2013 European Control Conference (ECC)
July 17-19, 2013, Zürich, Switzerland.

Smith Predictor Based Generalized PI Control for a Class of Input Delayed Nonlinear Mechanical Systems

M. Ramírez-Neria, H. Sira-Ramírez, A. Luviano-Juárez and A. Rodriguez-Angeles

Abstract— **This article addresses the problem of Linear Active Disturbance Rejection Control for a class of nonlinear mechanical input time delayed systems. To solve the problem, it is necessary to obtain a set of predictive lumped disturbance estimations, which is carried out by a purely linear high gain observer of Extended Luenberger type, denoted as a Generalized Proportional Integral (GPI) Observer. This task is performed using an approximation of the predictive disturbance using a truncated Taylor series expansion, where the set of necessary values for the estimation are provided by the observer. Once the (approximate) disturbance canceling is made, the control task is reduced to a simple linear Smith Predictor PD control, using the simplified model of the mechanical system. Some experimental results show the effectiveness of the strategy in a trajectory tracking task for a perturbed flywheel.**

I. INTRODUCTION

The control of time delayed systems has been object of attention of the control engineers and researchers, due to the fact that many physical systems may be affected by the presence of delays, which often generates poor behavior of controllers and even instabilities. The physical motivation of this class of systems come up with different arising and classical problems as congestion control schemes in packet networks [1], digital implementation in real time control systems [2], teleoperation systems [3], [4], process control [5], etc.

One of the most important approaches in the regulation and control of time delay systems consist in using predictors, which are included in the main controller to eliminate the effects of the time delay. Thus, this family of controllers are applied to transform a time delay system into a new system free of delay effects, taking the delay out of the control loop. The most applied predictor based control scheme is the so-called "Smith Predictor" (see [6], [7]). The effectiveness of the Smith Predictor depends on the precise knowledge of the system plant, then, in some cases, the response may not be acceptable when nonmodeled dynamics or disturbances are arisen. Thus, to achieve a good tracking result in presence of such effects, an additional problem of compensating external disturbance and internal unknown dynamics for complex systems must be incorporated in the control task, which for this class of systems is still a challenging control problem.

Some robust control schemes involving Smith predictors incorporate Disturbance Observers to enhance their response against disturbances (see [8]), but the nonmodeled dynamics are still a challenge. Another alternative scheme to solve this problem consists in the combination of the Smith Predictor and a disturbance linear observer of Generalized Proportional Integral (GPI) nature, as proposed in [9]. This approach has shown to be a good alternative for a class of differentially flat systems [10].

This controller consists in an observer based output feedback control with the following features:

1) A linear Extended Luenberger Like Observer which estimates the nonlinearities, nonmodeled dynamics, state dependent perturbations and external disturbance inputs, taken as a generalized lumped disturbance variable term. This observer also obtains the system phase variables.
2) A linear observer-based state feedback controller, including a disturbance cancelation strategy based on the disturbance estimation and a single PD based control with feedforward input to stabilize and achieve the trajectory tracking.
3) A classical Smith Predictor control scheme on the resulting simplified, dominantly linear, input output model (which is possible by virtue of the flatness property).

Using the fact that the disturbance observer can predict the lumped disturbance input (for a subsequent disturbance cancelation), the original nonlinear delayed input tracking control problem is approximately reduced to a simpler dominantly linear delayed input tracking problem, suitable for the application of the classical Smith Predictor control scheme.

This control approach is based on the philosophy of active disturbance rejection control (ADRC) (see [11], [12], [13], [14]), which, in general, implies the cancelation of the external disturbances but also of non-modeled dynamics and other terms, in contrast with a purely disturbance observer based control ([15], [16], [17]). The effects of the bounded perturbation input function on the performance of the observer estimation error dynamics may be adequately attenuated via high gain pole location. For the case of time delayed systems[1], the controller incorporates a disturbance prediction stage based mainly of a power series expansion of the lumped disturbance function, taken as a purely time signal, by a truncated Taylor series, where the necessary terms of the

M. Ramírez-Neria is with Department of Automatic Control, CINVESTAV-IPN, Av. IPN No. 2508, Col. San Pedro Zacatenco 07360, D.F, Mexico `mramirezn@ctrl.cinvestav.mx`

H. Sira-Ramírez and A. Rodriguez-Angeles are with the Department of Electrical Engineering, Mechatronics Section, CINVESTAV-IPN, Av. IPN No. 2508, Col. San Pedro Zacatenco 07360, D.F, Mexico `hsira@cinvestav.mx`

