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H∞-based PI-observers for web tension estimations in industrial unwinding-winding systems

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Abstract: The system under study is a web handling machine composed of an unwinder, several traction motors, several idlers with or without load cells and a winder. All flexible materials such as textiles, papers, polymers or metals are handled on rollers during their processing. Maintaining strip tension in the entire processing line while increasing web speed is a key factor for achieving good final product quality. Due to sources of disturbance and the high coupling introduced by elastic webs, robust multivariable control strategies such H∞-controllers require the knowledge of web tension in each span of the process. Estimators or observers represent a cost-effective method in order to limit the number of load cells or dancers. After a summary of the main laws used for system modeling, two different approaches to design tension observers in a section of a process line are presented and discussed. The first approach is based on a PI-observer calculated in a H∞ sense thanks to optimization techniques. The second approach uses Kalman filtering theory. Both approaches underline the importance of friction in estimation accuracy and propose alternatives to face this issue. This friction on rollers are generally neglected or assumed to be well-modeled in the literature. The proposed observers are also analyzed and discussed with variations in friction torques and nominal set points of the web velocity and tension. Both observers have the major advantage of being easily understandable for industrial applications and can be rapidly programmable in industrial plant controllers.

1. INTRODUCTION

Any continuous and flexible material whose width is significantly less than its length and whose thickness is significantly less than its width can be described as a web. The unwinder-winder systems handling web material such as textile, paper, polymer or metal are very common in the industry, because they represent a practical way of transporting and processing a product from one form to another. Modeling and control of web handling systems have been studied for several decades. One of the main objectives in this kind of system is to increase web speed as much as possible while maintaining the web tension within a close tolerance band over the entire processing line. Due to a number of sources of disturbance, i.e. vibrations, temperature and moisture, strong coupling between speed and tension is introduced by the web mechanical behavior, especially in the case of large scale systems with many actuators (Benlatreche *et al.*, 2004). So far, many industrial web transport systems have used decentralized PI-type controllers (Fig. 1). But recently, for better control performance and robustness to uncertainties, more efficient multivariable control strategies such as LQG or $\mathcal{H}_\infty$ (Knittel *et al.*, 2007, Koç, 2000, Koç *et al.*, 2002, Pagilla *et al.*, 2005) have been proposed. These more sophisticated strategies require the knowledge of the web tension in each span of the processing line (Knittel *et al.*, 2003, Shin, 2000).

Several methods have been developed to measure web tension in a processing line. The most classical one employed in an industrial context is the use of load cells mounted on idle rollers. Torque measurement of the traction rolls or contactless measurement of out-of-plane vibrations (Vedrines *et al.*, 2007) are other direct methods. An alternative to measurement consists in the use of a dancer (Thieffault *et al.*, 2005, Wolfermann, 1999) which imposes web tension with static balance. Because control requires the knowledge of the web tension along the processing line, these methods require sensors and/or dancers at each span of the line. The main drawback is that the installation of load cells or dancers in each is expensive. Therefore, the synthesis of observers, based on a system model, provides a cost-effective way of estimating web tension.

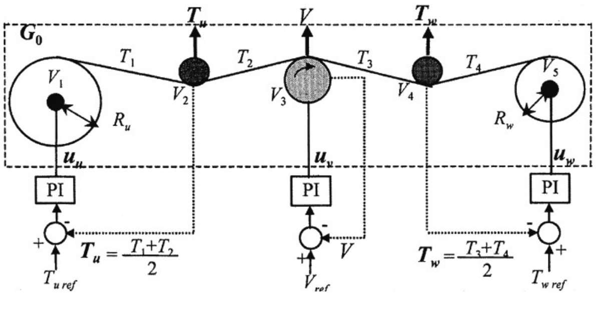


Fig. 1. Example of a 4-span web machine with decentralized PI-control strategy

Contrary to the study of system modeling or control strategies, there exist only a few papers that deal with the topic of observers in web handling systems. So far, no discussion has been made concerning the efficiency of such a strategy in an industrial and uncertain context. Different nonlinear observers in a two-span web machine were used in (Lynch, 2004). Observer-based tension feedback control in a system handling magnetic webs for tapes at low speed was proposed in (Lin, 2003). The main drawback of these observers is that they were based on the major assumptions that friction was well-identified and modeled or neglected on each roll. A first extended Kalman filter was proposed in (Boulter, 1999) and the linear and nonlinear uses of Kalman filter were compared and discussed in (Gassmann *et al.*, 2007) for web handling systems. They take into account the friction in the observer synthesis by using additional states to estimate them in order to face variations and uncertainties in an industrial plant.

