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1 Introduction

To meet future performance specifications, the product roadmap of high-precision mechatronic systems is typically translated toward servo-control in the direction of increased controller bandwidths. However, using linear control elements, the associated bandwidth is often limited by Bode's gain-phase relationship. In order to possibly surpass this fundamental limitation, recently in [1] a hybrid integrator-gain element (HIGS) has been introduced. Depending on specific switching conditions, this element switches between an integrator and gain mode in such a manner that the output is continuous, confined to a sector, and always of equal sign to the input. As such, the corresponding describing function $\mathscr{D}(j\omega)$ demonstrates first-order low-pass characteristics with a phase lag of only 38.15 degrees. Driven by the apparent phase advantage, in this abstract the idea of HIGS-based controller elements for bandwidth improvements of essentially linear systems is discussed.

2 HIGS-Based Controller Elements

A HIGS-based controller element is proposed as the series interconnection of the HIGS and a linear filter $\mathscr{N}(s)$. Through specific design of this filter, the element's describing function

$$\mathscr{D}_{NL}(j\omega) = \mathscr{D}(j\omega)\mathscr{N}(j\omega), \quad (1)$$

can be shaped in such a manner that it has desirable magnitude characteristics with reduced phase lag. For the purpose of example, consider the HIGS in series with a filter $\mathscr{N}(s)$, given in frequency domain by:

$$\mathscr{N}(s) = \frac{\omega_{lp}^2}{\omega_2} \cdot \frac{1}{s+\omega_1} \cdot \frac{(s+\omega_1)(s+\omega_2)}{s^2 + 2\beta\omega_{lp}s + \omega_{lp}^2}, \quad (2)$$

with corner frequencies ω_i, $i \in \{1,2\}$, ω_{lp}, and dimensionless damping coefficient β. It follows from the first-order low-pass characteristics of the HIGS, that by appropriate tuning of ω_2 in (2), the describing function (1) has similar magnitude characteristics as a classical linear second-order low-pass filter with complex poles, however, with significantly reduced phase lag. From a linear point-of-view, elements with such apparent properties could potentially aid the loopshaping design, and give rise to increased bandwidths.

3 Wafer Stage Measurement Results

To illustrate the potential of a HIGS-based controller, the nonlinear second-order low-pass filter is experimentally embedded in the motion control context of Fig. 1. Here, $\mathscr{C}$ is some base-linear controller (e.g. PID and notch filters) and $\mathscr{P}$ represents a scanning stage of an industrial wafer scanner. Using a quasi-linear loopshaping procedure, eval-

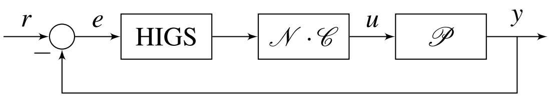

Figure 1: Feedback control structure.

uated through describing functions, the controller is structurally tuned and shows a bandwidth improvement of around 11% compared to an optimal linear controller design. Time-domain measurement results of several experiments are presented in Fig.2 in terms of the moving average $\mathscr{M}_A$ and the moving standard deviation $\mathscr{M}_{SD}$. These performance measures reflect the low-and high-frequency content of the measured data-sampled error $e(t)$, respectively. The results of the nonlinear controller (red) are compared to those of an optimally tuned linear controller (black). A substantial im-

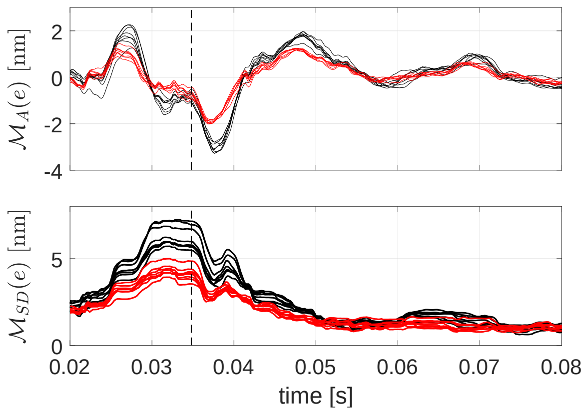

Figure 2: Moving average $\mathscr{M}_A(e)$ and moving standard deviation $\mathscr{M}_{SD}(e)$ for the linear (black) and nonlinear (red) closed-loop system.

provement in low-frequency disturbance suppression can be observed, without deterioration of the $\mathscr{M}_{SD}$. Although no rigorous stability criteria for the true nonlinear system are specified, this real-world closed-loop example shows convincingly robustly stable behavior.

References

[1] D.A. Deenen, M.F. Heertjes, W.P.M.H. Heemels and H. Nijmeijer, Hybrid integrator design for enhanced tracking in motion control, *American Control Conference*, (2017).