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LMI-Based Impulsive Observers for Sampled-Output Linear Descriptor Systems ⋆

J. Álvarez * **B. Castillo-Toledo.** *

* *CINVESTAV, Unidad Guadalajara, Zapopan, Jalisco, México.*
(e-mail: jorge.alvarez@cinvestav.mx).

Abstract: This paper introduces an impulsive observer for linear differential-algebraic equations systems with outputs available only at discrete sampling instants. By exploiting the Kronecker decomposition of the pencil (E, A) and modeling each sample as an impulse, we derive a discrete-time error recursion. A Lyapunov-based LMI framework is then formulated to enforce Schur-stability of the impulsive error. The resulting convex synthesis directly computes the observer gain, guaranteeing exponential convergence of the continuous-time estimation error. Numerical examples illustrate convergence behavior of the proposed impulsive observer.

Keywords: Impulsive observer, DAE systems, Lyapunov, Sampled output, Linear matrix inequalities.

1. INTRODUCTION

Descriptor systems, also known as differential–algebraic equation (DAE) models, arise in a wide range of engineering and scientific applications where dynamic behavior is coupled with algebraic constraints. Such models naturally capture phenomena in constrained mechanical systems, electrical power networks, chemical reaction processes and multibody dynamics, among others Dai (1989). The presence of a singular matrix imposes both differential and algebraic relations, rendering classical state–space analysis tools insufficient. In particular, issues of existence and uniqueness of solutions, regularity of the matrix pencil, and impulse-free initialization must be addressed explicitly. Over the last decade, convex optimization techniques—particularly those based on linear matrix inequalities (LMIs)—have enabled systematic analysis and controller/observer design for descriptor models Darouach et al. (2017); Koenig et al. (2016); Oucief et al. (2016); Luzanilla et al. (2021); Huang et al. (2021); Jafari and Binazadeh (2020); Zhang et al. (2021); Perez and Mera (2015); Portela et al. (2025).

State estimation for continuous-time descriptor systems has been tackled through functional observers, interval observers and unknown-input observers. Functional observers aim to reconstruct specified combinations of states rather than the full state vector and have been synthesized via LMIs in Darouach et al. (2017). Interval observers provide guaranteed bounds on each state component under model uncertainties and switching Huang et al. (2021), while adaptive schemes handle Lipschitz nonlinearities and unknown disturbances Oucief et al. (2016). Switched descriptor systems and quantized measurements have been incorporated through robust LMI frameworks in Perez and Mera (2015), and tracking with constrained inputs has been addressed in Jafari and Binazadeh (2020). Recently, prescribed-time functional observers for descriptor models with unknown inputs were proposed in Zhang et al. (2021).

In parallel, the observer design problem for nonlinear DAEs has been studied in Álvarez et al. (2022); Bernal et al. (2025), where sufficient LMI-based conditions are given for continuous-time observer gain design. On the other hand, the sampled-data observer problem for ordinary differential equation (ODE) systems has been studied extensively. The work in Guillén-Flores et al. (2013) introduced LMI conditions for sampled-data observers, later extended to handle Lipschitz nonlinearities Dinh et al. (2015), for Takagi-Sugeno systems in Jaramillo et al. (2020), measurement delays, and multirate sampling Zhang et al. (2016b); Zhang and Shen (2017); Zhang et al. (2016a). Robust trade-offs between convergence and sampling intervals were analyzed in Yu and Shen (2018), while the impulsive-system formalism introduced in Briat (2016) provided a unifying framework by modeling sampling as discrete jumps, leading to stability results via dwell-time LMIs.

Despite these advances, the intersection of DAEs and sampled-data observers remains under-explored. Most descriptor-observer methods assume continuous output feedback or address functional estimation Darouach et al. (2017); Koenig et al. (2016), but do not explicitly model the hybrid nature induced by periodic sampling. Impulsive observers—where the continuous DAE dynamics are periodically reset using discrete measurements—are particularly appealing for modern digital implementations, yet no systematic LMI-based design exists for full-order state estimation in this context.