A. Luviano-Juárez is with UPIITA-IPN, Av. IPN No. 2580, Col. Barrio la Laguna Ticomán 07340, D.F, Mexico `aluvianoj@ipn.mx`

This work was supported by SIP-IPN under research grant 20130415

---

[1] for another interesting approach to ADRC for time delay systems, the reader is referred to [18]

expansion are provided by the GPI observer. In this article, a Smith Predictor based active disturbance rejection control strategy is proposed for the trajectory tracking task for a class of mechanical systems with time delayed input, with a study case consisting in the trajectory tracking of a perturbed flywheel system. The remainder of the article is given as follows: Section II introduces the problem formulation, the class of systems to be controlled, and the preliminary results for the proposed control approach. Section III describes the application of the control strategy for a perturbed flywheel with time delayed input; Section IV depicts the experimental control results obtained on the trajectory tracking task of the prototype. Finally, Section V contains the conclusions and suggestions for further research.

II. PROBLEM FORMULATION

Consider the following class of disturbed nonlinear systems with time delayed input, obtained from the classic Euler Lagrange Methodology:

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) = u(t-T) + \eta(t) \tag{1}$$

where $q \in \mathbb{R}^n$ represents the measurable position coordinates of the generalized coordinates, $u(t-T) \in \mathbb{R}^n$ stands for the generalized delayed input forces. $M(q) \in \mathbb{R}^{n\times n}$ is the inertia matrix, being symmetric positive definite, $C(q,\dot{q})\dot{q} \in \mathbb{R}^n$ is the Coriolis and centripetal forces vector, $G(q) \in \mathbb{R}^n$ includes the gravitational effects vector and $\eta(t) \in \mathbb{R}^n$ is a disturbance input vector which considers nonmodeled dynamics, friction forces and external disturbances.

The following assumptions are assumed:

- A1 T is the fully known input deadtime of delay.
- A2 $q(t), \eta(t)$ are bounded (in an almost sure sense).
- A3 For all bounded solutions, $q(t)$, of (1), obtained by means of suitable control input u, the additive, lumped generalized disturbance input $\psi(t) \triangleq \eta(t) - C(q,\dot{q})\dot{q} - G(q)$ is uniformly absolutely bounded with bounded finite time derivatives.
- A4 $M(q)$ is perfectly known.

The control problem is given as follows:

Given a desired output reference trajectory, $q^*(t)$, devise a linear output feedback controller for the system (1) *such that in spite of the lumped generalized disturbance input $\psi(t, q(t), \dot{q}(t))$, the output q tracks the desired reference signal even if in an approximate fashion (the tracking error, $e(t) = y - y^*(t)$, and its finite time derivatives, globally exponentially converge towards a small as desired neighborhood of the origin in the reference trajectory tracking error phase space).*

A. Model simplification and GPI approach

Using A3 and A4, the system (1) can be expressed as:

$$\begin{aligned} \ddot{q} &= M^{-1}(q(t))u(t-T) + \overline{\psi}(t,q,\dot{q}) \\ \overline{\psi} &= M^{-1}(q(t))\psi \end{aligned} \tag{2}$$

In order to design an observer which, simultaneously, estimates the lumped perturbation input: $\overline{\psi}(t, q(t), \dot{q}(t))$ and the state variable $\dot{q}$. The system is taken as the disturbed system, where the lumped disturbance input $\overline{\psi}(t, q(t), \dot{q}(t))$, is obtained with an internal approximating model at the observer.

Notice that the unknown disturbance input in the simplified system (2), can be expressed in terms of the delayed input u, the system output q, and a finite number of its time derivatives. That is, $\overline{\psi} = \ddot{q} - M^{-1}(q)u(t-T)$, which implies that $\overline{\psi}$ can be estimated through an unknown input observer.