This contribution proposes a PI-observer calculated in an H∞ sense to provide tension estimates in a section composed of several traction motors of a web processing line. This observer uses friction estimation and its static gain matrix is calculated thanks to local optimization techniques. It will be shown that the calculation of the observer appears to be like a standard H∞ synthesis problem of a static output feedback controller (zero-order controller). To compare with another type of linear observer, the Kalman filtering approach of (Gassmann *et al.*, 2007) is then recalled. Both are analyzed and discussed for parameter variations, i.e. friction and nominal set point. The objective is mainly to prove that frictions have a major contribution to estimation accuracy. Both observers have been chosen because they present the major advantages of being first easily understandable for industrial applications and then to be rapidly programmable in industrial plant controllers. The fundamental laws used for web handling systems modeling are also summarized.

2. SYSTEM MODELING

The nonlinear model of a web transport system is built from the equations describing the web tension behavior between two consecutive rolls and the velocity of each roll. This model was identified on the web machine shown in Fig. 2 which exhibits all inherent problems of this kind of system in order to build a non linear simulator.

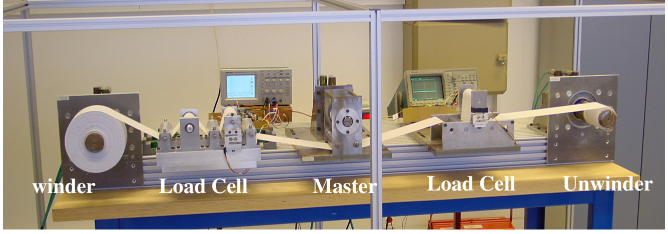


Fig. 2. Experimental setup with 3 motors and 2 load cells

This simulator enables systems of larger scale to be built. The machine considered in this contribution is composed of an unwinder, three traction rolls and a winder.

2.1 Web velocity determination

The velocity dynamics of the k^{th} roll is given by torque balance on it. Assuming the absence of slippage between the web and the roll, the web velocity V_k is equal to the peripheral velocity of the roller. The velocity dynamics is :

$$\frac{d(J_k \Omega_k)}{dt} = R_k(T_k - T_{k-1}) + K_k U_k - C_{rk} \tag{1}$$

where $\Omega_k = V_k/R_k$ is the angular velocity of the k^{th} roll, T_k is the web tension between the k^{th} and the $(k+1)^{th}$ rolls, $K_k U_k$ is the motor torque (if the roll is driven), C_{rk} corresponds to all the friction torque, J_k is roll inertia and R_k is roll radius.

2.2 Web tension determination

The calculation of web tension between two consecutive rolls is based on three laws (Koç, 2000, Koç *et al.*, 2002).

- Hooke's law:

The tension T of an elastic web is a function of the web strain ε :

$$T = ES\varepsilon = ES\frac{L - L_0}{L_0} \tag{2}$$

where E is the Young's modulus, S is the web section, L is the web length under stress and L_0 is the nominal web length.

- Coulomb's law:

The study of a web tension on a roll can be considered as a problem of friction between solids (Koç, 2000, Koç *et al.*, 2002).

- Mass conservation law:

The equation of continuity applied to the web transport systems gives (Koç, 2000, Koç *et al.*, 2002) :

$$\frac{d}{dt}\left(\frac{L_k}{1+\varepsilon_k}\right) = -\frac{V_{k+1}}{1+\varepsilon_k} + \frac{V_k}{1+\varepsilon_{k-1}} \tag{3}$$

where L is the web length between the k^{th} and the $(k+1)^{th}$ rolls, ε_k is the strain of the corresponding web span.

Similar to usual controller synthesis, a linearized plant model is necessary in order to calculate classical observers such as Luenberger type or Kalman filters. The linear model is obtained by linearizing the previous equations around the nominal web tension and velocity and by assuming slow variations of the radii and inertia. If V_0 and T_0 are respectively the nominal web velocity and tension and , the relationship (6) becomes

$$L_k \frac{dT_k}{dt} = (ES + T_0)(V_{k+1} - V_k) + V_0(T_{k-1} - T_k) \tag{4}$$

3. PI-OBSERVER

For the synthesis of the observer, the system considered is a section (dashed box P) of the process line presented in Fig. 3. The complete system is composed of an unwinder, three traction rolls and a winder whereas the plant for the observer takes only into account the three master rolls.