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To fill this gap, we propose a novel hybrid impulsive observer for linear descriptor systems with measurements available only at sampling instants. By exploiting the Kronecker decomposition Dai (1989); Kunkel and Mehrmann (2006) of the descriptor pencil and representing the sampling process as an impulse, we derive a discrete-time error recursion that captures both differential and algebraic modes. We then formulate a discrete-time Lyapunov argument yielding convex LMIs for observer gain synthesis. Our main contributions are:

- *Hybrid formulation.* An impulsive observer structure is proposed, where the state estimation evolves according to a DAE between sampling instants and is updated through impulsive corrections at measurement times. This formulation integrates algebraic constraints naturally within a hybrid dynamical framework.
- *LMI-based synthesis.* LMI conditions for the design of the observer gain are established, guaranteeing Schur stability of the impulsive error dynamics. The resulting conditions are convex and suitable for numerical implementation via semidefinite programming.

The rest of this paper is organized as follows. Section 2 presents the preliminaries on linear DAEs systems and the problem formulation. Section 3 states the main design result, deriving the impulsive observer and its LMI-based synthesis conditions. Section 4 provides two numerical examples that illustrate the convergence and robustness of the proposed observer. Finally, Section 5 concludes the paper and outlines directions for future work.

2. PRELIMINARIES AND PROBLEM FORMULATION

In this work, we focus on linear differential–algebraic equation systems with sampled output of the form

$$\begin{aligned} E\dot{x}(t) &= Ax(t) + Bu(t), \quad \forall t \geq 0, \\ y(k\delta) &= Cx(k\delta), \quad \forall k \in \mathbb{Z}^+ \end{aligned} \tag{1}$$

where $x(t) \in \mathbb{R}^n$ is the state, $u(t) \in \mathbb{R}^r$ the input, $y(k\delta) \in \mathbb{R}^m$ is the measurement output available only at discrete instants $k\delta$ with the sampling period $\delta > 0$. and $E, A \in \mathbb{R}^{n\times n}$, $B \in \mathbb{R}^{n\times r}$, and $C \in \mathbb{R}^{m\times n}$ are constant matrices. We consider that the matrix E can be singular, imposing both differential and algebraic constraints on x. In order to guarantee the existence and uniqueness of the solution of the linear DAE system (1), we assume there exist $\gamma \in \mathbb{C}$ such that $\det(\gamma E - A) \neq 0$, i.e., the matrix pencil $\gamma E - A$ is regular.

Lemma 1. (Darouach (2014)). Consider the descriptor system (1) with $u(t) = 0$. The triplet (C, E, A) is said to be *impulse-observable* if and only if every impulse in the output $y(t)$ for $t > 0$ implies a corresponding impulse in the state $x(t)$ for $t > 0$. Equivalently, the triplet (C, E, A) is impulse-observable if and only if one of the following matrix rank conditions holds

$$\operatorname{rank}\begin{bmatrix} E & A \\ 0 & E \\ 0 & C \end{bmatrix} = n + \operatorname{rank}(E),$$

$$\text{or equivalently} \quad \operatorname{rank}\begin{bmatrix} E^{\perp}A \\ C \end{bmatrix} = n,$$

where a full-row-rank matrix $E^{\perp} \in \mathbb{R}^{(n-l)\times n}$ is such that

$$E^{\perp}E = 0, \quad E^{\perp}(E^{\perp})^T > 0,$$

with $l = \operatorname{rank}(E)$.

Lemma 2. (Duan (2010)). Under the regularity assumption, there exist nonsingular matrices $M, Q \in \mathbb{R}^{n\times n}$ and an integer $l \leq n$ such that

$$M\,E\,Q = \begin{bmatrix} I_l & 0 \\ 0 & N \end{bmatrix}, \qquad M\,A\,Q = \begin{bmatrix} J & 0 \\ 0 & I_{n-l} \end{bmatrix},$$

where $J \in \mathbb{R}^{l\times l}$ is in real Jordan form and $N \in \mathbb{R}^{(n-l)\times(n-l)}$ is a nilpotent matrix.

