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Reference-dependent variable-gain control for a nano-positioning motion system[★]

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Abstract: In this paper, we develop a variable-gain (VG) control strategy that allows for a reference-dependent 'bandwidth' of the feedback controller. The proposed controller architecture can achieve improved performance given time-varying, reference-dependent performance requirements compared to linear time-invariant control, which suffers from design trade-offs between low-frequency tracking performance and sensitivity to higher-frequency disturbances. The VG controller consists of frequency-domain loop-shaped linear filters and a VG element. The gain of this element depends on reference information and determines the desired reference-dependent bandwidth of the resulting controller. We present data-based frequency-domain conditions to verify stability and convergence of the closed-loop system. The complete controller design process and the ability of the 'bandwidth-on-demand' controller to outperform linear time-invariant controllers are illustrated through experiments on an industrial nano-positioning motion system.

Keywords: Variable-gain control; bandwidth; performance; experiments.

1. INTRODUCTION

The increasing performance demands on speed, accuracy, throughput, etc., of today's high-precision motion systems require them to operate under diverse modes of operation, each related to a distinct set of performance requirements. If this comes with the presence of multiple disturbance sources, active in various frequency ranges, this poses a challenging control design task. This is due to the fact that the vast majority of controller designs techniques employed in the scope of motion control generally relies on classical linear control theory in which fundamental design trade-offs are inherently present. Namely, increasing the bandwidth of the controlled system improves the low-frequency disturbance rejection properties, and, hence, the tracking-performance, but due to the waterbed effect, this also results in a larger sensitivity to higher-frequency disturbances (i.e., around and/or above the bandwidth), see, e.g., Seron et al. (1997). This fundamental trade-off can already be challenging when just one mode of operation is considered, but this is severely aggravated when high performance is required in multiple modes of operation because this generally means that the control objectives vary over time, e.g., depend on the reference. Due to fundamental limitations in linear time-invariant (LTI) feedback control, the design of one LTI controller typically requires a compromise between these conflicting design goals thereby limiting the overall performance achievements of the controlled system.

In this paper, we propose a variable-gain (VG) control strategy that allows for a reference-dependent, and thus time-varying, 'bandwidth' of the feedback controller. By taking on-line reference information into account, this feature allows the controller to 'anticipate' on the required 'bandwidth' for each mode of operation. This allows, contrary to LTI control, to deal with the conflicting control objectives induced by reference-dependent dominance of multiple disturbance sources that are acting in various frequency ranges. The proposed controller consists of frequency-domain loop-shaped linear filters and a VG element, with its gain depending on reference information and inducing the desired 'bandwidth' of the resulting controller. The proposed controller structure supports the design of all the linear components of the VG controller configuration using well-known (frequency-domain) loop-shaping techniques, see, e.g., Steinbuch and Norg (1998). It therefore connects to the state-of-the-art industrial motion control setting, in which easy-to-measure frequency response functions (FRFs) play an important role in the controller design, e.g., by using frequency-domain loop-shaping techniques. This is in contrast to many other techniques that can deal with the considered trade-off, such as linear parameter varying (LPV) control, see, e.g., Groot Wassink et al. (2005); Shamma and Athans (1991) and switched controller design, see, e.g., Hespanha and Morse (2002); Liberzon (2003), which require accurate parametric models and LMI-based designs that are not so easily embraced by control engineers in industry.

The concept of VG control has already been successfully applied in numerous industrial applications to improve the performance of (linear) motion systems, see, e.g.,

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Hunnekens et al. (2014); Zheng et al. (2005); van de Wouw et al. (2008); Heertjes et al. (2009); Armstrong et al. (2001). In fact, the use of VG control to target similar LTI control design trade-offs as considered in this paper, i.e., balancing trade-offs between low-frequency tracking properties and sensitivity to higher-frequency disturbances, has been considered in e.g., van de Wouw et al. (2008); Heertjes et al. (2009). The novelty in our approach lies in the fact that we couple this fundamental trade-off to time-varying control objectives depending on on-line reference information, which makes it possible to design a time-varying controller with a 'bandwidth-on-demand' characteristic.

Summarizing, the main contributions of this paper are as follows. Firstly, a novel reference-dependent VG control strategy is introduced that has a 'bandwidth-on-demand' characteristic. Secondly, graphical data-based conditions to verify stability and convergence of the VG controlled closed-loop system are presented. Thirdly, the entire design process and its potential to outperform LTI controllers are experimentally demonstrated on an industrial case study of a nano-positioning motion stage.

1.1 Nomenclature

The following notational conventions will be used. Let $\mathbb{C}$, $\mathbb{R}$ denote the set of complex and real numbers, respectively, and $\mathbb{R}^n$ denote the space of n-dimensional vectors with the standard Euclidean norm denoted by $\|\cdot\|$. The real part of a complex variable z is denoted by $Re(z)$. The Laplace transform of a signal $x : \mathbb{R}_{\geq 0} \to \mathbb{R}^n$ is denoted by $\mathfrak{L}\{x\}$ and $s \in \mathbb{C}$ denotes the Laplace variable.

