Hybrid integrator-gain systems:

An overview of some recent results

B. Sharif[1], M.F. Heertjes[1,2] , H. Nijmeijer[1], W.P.M.H. Heemels[1]

[1]Department of Mechanical Engineering, Eindhoven University of Technology, The Netherlands

[2] Mechatronics System Design Department, ASML, The Netherlands

b.sharif@tue.nl

Abstract

Hybrid integrator-gain systems (HIGS), are control elements recently introduced to overcome fundamental limitations of linear time-invariant (LTI) control [1], and have enjoyed engineering success in control of high precision mechatronics. Similar to reset integrators, HIGS have a phase advantage over linear integrators (see Figure 1b below). However, as shown in Figure 1a, contrary to reset integrators, HIGS achieve this phase advantege while generating continuous control signals which

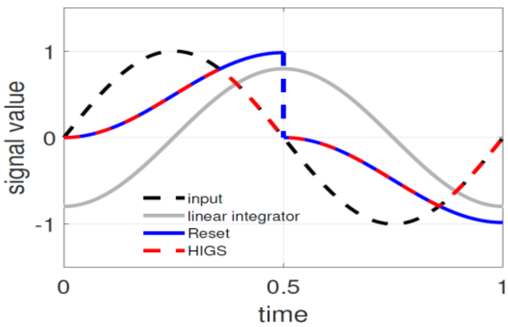

Figure 1a: Response of a linear integrator, a reset integrator and a HIGS element to a sinusoidal input.

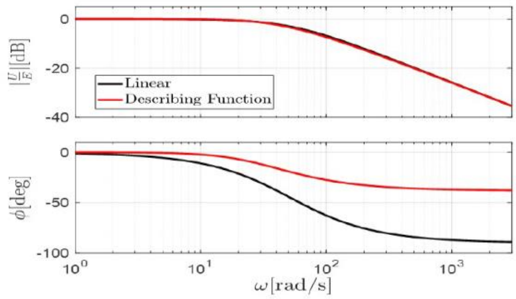

Figure 1b: Describing function of HIGS vs Bode plot of a linear lowpass filter

appear beneficial for example in dynamical systems that have lightly-damped flexible modes. HIGS are formally studied in the framework of extended projected dynamical systems (ePDS) and are shown to be well-posed in the sense of existence and forward completeness of solutions. Using the ePDS framework, we also obtain sufficient conditions, in the form of linear matrix inequalities (LMIs) to verify properties such as incremental stability and convergence [2] of HIGS-controlled systems. It is also possible to achieve performance objectives using HIGS-based control, that are impossible to achieve with any LTI controller. As an example, in Figure 2, the step-response of a closed-loop

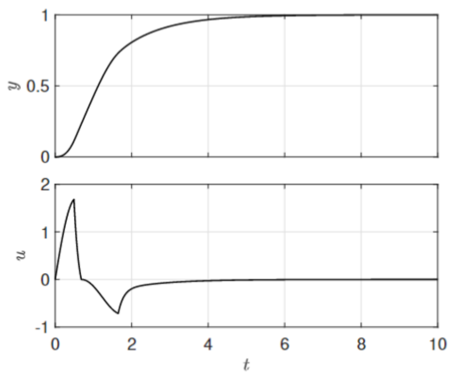

Figure 2: Step-response of HIGS-controlled system with a double integrator plant.

HIGS-controlled system wherein the plant contains two open-loop integrators, is shown. Note that no overshoot in the step-response can be observed. Given that the plant has two open-loop integrators, as shown in [3], a step response with no overshoot would be impossible to achieve with any LTI controller.

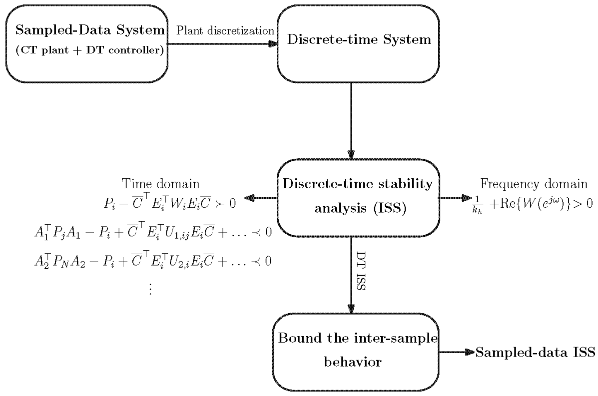

Figure 3: Procedure for smapled-data analysis

Furthermore, given that HIGS-based controllers are implemented digitally and thus in discrete-time (DT), HIGS-controlled systems are essentially sampled-data (SD) systems consisting of DT controllers and continuous-time (CT) plants. To analyze stability of these systems, the procedure in Figure 3 is proven useful. As shown in Figure 3, we propose two approaches for stability analysis. The first approach has the advantage of solely relying on the easy-to-measure frequency response functions. The second approach relies on the feasibility of a set of LMIs, which may appear less insightful and numerically challenging but provide less conservative results (see Figure 4 below).