The above decomposition separates the finite dynamics $\dot{z}_1 = J\,z_1$, from the algebraic constraints $N\,\dot{z}_2 = z_2$, where $z = Q^{-1}x = \begin{bmatrix} z_1^T & z_2^T \end{bmatrix}^T$.

Problem formulation: Consider the sampled-output DAE system (1) with regular pencil (E, A) and assume that (C, E, A) is impulse-observable. Consider an impulsive observer with the following DAE structure

$$\begin{aligned} E\dot{\hat{x}}(t) &= A\hat{x}(t) + Bu(t), \quad \forall t \geq 0, \\ \hat{y}(k\delta) &= C\hat{x}(k\delta), \quad \forall k \in \mathbb{Z}^+, \\ \hat{x}(k\delta^+) &= \hat{x}(k\delta) - G(y(k\delta) - \hat{y}(k\delta)), \end{aligned} \tag{2}$$

where $\hat{x}(k\delta^+) := \lim_{\varepsilon\to 0} \hat{x}(k\delta + \varepsilon)$ and G is the observer gain to be designed such that the error signal $e(t) = x(t) - \hat{x}(t)$ satisfies

$$\lim_{t\to\infty} e(t) = 0 \tag{3}$$

for all consistent initial conditions.

3. IMPULSIVE OBSERVER FOR DAES SYSTEMS

In this section, we present the main result as a formal theorem, which gives sufficient conditions in the form of linear matrix inequalities to design the observer gain. These conditions capture both the continuous-time error propagation between samples and the discrete-time impulsive correction. The feasibility of the LMIs directly yields a gain that ensures the asymptotic convergence of the estimation error.

Theorem 3. The observer state $\hat{x}(t)$ of the impulsive observer DAE system (2) converges asymptotically to the state $x(t)$ of the DAE system (1) if there exist matrices $P > 0$ and $Y \in \mathbb{R}^{n\times m}$, such that the following LMI is satisfied

$$\begin{bmatrix} -P & \Phi(\delta)^T P + \Phi(\delta)^T C^T Y^T \\ P\,\Phi(\delta) + Y\,C\,\Phi(\delta) & -P \end{bmatrix} < 0, \tag{4}$$

for some $\delta > 0$. The observer gain is recovered as $G = Y\,P^{-1}$.

Proof. Define the continuous-time error $e(t) = x(t) - \hat{x}(t)$, which, between sampling instants $t \neq k\delta$, has the following dynamic

$$E\,\dot{e}(t) = E\dot{x}(t) - E\dot{\hat{x}}(t) = A\,e(t). \tag{5}$$

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By regularity and consistent initialization, the solution of the system (1) is continuous at sampling instants, thus $x(k\delta^+) = x(k\delta)$, the updated error for each sampling period is $e(k\delta^+) = x(k\delta^+) - \hat{x}(k\delta^+)$ and combining with the last equation in (2) can be written as

$$e(k\delta^+) = (I + G\,C)\,e(k\delta). \tag{6}$$

In order to solve (5), we consider the Kronecker form defined in Lemma 2, defining the following change of variable

$$z(t) \;=\; Q^{-1}\,e(t) \;=\; \begin{bmatrix} z_1(t) \\ z_2(t) \end{bmatrix}, \quad z_1 \in \mathbb{R}^l,\; z_2 \in \mathbb{R}^{n-l},$$

therefore, the dynamic equation (5) can be written in the new variables as

$$\dot{z}_1(t) = J\,z_1(t), \quad N\,\dot{z}_2(t) = z_2(t).$$

The solution of the finite-dimensional subsystem over $[k\delta^+, (k+1)\delta]$ is