Moreover, let us make precise what is meant by bandwidth given its prominent role in this paper. Consider therefore the linear feedback control configuration in Fig. 1 with linear plant $\mathcal{P}(s)$, $s \in \mathbb{C}$, and a linear controller $\mathcal{C}(s)$. The bandwidth ω_b is defined as the frequency $\omega \in \mathbb{R}^+$, where the magnitude of the open-loop $|\mathcal{P}(j\omega)\mathcal{C}(j\omega)|$ crosses 1 from above for the first time, see, e.g., Skogestad and Postlethwaite (2005). By definition, bandwidth is a linear time-invariant (LTI) concept and, hence, does not apply to our proposed time-varying control strategy. Nevertheless, with abuse of definition, we will use the term 'bandwidth' in this paper (to indicate the bandwidth of the linear controller underlying the proposed strategy) but use quotation marks to avoid confusion with the LTI case. Moreover, from this point onward we sometimes use the terms 'low-bandwidth/high-bandwidth' controller to denote a controller that results in a low/high bandwidth, respectively.

2. SYSTEM DESCRIPTION AND PROBLEM FORMULATION

The nano-positioning motion system considered in this paper is an experimental setup of a high-precision motion system that requires movements with velocities ranging from standstill, to nanometers per second (nm/s), to even millimeters per second (mm/s), all with (sub)nanometer resolution. The nano-positioning motion system has several key modes of operation, namely: (i) standstill, (ii) constant velocities in a broad range, and (iii) fast (user-operated) point-to-point movements. We will show that due to the presence of multiple disturbance sources in various frequency ranges (depending also on the mode of operation), this results in conflicting control design trade-offs when using LTI control.

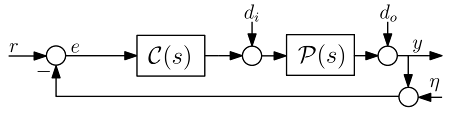

Fig. 1. Schematic representation of a classical LTI feedback controlled system.

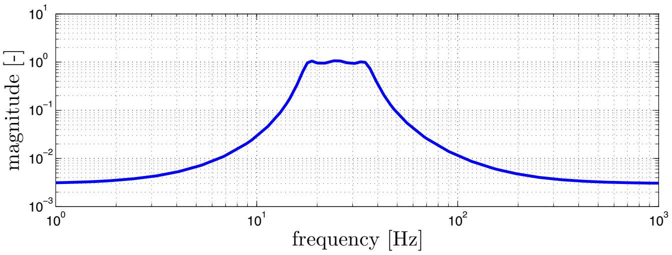

Fig. 2. Bode magnitude plot of the filter $\mathcal{H}(j\omega)$.

2.1 Nano-positioning motion stage

The nano-positioning motion system is driven by piezoelectric actuators, positioned on a vibration isolation table and equipped with a 1^{st}-order 100 Hz low-pass actuation filter $\mathcal{P}_{act}(s)$ in the hardware to filter off high-frequency actuator noise. Based on measured frequency response functions, it is known that, firstly, the plant $\mathcal{P}_n(j\omega)$ behaves as a rigid-body system in the frequency range of interest, and secondly, the presence of a significant, and thus bandwidth-limiting, delay.

Consider Fig. 1, in which the plant is given by $\mathcal{P}(s) = \mathcal{P}_n(s)\mathcal{P}_{act}(s)$. Based on identification[1], the following disturbances are acting on the system: Sensor noise η, modeled as white noise with zero mean and variance $\lambda_\eta^2 = (10^{-9})^2$, actuator noise $d_{i,act}$ modeled as white noise with zero mean and variance $\lambda_{d_{i,act}}^2 = (\sqrt{10^{-19}})^2$, and periodic impact disturbances $d_{i,p}$ (induced by piezoelectric actuators) that depend on the reference velocity v. Moreover, because the experimental nano-positioning motion setup operates in a lab-environment instead of in its dedicated application, additional environmental disturbances are emulated to recover the real situation in the application as much as possible. Based on measurement data, an output disturbance $d_{o,add} = \mathcal{H}(s)\varepsilon$ has been identified, where the magnitude of $\mathcal{H}(j\omega)$ is depicted in Fig. 2 and ε is normally distributed white noise with zero mean and variance $\lambda_\varepsilon^2 = (2 \cdot 10^{-9})^2$.

2.2 Problem formulation

Let us now study the control design trade-off in a model-based environment, in which $\mathcal{P}_n(s)$ represents a 2^{nd}-order LTI model identified based on measured FRF data. In

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[1] To protect the interests of the manufacturer, we can not provide concrete information about the disturbance modeling and the reference velocities (and thus scheduling variables v to be introduced later). For the same reason, most figures in this paper have either been scaled or use blank axes in terms of units.