In order to smooth out the noise effects on the on-line computation of the time derivatives, we carry out an integration of the measured signal, $q(t)$, denoted by $q_0(t)$. Assuming that $q_0(t)$ is uniformly absolutely bounded, we have the following general result: Let us propose the following linear observer of Generalized PI form:

$$\begin{aligned} \dot{\hat{q}}_0 &= \hat{q}_1 + \lambda_{p+2}(q_0 - \hat{q}_0) \\ \dot{\hat{q}}_1 &= \hat{q}_2 + \lambda_{p+1}(q_0 - \hat{q}_0) \\ \dot{\hat{q}}_2 &= M^{-1}(q)u(t-T) + \hat{z}_1 + \lambda_p(q_0 - \hat{q}_0) \\ \dot{\hat{z}}_1 &= \hat{z}_2 + \lambda_{p-1}(q_0 - \hat{q}_0) \\ &\vdots \\ \dot{\hat{z}}_{p-1} &= \hat{z}_p + \lambda_1(q_0 - \hat{q}_0) \\ \dot{\hat{z}}_p &= \lambda_0(q_0 - \hat{q}_0) \\ \widehat{\overline{\psi}}(t) &= \hat{z}_1 \end{aligned} \tag{3}$$

The integral estimation error $\tilde{e} = q_0 - \hat{q}_0$, satisfies the following disturbed dominantly linear dynamics

$$\tilde{e}^{(p+3)} + \lambda_{p+2}\tilde{e}^{(p+2)} + \cdots + \lambda_0\tilde{e} = \overline{\psi}^{(p)}(t) \tag{4}$$

From assumption A3, $\overline{\psi}(t)^{(p)}(t)$ is assumed to be uniformly absolutely bounded, then there exists coefficients λ_k such that $\tilde{e}$ converges to a small vicinity of zero, provided the roots of the associated characteristic polynomial in the complex variable s:

$$s^{p+n+1} + \lambda_{p+n}s^{p+n} + \cdots + \lambda_1 s + \lambda_0 \tag{5}$$

are all located deep into the left half of the complex plane. The further away from the imaginary axis, of the complex plane, are these roots located,the smaller the neighborhood of the origin, in the estimation error phase space, where the estimation error $\tilde{e}$ will remain ultimately bounded. Clearly, if $\tilde{e}$, and its time derivatives, converge towards a neighborhood of the origin, then $z_j - \overline{\psi}^{(j-1)}$, $j = 1, 2, ...$, also converge towards a small vicinity of zero.

Let us denote by $\hat{q}_j$ the estimate of $q^{(j-1)}$ for $j = 1, 2$. From the observer structure, the variable $\hat{z}_1$ denotes an internal model of the disturbance input $\overline{\psi}(t)$ (see [19]).

The model for z_1 is hypothesized as an element of a family of fixed degree time-polynomials, say of degree $p - 1$ [20]. The model takes a *self updating* character when incorporated as part of an extended linear Luenberger type observer. The observer injection gains are tuned such that the estimation error converges to a small neighborhood of the origin, whose size, as well as the convergence time depend on the order of the internal model p, and the gain selection.

Thus, the self-updating residual function, $r(t)$, in the approximation, $\overline{\psi}(t) = \hat{z}_1 + r(t)$, and its finite time derivatives, say $r^{(p)}(t)$, are uniformly absolutely bounded. In the remainder of this section the GPI observer is used in the context of the Smith Predictor based control.

1) Smith Predictor GPI controller: From (2), the "forward system" is defined as follows:

$$\ddot{q}_f(t) = M^{-1}(q(t+T))u(t) + \overline{\psi}(t+T, q_f, \dot{q}_f), \qquad (6)$$

where $\overline{\psi}(t+T, q_f, \dot{q}_f)$ is the *predicted disturbance input* to be reproduced, in an approximate form, using the estimated states of the original system. Let us assume the disturbance input is given as a purely time-dependent expression, i.e, $\overline{\psi}(t+T)$ (this assumption is proposed since the controller uses a time-polynomial model of the nonlinear state-dependent perturbation).

Taking a Taylor series expansion, it is obtained the following disturbance input predictor:

$$\overline{\psi}(t+T) = \overline{\psi}(t) + \dot{\overline{\psi}}(t)T + \frac{1}{2!}\ddot{\overline{\psi}}(t)T^2 + \ldots \qquad (7)$$

Then, using the input disturbance estimator and a truncated version of (7), an approximate disturbance input predictor is given as follows[2]:

$$\hat{\overline{\psi}}(t+T) = \hat{z}_1(t) + \hat{z}_2(t)T + \ldots + \frac{1}{(p-1)!}\hat{z}_p T^{p-1} \qquad (8)$$

As it occurs in polynomial series approximation, increasing the value of p allows a better approximation; however, the numerical complexity of the observer is enlarged.