$$z_1(t) = \exp\big(J\,(t - k\delta)\big)\,z_1(k\delta^+),$$

due to the decomposition in Lemma 2 satisfies $N\dot{z}_2 = z_2$ with $N^\nu = 0$ and consistent initial data $z_2(k\delta^+) = 0$, the only classical solution is $z_2(t) \equiv 0$ for $t \geq k\delta$ Dai (1989). Thus, the consistency manifold is $\mathcal{M} := \{e = Qz \in \mathbb{R}^n : \; z_2 = 0\}$. For any $\tau \geq 0$, we define the map $\Phi(\tau) : \mathcal{M} \to \mathcal{M}$ by

$$\Phi(\tau) : e(k\delta^+) \mapsto e(k\delta + \tau) = Q\begin{bmatrix} \exp(J_r\tau) & 0 \\ 0 & 0 \end{bmatrix} Q^{-1}e(k\delta^+),$$

so that for $\tau = \delta$ we have

$$e\big((k+1)\delta\big) = \Phi(\delta)\,e(k\delta^+).$$

Combining the above equation with the impulsive update (6) gives the discrete-time error

$$\begin{aligned} e\big((k+1)\delta^+\big) &= (I + G\,C)\;e\big((k+1)\delta\big) \\ &= (I + G\,C)\,\Phi(\delta)e(k\delta^+). \end{aligned} \tag{7}$$

Considering the candidate Lyapunov function

$$V(e_k) = e_k^T P\,e_k, \qquad P = P^T > 0,$$

where $e_k = e(k\delta^+)$, its one-step difference is

$$\begin{aligned} \Delta V &= V(e_{k+1}) - V(e_k), \\ &= e_k^T\Big[(I + GC)\Phi(\delta)\Big]^T P(I + GC)\Phi(\delta)e_k - e_k^T P e_k. \end{aligned}$$

Requiring $\Delta V < 0$ for all $e_k \neq 0$ yields the condition

$$\big[(I + G\,C)\,\Phi(\delta)\big]^T P\,(I + G\,C)\,\Phi(\delta) \;-\; P \;<\; 0$$

which by Schur's complement is equivalent to

$$\begin{bmatrix} -P & \big[(I + G\,C)\,\Phi(\delta)\big]^T P \\ P\,(I + G\,C)\,\Phi(\delta) & -P \end{bmatrix} < 0,$$

defining $Y = PG$, and applying congruence with $\mathrm{diag}\{I, P\}$, the condition becomes linear in the pair (P, Y), yielding exactly the LMI of Theorem 3. Moreover, since feasibility of the LMI implies that the discrete-time operator $(I + G\,C)\,\Phi(\delta)$ is Schur stable, there exists a scalar $\rho \in (0, 1)$ such that

$$\|e_{k+1}\| \;\leq\; \rho\,\|e_k\|, \qquad \forall k \geq 0.$$

Furthermore, for any $t \in [k\delta, (k+1)\delta)$, the continuous evolution satisfies

$$e(t) = \Phi\big(t - k\delta\big)\,e_k,$$

and the flow matrix $\Phi(\tau)$ is bounded on $[0, \delta]$, i.e. there exist $H > 0$ with $\|\Phi(\tau)\| \leq H$. Hence

$$\|e(t)\| \;\leq\; H\,\|e_k\| \;\leq\; H\,\rho^k\|e(0)\| \;\to\; 0 \quad \text{as } k \to \infty,$$

which shows $\lim_{t\to\infty} e(t) = 0$. This completes the proof.

Remark 4. Several practical considerations should be noted when implementing the impulsive observer design:

- *Initial consistency.* The initial estimate $\hat{x}(0)$ must satisfy the algebraic constraints of the original DAE to avoid numerical inconsistencies during continuous integration.
- *Sampling period selection.* Although the LMI guarantees convergence for any $\delta > 0$, a very large δ can lead to poor conditioning of $\Phi(\delta)$ and insufficient impulsive correction. It is advisable to test and adjust δ in practical implementations.
- *Impulse-observability requirement.* The method relies on (C, E, A) being impulse-observable. If this condition fails, hidden impulsive modes will not be corrected and will manifest as persistent errors in the algebraic components.
- *Numerical robustness.* Computing Q and $\Phi(\delta)$ may involve inverting near-singular matrices. Use numerically stable decompositions (e.g. Schur or QR Golub and Van Loan (2013); Trefethen and Bau (1997)) and scaling techniques to improve reliability.
- *Decay rate tuning.* To impose a desired exponential decay rate $\alpha > 0$, replace the LMI $\Phi(\delta)^T P\,\Phi(\delta) - P < 0$ with $\Phi(\delta)^T P\,\Phi(\delta) - \exp\big(-2\alpha\delta\big)P < 0$, directly enforcing the rate in the discrete-time contraction Boyd et al. (1994).