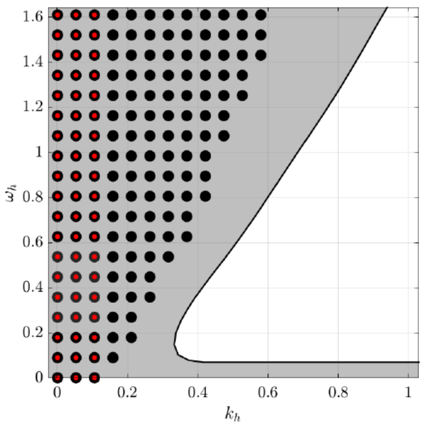

Figure 4: An example with stable region (gray area), LMI results (black dots), frequency domain results (red dots) as function of design paramters of HIGS.

As an industrial application, let us consider the industrial active vibration isolation system in Figure 5.

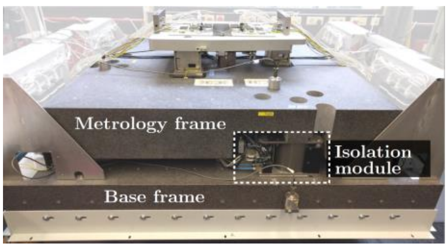

Figure 5: Active vibration isolation system

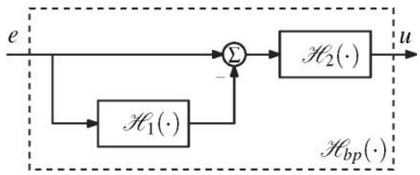

Figure 6: HIGS-based band-pass filter

Such a system is used in high precision mechatronic applications, such as in wafer scanners, to isolate the optical systems, e.g., the projection lens, from frame and/or floor vibrations. At the same time, such a system houses (among others) the interferometers used for stage positioning measurement and as such provides a reference for measurement, which is called metrology frame. A HIGS-based bandpass filter is proposed as in Figure 6, for active vibration isolation with improved skyhook damping [4]. As portrayed in Figure 7, our experiments show superior transient performance in terms of settling time and overshoot. In addition, as shown in Figure 8, the HIGS-based bandpass filter has a reduced phase lag when compared to the linear bandpass filter. This in turn allows for significantly larger active damping gains ζ, thereby enabling superior active vibration isolation.

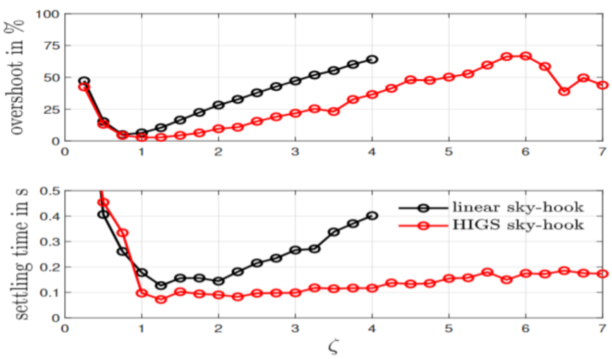

Figure 7: Transient performance vs damping gain ζ.

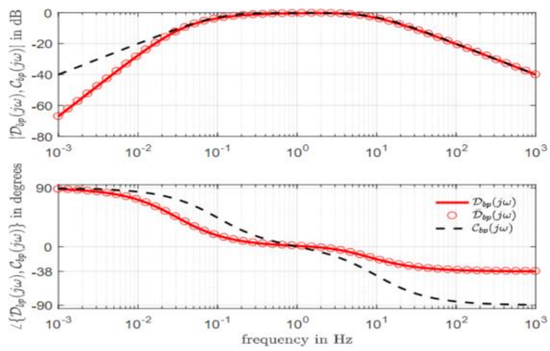

Figure 8: Bode diagram of LTI bandpass filter $C_{bp}(j\omega)$ and describing function of HIGS-based filter $D_{bp}(j\omega)$.

Future work related to HIGS include multivariable HIGS-based control, formulation of less conservative frequency-domain stability analysis tools as well as other HIGS-based control designs such as PID and lowpass filter design for motion control, PI^{3}D design for control of projection optics as well as synthesis of HIGS-based controllers.

References:

[1]- D. Deenen, B. Sharif, S. van den Eijnden, H. Nijmeijer, M. Heemels, M. Heertjes, Projection-based integrators for improved motion control: Formalization, well-posedness and stability of hybrid integrator-gain systems, Automatica,2021.

[2] – A. Pavlov, N. van De Wouw, H. Nijmeijer. Uniform output regulation of nonlinear systems: a convergent dynamics approach , Birkhäuser, 2006.

[3]- M.M. Seron, J. H. Braslavsky, G.C. Goodwin, Fundamental limitations in filtering and control., Springer Science & Business Media, 2012.

[4]- M. Heertjes, S. van den Eijnden, B. Sharif, M. Heemels, H. Nijmeijer. Hybrid integrator-gain system for active vibration isolation with improved transient response. IFAC-PapersOnLine, 2019.