We have the following control law for the forward system using the disturbance predictor estimation

$$\begin{aligned} u(t) = \Big[& M(q) - \hat{\overline{\psi}}(t+T) + \ddot{q}^*(t+T) \qquad (9) \\ & - (\kappa_1[\dot{e}_f(t) + \dot{e}_{rr}(t)] + \kappa_0[e_f(t) + e_{rr}]) \Big] \\ e_f(t) &= \hat{q}(t) - q_f^*(t-T) \\ e_{rr} &= q(t) - q_f(t-T) \end{aligned}$$

where κ_1, κ_0 are diagonal positive definite matrices with the control gains of a classical multivariable PD controller, such that the linear dominant dynamics is Hurwitz. $\hat{q}^{(j)}(t)$, $j = 0, 1$ are supplied by the GPI observer and $q_f^{(j)}(t)$ are, through algebraic manipulations, available for measurement. The terms $e_f^{(j)}$ are introduced in order to handle possible errors in the disturbance prediction, as a part of the Smith Predictor methodology. This terms use the difference between the plant output and the time delayed forward output to compensate possible differences between the delayed system and the delayed forward model.

Figure 1 shows an schematic of the control design, where $f(q\dot{q}, \overline{\varphi}(t))$, represents the plant dynamics:

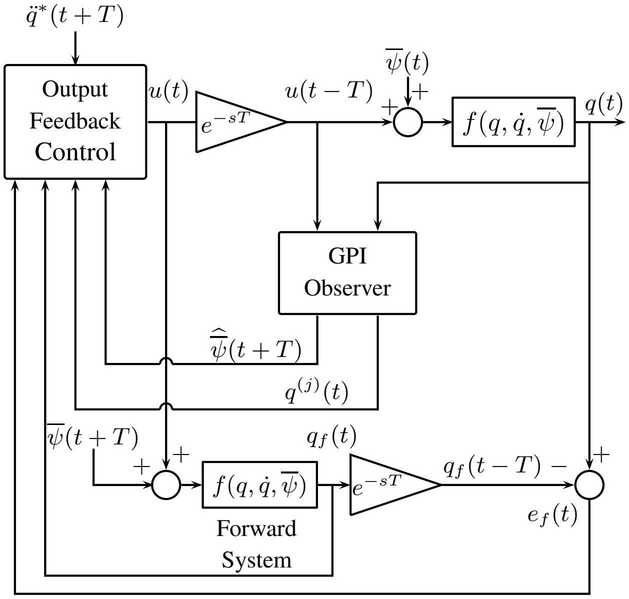

Fig. 1. Control scheme.

III. CONTROL OF A PERTURBED FLYWHEEL WITH DELAYED INPUT

Consider a perturbed flywheel system (see figure 2), with delayed input. The flywheel consists in a aluminium wheel of radius R, mass M, and an extra perturbation mass, of value m, attached on the circumference of the wheel. The system is actuated by a DC motor, and the angular displacement of the rotor shaft is denoted by θ. The model of the nonlinear system is given by

$$(J_m + J + mR^2)\ddot{\theta} + mgR\sin\theta = \tau(t-T) \qquad (10)$$

where T is the, known, fixed time delay, J is the inertia of the flywheel and J_m is the inertia of the rotor of motor. Terms such as the viscous friction, Coulomb friction (typically acting through a *sign* function of the angular velocity), air resistance, etc. are not specifically modeled in (10). These torques, however, were found to significantly act on the motion of the flywheel. All these disturbances are assumed to be unknown, and they are given by the disturbance term $\eta(t, \theta, \dot{\theta})$, which, as well as the position-dependent gravitational nonlinearity of the extra mass on flywheel, are, according to our proposal, considered to form a bounded generalized disturbance input signal, lumped into a single additive time-varying function, $\tilde{\psi}(t)$.

$$\tilde{\psi}(t) = -(1/(J_m + J + mR^2))\,(mgR\sin\theta + \eta(t)) \quad (11)$$

---

[2] Since the input predictor is given in terms of a Taylor series expansion, the size of T is restricted to a valid domain of the approximation.