4. NUMERICAL EXAMPLES

In this section two numerical examples are provided to illustrate the effectiveness of the approach seen in the previous Section 3.

Example 1. Considering the DAE system (1) with the following matrices

$$E = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix},\; A = \begin{bmatrix} 1 & -2 & 2 & 1 \\ 0 & -1 & 1 & 0 \\ 0 & 0 & 1 & 1 \\ 1 & 1 & 0 & 1 \end{bmatrix},\; B = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix},\; C = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 1 \\ 0 & 0 \end{bmatrix}^T.$$

It can be easily checked that the pencil of (E, A) is regular and the triplet (C, E, A) is impulse-observable. Considering the impulsive DAE observer (2), the error dynamics can be written as follows

$$\begin{aligned} E\,\dot{e}(t) &= A\,e(t), \quad \forall t \neq k\delta \\ e(k\delta^+) &= (I + G\,C)\,e(k\delta), \quad t = k\delta. \end{aligned}$$

By Lemma 2, the Kronecker form can be obtained with the matrices

$$M = \begin{bmatrix} 0 & -1 & 1 & -1 \\ -1 & 1 & 1 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad Q = \begin{bmatrix} -1 & -1 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ -2 & -1 & 1 & -1 \\ 2 & 1 & 0 & 1 \end{bmatrix},$$

$$J = \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix}, \quad N = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}.$$

Finally the matrix $\Phi(\delta)$ is obtained considering $\delta = 0.1$. The LMI (4) has been programmed using the LMI-Toolbox Gahinet et al. (1995) within MATLAB R2023b platform, obtaining a feasible solution with the following matrices

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$$P = 63.07 I_4,\ Y = \begin{bmatrix} -63.08 & 0 \\ 31.54 & -31.54 \\ -31.54 & -31.54 \\ 31.54 & 31.54 \end{bmatrix},\ G = \begin{bmatrix} -1 & 0 \\ 0.5 & -0.5 \\ -0.5 & -0.5 \\ 0.5 & 0.5 \end{bmatrix}.$$

For simulation, we consider the control signal $u(t) = -4x_1 + 4\sin(6t) + 0.5\cos(18t)$ which can be seen in Figure 1, and the consistent initial conditions $x(0) = [-0.5,\ 1,\ 0.5,\ -0.5]^T$ for the DAE system, and $\hat{x}(0) = 0$ for the impulsive observer. Figures 2 and 3 show the time evolution of the system state $x(t)$ (dashed lines) and their corresponding observer estimates $\hat{x}(t)$ (solid lines). The plots confirm that the proposed impulsive observer achieves rapid convergence after a few samples, with negligible steady-state error even in the presence of oscillatory input signals. Figure 4 plots the error signals $e(t)$, confirming the asymptotic convergence of the observer state signals to the real ones.

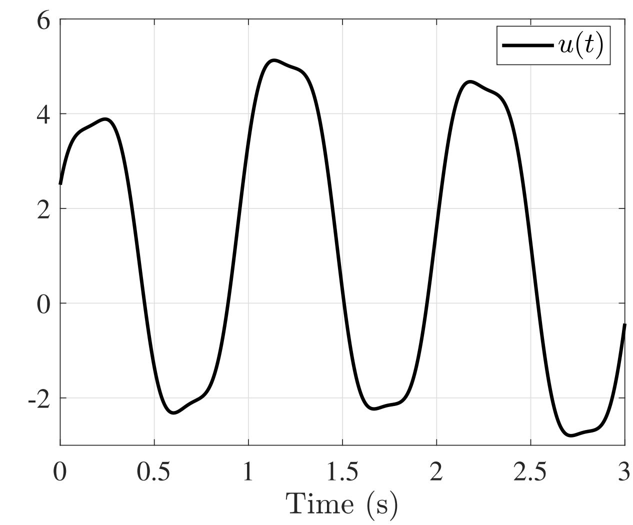

Fig. 1. Example 1: control signal.

