “Anti-windup scheme tuning for flexible mode compensation control loop”. 1st DECOD Workshop. Nov. 2017.

[B6] J. Bušek, T. Vyhlídal, and P. Zítek. “IAE based tuning of controller anti-windup schemes for first order plus dead-time system”. In: *2017 21st International Conference on Process Control (PC)*. June 2017, pp. 18–23. doi: `10.1109/PC.2017.7976182`.

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[B7] J. Bušek, M. Kuře, M. Hromčík, and T. Vyhlídal. “Control design with inverse feedback shaper for quadcopter with suspended load”. In: *Proceedings of the ASME 2018 Dynamic Systems and Control Conference*. 2018.

[B8] J. Bušek, M. Kuře, T. Vyhlídal, and M. Hromčík. “Time delay algorithms for control of a quadcopter with suspended load”. 14th IFAC workshop on time delay systems. 2018.

[B9] D. Pilbauer, W. Michiels, J. Bušek, D. Osta, and T. Vyhlídal. “Control design and experimental validation for flexible multi-body systems pre-compensated by inverse shapers”. In: *Systems & Control Letters* 113 (Mar. 2018), pp. 93–100. doi: `10.1016/j.sysconle.2018.01.002`.

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Education

2011 - 2018	CTU in Prague, Faculty of Mechanical Engineering Doctoral Study Programme: Mechanical Engineering, Technical Cybernetics
2009 – 2011	CTU in Prague, Faculty of Mechanical Engineering Master Study Programme: Mechanical Engineering, Control and Systems Engineering Master Thesis: Robust tuning of PID controller applied to water levitation system Graduated with Honors.
2005 – 2009	CTU in Prague, Faculty of Mechanical Engineering Bachelor Study Programme: Engineering, Instrumentation and Control Engineering Bachelor Thesis: Data acquisition from belt scales of stones sorting line Graduated with Honors.
2004 - 2005	Charles University, Faculty of Mathematics and Physics Bachelor Study Program: Physics 1st year finished.
2000 - 2004	Gymnazium Rumburk Final exams: Czech language, Mathematics, Physics, English.

Professional Experience

Sept. 2013 - present	teacher at Secondary Technical School Prosek Lessons: Automation, Mechatronics, Control and Regulation
Nov. 2011 - present	self-employer Consulting services in the field of industrial automation, PLC and SCADA programming, control system design, network configuration.

Jan. 2016 - present	Mechanical engineer in development at CTU in Prague, Faculty of Mechanical Engineering

Publications

Author or co-author of 5 papers in conference proceedings, 4 papers in journals and 1 chapter in book.

Web of Science: 5 records, h-index 1, 5 citations (without self citations)

Projects

2017 - 2019	Active multidimensional vibration absorbers for complex mechanical structures based on delayed resonator method
2018 - 2019	Time-delay control laws for upcoming transportation UAV systems
2018 - 2019	Centre for Applied Cybernetics 3

Additional Information

Languages	English spoken and written, very good command German spoken and written, basic communication skills
Awards	Prize of Josef Hlávka for the Best Students and Graduates ("Nadání Josefa, Marie a Zdeňky Hlávkových") (2011)