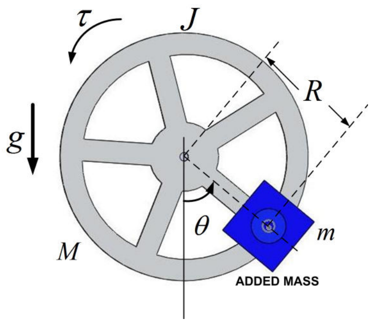

Fig. 2. Schematics of flywheel system

The simplified model of the flywheel system, in terms of the flywheel angle, is given by:

$$\ddot{\theta}(t) = (1/(J_m + J + mR^2))\tau(t-T) + \tilde{\psi}(t) \tag{12}$$

From the DC motor dynamics, the relation between the torque and the voltage input is given by

$$\tau(t-T) = \frac{K_1 N}{R_a} V(t-T) - \frac{K_1 K_2 N^2}{R_a}\dot{\theta} \tag{13}$$

where R_a $[\Omega]$ is the armature resistance, K_1 $[N \cdot m/A]$ denotes the torque constant, K_2 $[N \cdot m \cdot s/rad]$ is the back electromotive force constant, and N is the gear ratio relation. Using (13) in (12):

$$\ddot{\theta}(t) = M^{-1}V(t-T) + \overline{\psi}(t) \tag{14}$$

where $M^{-1} = \frac{K_1 N}{R_a(J_m+J+mR^2)}$, $\overline{\psi}(t) = \tilde{\psi} - \frac{K_1 K_2 N^2 \dot{\theta}}{R_a}$.

According to the problem formulation, given a reference angular position trajectory, say θ^*, it is desired to devise a, Smith Predictor based, GPI class active disturbance rejection controller to obtain a robust tracking of the reference function in spite of the nonmodeled dynamics, nonlinear effects and external disturbances, all of them lumped in the disturbance input $\overline{\psi}$.

Let us propose the following GPI observer with forward input and approximation parameter $p = 6$:

$$\begin{aligned}
\dot{\hat{\theta}}_0 &= \hat{\theta}_1 + \lambda_8(\theta_0 - \hat{\theta}_0) \\
\dot{\hat{\theta}}_1 &= \hat{\theta}_2 + \lambda_7(\theta_0 - \hat{\theta}_0) \\
\dot{\hat{\theta}}_2 &= M^{-1}V(t-T) + \hat{z}_1 + \lambda_6(\theta_0 - \hat{\theta}_0) \\
\dot{\hat{z}}_1 &= \hat{z}_2 + \lambda_5(\theta_0 - \hat{\theta}_0) \\
&\vdots \\
\dot{\hat{z}}_5 &= \hat{z}_6 + \lambda_1(\theta_0 - \hat{\theta}_0) \\
\dot{\hat{z}}_6 &= \lambda_0(\theta_0 - \hat{\theta}_0) \\
\theta_0 &= \int \theta(t)dt \\
\hat{\overline{\psi}} &= \hat{z}_1
\end{aligned} \tag{15}$$

which leads to a characteristic polynomial for the integral error in the linear dominant part:

$$P(s) = s^9 + \lambda_8 s^8 + \lambda_7 s^7 + \ldots + \lambda_2 s^2 + \lambda_1 s + \lambda_0 \tag{16}$$

The observer gain parameters λ_j, for $j = 0, 1, 2, \cdots, 8$ are chosen with the following procedure. Consider a characteristic polynomial $p(s)$ of the form:

$$a_n s^n + a_{n-1}s^{n-1} + \cdots + a_2 s^2 + a_1 s + a_0, \qquad a_i > 0 \tag{17}$$

and let α_i be the characteristic ratios of $p(s)$. It is said that $p(s)$ is Hurwitz if the following two conditions hold:

A) $\alpha_1 > 2$;

B) $\alpha_k = \dfrac{\sin\left(\frac{k\pi}{n}\right) + \sin\left(\frac{\pi}{n}\right)}{2\sin\left(\frac{k\pi}{n}\right)}\alpha_1$

for $k = 2, 3, \ldots, n-1$. The construction of the all-pole stable characteristic polynomial involves only α_1 which we require to be larger than 2. Thus, this result allows us to characterize the reference all-pole systems by adjusting a single parameter α_1 to achieve the desired damping. Since the *generalized time constant* can be chosen independently of α_i, the coefficients of $p(s)$ are calculated using the procedure given in [21]:

For an arbitrary a_0 and $\tau > 0$:

$$\begin{aligned}
a_1 &= \tau a_0 \\
a_i &= \frac{\tau^i a_0}{\alpha_{i-1}\alpha_{i-2}^2\alpha_{i-3}^3 \cdots \alpha_1^{i-1}} \\
&\quad \text{for } i = 2, 3, \ldots, n \\
\lambda_j &= \left(\frac{a_j}{a_n}\right) \\
&\quad \text{for } j = 0, 1, , 3, \ldots, 8
\end{aligned}$$

which helps to find a fast tracking response, avoiding overshooting effects.