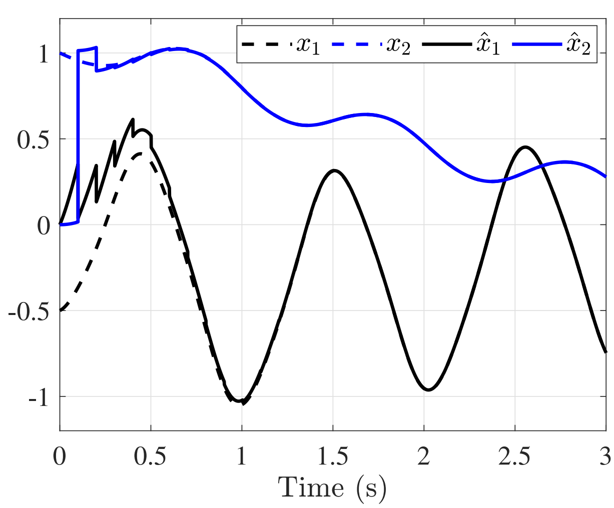

Fig. 2. Example 1: system states x_1, x_2 vs observer states $\hat{x}_1$, $\hat{x}_2$.

Example 2. Consider the DAE system (1) with the following matrices

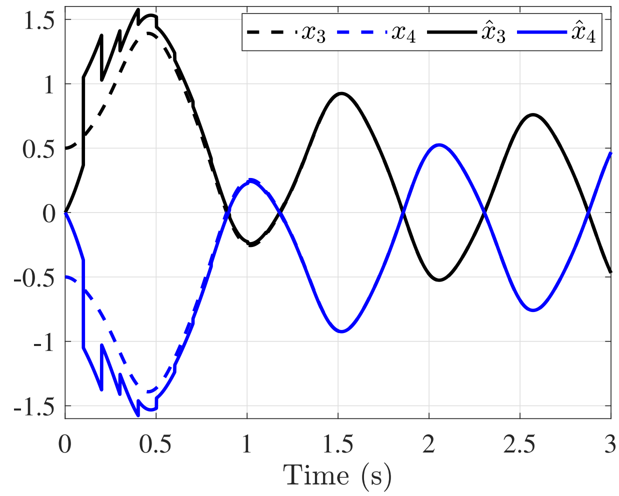

Fig. 3. Example 1: system states x_3, x_4 vs observer states $\hat{x}_3$, $\hat{x}_4$.

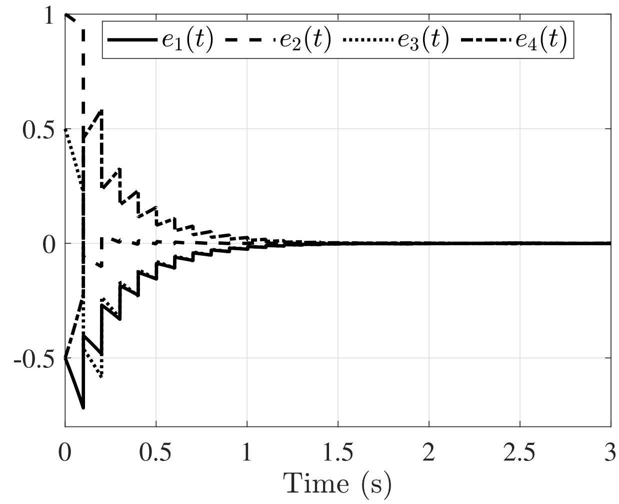

Fig. 4. Example 1: errors signals.