The GPI observer provides an online approximation of the disturbance input $\overline{\psi}$ by $\hat{z}_1$, besides, it obtains a finite number of time derivatives of the disturbance input, given by $\hat{z}_2, \ldots, \hat{z}_6$. Using the Taylor series expansion, the prediction of the disturbance input is calculated as follows:

$$\begin{aligned}
\hat{\overline{\psi}}(t+T) = {} & \hat{z}_1(t) + \hat{z}_2(t)T + \frac{1}{2!}\hat{z}_3(t)T^2 + \frac{1}{3!}\hat{z}_4(t)T^3 + \\
& + \frac{1}{4!}\hat{z}_5(t)T^4 + \frac{1}{5!}\hat{z}_4(t)T^5
\end{aligned} \tag{18}$$

Using the Smith predictor methodology, the forward system with time forward T, for the disturbed linear system (14) is

$$\ddot{\theta}_f = M^{-1}V(t) + \hat{z}_1(t+T) \tag{19}$$

The trajectory tracking error of the forward plant is defined as follows:

$$e_{\theta f} = \theta_f(t) - \theta^*(t+T)$$

and the error between the delayed forward system and the actual plant as

$$e_{\theta rr} = \theta(t) - \theta_f(t-T) \tag{20}$$

where $e_{\theta rr}$ represents the discrepancies between the forward system and the actual system, and it is to be used as a compensation term. It is proposed a PD with a disturbance compensation term controller for the forward system

$$\begin{aligned} V(t-T) = -M\big[\hat{z}_1(t+T) + 2\zeta_c\omega_{nc}(\dot{e}_{\theta rr} + \dot{e}_{\theta f}) + \\ + \omega_{nc}^2(e_{\theta rr} + e_{\theta f}) - \ddot{\theta}_f^*(t)\big] \end{aligned} \tag{21}$$

with $\zeta_c, \omega_{nc} > 0$.

IV. EXPERIMENTAL RESULTS

Some experiments were carried out on the test bed system to show the effectiveness of the control strategy. The angular position of the motor shaft was obtained by means of an incremental encoder of 1000 CPR, which is increased to 4000 CPR from the data acquisition card. The position data was sent to the main controller by means of a data acquisition card Sensoray Model 626. The controller was implemented in the Matlab-Simulink platform, and the control signals were transferred to the actuator through a power amplifier Sanyo: Model STK4050II. The actuator consisted in a DC motor NISCA: Model NC5475. The motor parameters were the following: The motor inertia $J_m = 4.0101\text{x}10^{-5}[K_g m^2]$, a torque constant $K_1 = 0.0724[N-m/A]$, the armature resistance was $R_a = 2.983[\Omega]$, and the back electromotive force constant, $K_2 = 0.0687[N-m-s/rad]$ respectively. The inertia of the flywheel was $J = 9.611\text{x}10^{-3}[Kg-m^2]$, the flywheel mass $M = 1.315[Kg]$, as well as the added mass $m = 0.1[Kg]$. The flywheel radius parameter was $R = 0.1[m]$ and the input delay time T was chosen to be $0.07[s]$. Finally, the sampling time was set to be $0.0005[s]$.

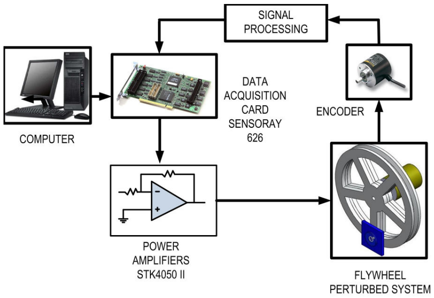

Fig. 3. Flywheel system prototype

The initial conditions for the system were $\theta(0) = 0$. The observer gain parameters were set to be as follows: $n = 9$, $\tau = 6$, $a_0 = 15^{10}$, $\alpha_1 = 3.5$. The controller design parameters were specified to be: $\zeta_c = 3$ and $\omega_{nc} = 5$.

The tracking results using the Smith predictor based control in a rest to rest path are depicted in figure 5, where the presented results, for a constant time delay T, were satisfactory, as shown that the error signal remains bounded as stated in the problem approach, with an absolute peak error less than 0.2 [rad] (see figure 6). Figure 7 shows the control inputs for the tracking process and finally, figure 8 depict the disturbance input estimation as well as its prediction.

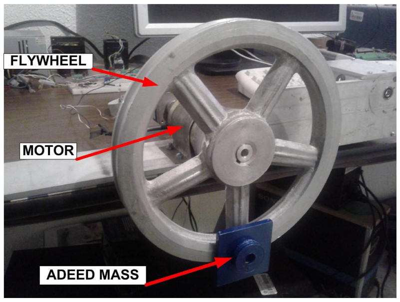

Fig. 4. Experimental system block diagram

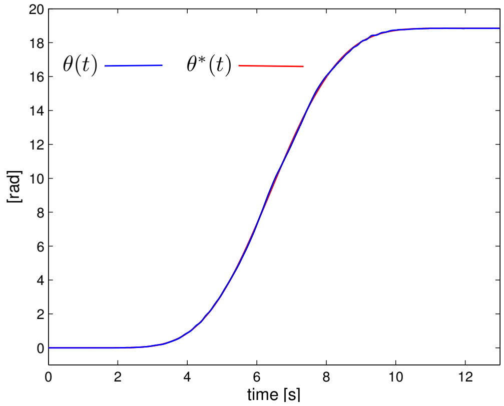

Fig. 5. Tracking behavior position reference trajectory

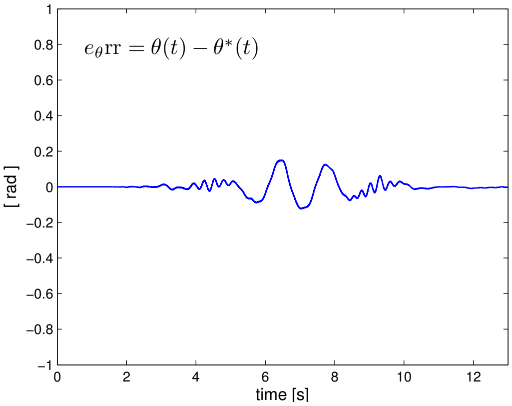

Fig. 6. Reference trajectory tracking error

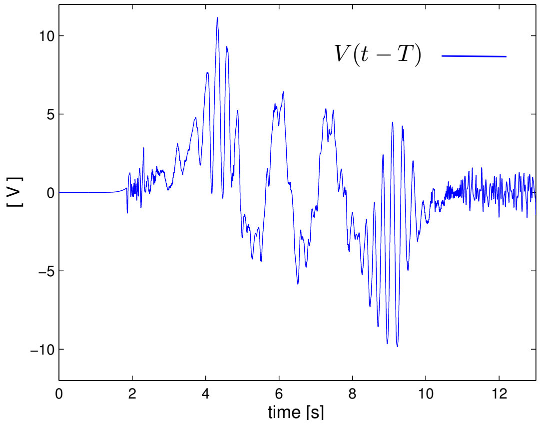

Fig. 7. Voltage control input

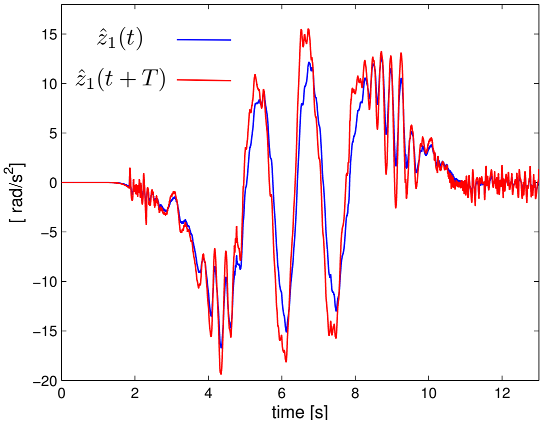

Fig. 8. Disturbance input predictor

V. CONCLUDING REMARKS

In this article, the observer based linear output feedback control for trajectory tracking on a class of input delayed mechanical systems was solved using only a partial knowledge of its dynamics, which may contain external disturbance inputs and complex nonmodeled dynamics. The problem was taken from an input output point of view, where the input-output description of the plant was modeled as a set of second order integration systems with an input gain matrix, possible depending on the outputs, using the principles of active disturbance rejection control, in which the problem is to reject all possible effects of additive disturbances (external and internal) lumped in a disturbance function. The time delay influence was compensated by means of a GPI observer, with a truncated Taylor series expansion to approximately estimate the prediction of the lumped disturbance, which enabled the direct use of the Smith predictor control scheme in the simplified system. The proposed control law was tested in an actual flywheel system with a load coupled in its tip. The experimental results showed a bounded tracking error in a rest to rest desired trajectory.