$$E = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{bmatrix},\ A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 1 & -2 & 0 & 0 \\ 0 & 0 & 1 & 1 \\ 1 & 0 & 0 & 1 \end{bmatrix},\ B = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix},\ C = \begin{bmatrix} 2 & 0 \\ 0 & 0 \\ 0 & 1 \\ 1 & 0 \end{bmatrix}^T.$$

The pencil (E, A) is regular and the triplet (C, E, A) satisfies the impulse observability condition. Considering the impulsive observer (2), the estimation error evolves according to:

$$E\,\dot{e}(t) = A\,e(t), \quad \forall t \neq k\delta,$$
$$e(k\delta^+) = (I + G\,C)\,e(k\delta), \quad t = k\delta.$$

Using Lemma 2, the Kronecker canonical form is obtained with the following matrices

$$M = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 1 & -1 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad Q = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & -1 & 1 & 0 \\ -1 & 0 & 0 & 1 \end{bmatrix},$$

$$J = \begin{bmatrix} 0 & 1 \\ 1 & -2 \end{bmatrix}, \quad N = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}.$$

The matrix $\Phi(\delta)$ is obtained considering a sampling period $\delta = 0.1$. The LMI (4) is feasible obtaining the following matrices

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$$P = \begin{bmatrix} 0.942 & 0.425 & -0.004 & 0.323 \\ 0.425 & 1.351 & 0.009 & -0.218 \\ -0.004 & 0.009 & 1.107 & 0.005 \\ 0.323 & -0.218 & 0.005 & 0.769 \end{bmatrix},$$

$$Y = \begin{bmatrix} -1.235 & 0.485 \\ -1.949 & 1.517 \\ 0.007 & -1.119 \\ 0.846 & -0.251 \end{bmatrix}, \quad G = \begin{bmatrix} -1.51 & 0 \\ -0.72 & 1.13 \\ 0 & -1.02 \\ 1.53 & 0 \end{bmatrix},$$

the gain matrix G ensures the convergence of the error dynamics to zero. Simulation results using the control input $u(t) = 4\sin(6t) + 0.5\cos(18t)$ plotted in Figure 5 and initial conditions $x(0) = [-1, 0.5, -0.5, 0.2]^T$, $\hat{x}(0) = 0$, confirm the convergence of the proposed observer. Time evolution of the state signals as well as the observer signals are shown in Figures 6 and 7 where the behavior of the impulsive observer is as expected. Figure 8 illustrates the estimation error$e(t)$, showing asymptotic decay towards zero. The convergence corroborates the theoretical results derived from the LMI condition in Theorem 3.

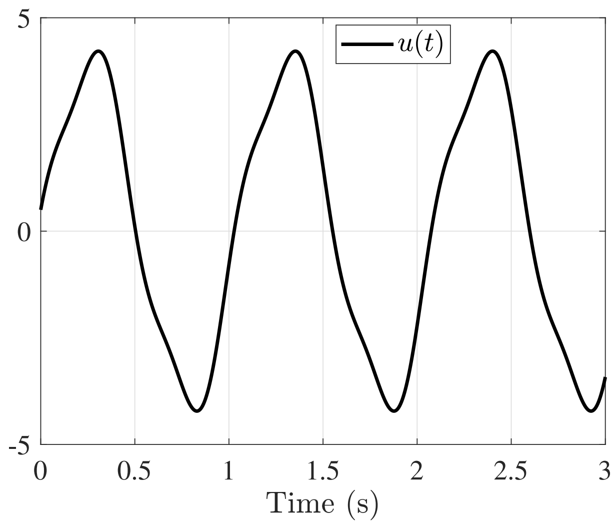

Fig. 5. Example 2: control signal.