REFERENCES

[1] D. Cavendish, M. Gerla, and S. Mascolo, "A control theoretical approach to congestion control in packet networks," *IEEE/ACM Transactions on Networking*, vol. 12, no. 5, pp. 893–906, October 2004.

[2] K. Shin and X. Cui, "Computing time delay and its effects on real time control systems," *IEEE Transactions on Control Systems Technology*, vol. 3, no. 2, pp. 218–224, June 1995.

[3] J. Ryu and C. Preusche, "Stable bilateral control of teleoperators under time-varying communication delay: Time domain passivity approach," in *Proceedings fo the IEEE International Conference on Robotics and Automation*, Roma, Italy, April 2007, pp. 3508–3513.

[4] K. Natori, T. Tsuji, K. Ohnishi, A. Hace, and K. Jezernik, "Time-delay compensation by communication disturbance observer for bilateral teleoperation under time-varying delay," *IEEE Transaction on Industrial Electronics*, vol. 57, no. 3, pp. 1050–1062, March 2010.

[5] M. Matausek and A. Ribic, "Control of stable, integrating and unstable processes by the modified smith predictor," *Journal of Process Control*, vol. 22, pp. 338–343, 2012.

[6] O. Smith, "Closer control of loops with dead time," *Chemical Engineeering Science*, vol. 53, pp. 217–219, 1957.

[7] C. Smith and A. B. Corripio, *Principles and Practise of Automatic Process Control*. New York: Wiley, 1985.

[8] J. Yang, S. Li, X. Chen, and Q. Li, "Disturbance rejection of dead-time processes using disturbance observer and model predictive control," *Chemical Engineering Research and Design*, vol. 89, no. 2, pp. 125–135, 2011.

[9] H. Sira-Ramírez, M. Velasco-Villa, and A. Rodríguez-Ángeles, "Trajectory tracking control of an input delayed monocycle," in *Proceedings of the American Control Conference*, Baltimore, MD, USA, June-July 2010, pp. 1184–1189.

[10] H. Sira-Ramírez and S. Agrawal, *Differentially flat systems*. Marcel Dekker Inc., 2004.

[11] J. Han, "From PID to active disturbance rejection control," *IEEE Transactions on Industrial Electronics*, vol. 56, no. 3, pp. 900–906, March 2009.

[12] Z. Gao, Y. Huang, and J. Han, "An alternative paradigm for control system design," in *40th IEEE Conference on Decision and Control*, vol. 5, 2001, pp. 4578–4585.

[13] Z. Gao, "Active disturbance rejection control: A paradigm shift in feedback control system design," in *American Control Conference*, Minneapolis, Minnesota, USA, June 2006, pp. 2399–2405.

[14] D. Sun, "Comments on active disturbance rejection control," *IEEE Transactions on Industrial Electronics*, vol. 54, no. 6, pp. 3428–3429, December 2007.

[15] W.-H. Chen, D. Ballance, P. Gawthrop, and J. O'Reilly, "A nonlinear disturbance observer for robotic manipulators," *IEEE Transactions on Industrial Electronics*, vol. 47, no. 4, pp. 932–938, August 2000.

[16] D. Xing, J. Su, Y. Liu, and J. Zhong, "Robust approach for humanoid joint control based on a disturbance observer," *IET Control Theory Applications*, vol. 5, no. 14, pp. 1630–1636, 2011.

[17] Y.-D. Yoon, E. Jung, and S.-K. Sul, "Application of a disturbance observer for a relative position control system," *IEEE Transactions on Industrial Applications*, vol. 46, no. 2, pp. 849–856, March/April 2010.

[18] Y. Xia, P. Shi, G. Liu, D. Rees, and J. Han, "Active disturbance rejection control for uncertain multivariable systems with time-delay," *IET Control Theory and Applications*, vol. 1, no. 1, pp. 75–81, January 2007.

[19] C. D. Johnson, "Accommodation of external disturbances in linear regulator and servomechanism problems," *IEEE Transactions on Automatic Control*, vol. AC-16, no. 6, December 1971.

[20] A. Luviano-Juarez, J. Cortes-Romero, and H. Sira-Ramirez, "Synchronization of chaotic oscillators by means of generalized proportional integral observers," *International Journal of Bifurcation and Chaos*, vol. 20, no. 5, pp. 1509–1517, 2010.

[21] Y. Kim, L. Keel, and S. Bhattacharyya, "Transient response control via characteristic ratio assignment," *IEEE Transactions on Automatic Control*, vol. 48, no. 12, pp. 2238–2244, December 2003.