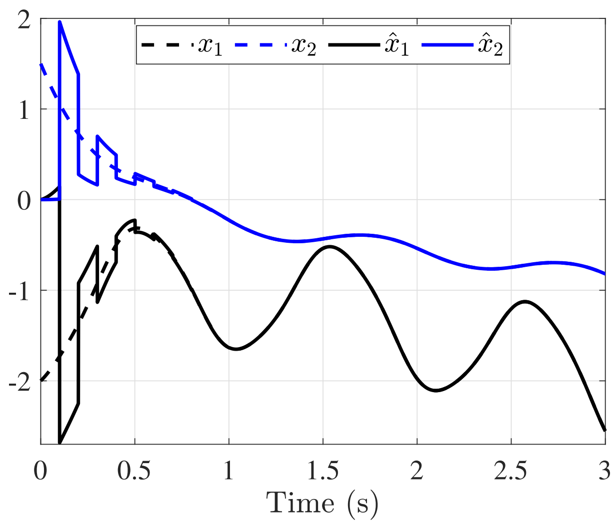

Fig. 6. Example 2: system states x_1, x_2 vs observer states $\hat{x}_1$, $\hat{x}_2$.

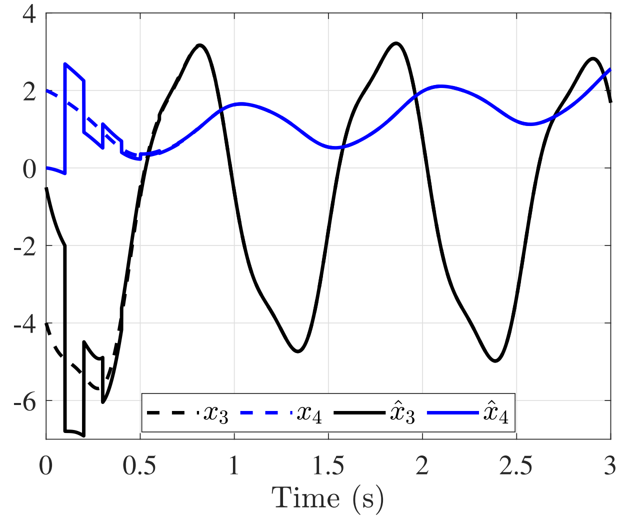

Fig. 7. Example 2: system states x_3, x_4 vs observer states $\hat{x}_3$, $\hat{x}_4$.

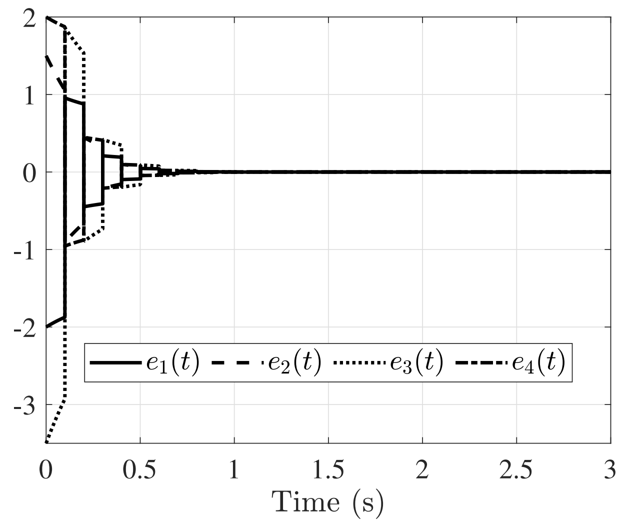

Fig. 8. Example 2: errors signals.

5. CONCLUSIONS

This paper presented a novel impulsive observer design for linear descriptor systems with sampled-output measurements. By leveraging the Kronecker decomposition of the descriptor pencil and modeling the sampling mechanism as impulsive updates, we derived an exact discrete-time error recursion that captures both the differential and algebraic behavior of the estimation error. A Lyapunov-based LMI condition was then formulated to ensure Schur stability of the impulsive error dynamics, enabling convex synthesis of the observer gain. Two numerical examples confirm the theoretical findings, showing asymptotic convergence of the observer error and accurate reconstruction of the full state. Future work will explore extensions to nonlinear descriptor models, robustness under measurement noise, and adaptive schemes under uncertain dynamics.

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