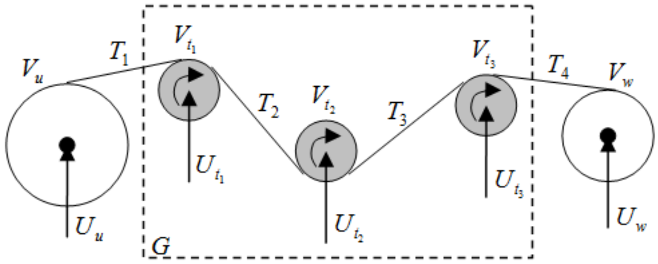


Fig. 3. System G under study (dashed box)

The available measurements are the linear speed of each roll and all web tensions except T_3 which will be estimated. Furthermore, friction and loss torque estimations of each roll are also added as observer inputs. In industrial cases, these losses are not negligible and can vary substantially.

3.1 H∞ standard problem for state observer

In order to determine the gain of the state observer, the following LTI system is first considered

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t) + B_w w(t) \\ y(t) = Cx(t) \end{cases} \tag{5}$$

where $x(t) \in \Re^n$ is the state vector, $u(t) \in \Re^m$ is the control input, $y(t) \in \Re^p$ is the measured output and $w(t) \in \Re^q$ represents disturbances which are assumed to be torque disturbances in this case. The matrix D is null and the dimensions of the matrices are assumed to be appropriate.

Furthermore the Luenberger state observer is as follows

$$\begin{cases} \dot{\hat{x}} = Ax + Bu + K(y - \hat{y}) \\ \hat{y} = Cx \end{cases} \tag{6}$$

where K denotes the observer gain matrix and $\hat{x}(t) \in \Re^n$ is the estimated state vector.

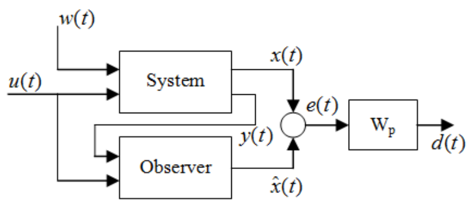


Fig. 4. Block diagram of error dynamics for the optimization of the Luenberger state observer synthesis

The objective is to optimize the observer gain matrix K in order to minimize the H∞ norm of the transfer function matrix from the disturbances *w(t)* to the weighted state estimation error (Fig. 4) defined as follows

$$d(s) = W_p(s)\left(x(s) - \hat{x}(s)\right) \tag{7}$$

where W_p is the weighting transfer function matrix. The H∞ optimization problem of the constants observer gain matrix K can be seen as a standard H∞ synthesis problem of a static output feedback controller (Ibaraki *et al.*, 2001). The weighting function W_P has a high gain at low frequency in order to reject low frequency disturbances. This structure can be improved by adding the integration of the error. Consequently a PI-based observer is obtained that is represented in Fig. 5. Such a kind of configuration has already been proposed and some illustrations are provided in (Beale *et al.*, 1988, Doyle *et al.*, 1979, Kaczorek, 1979).

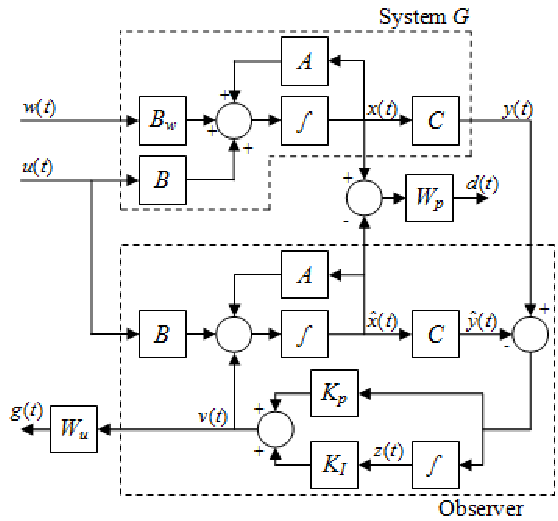


Fig. 5. Block diagram of PI-observer of the system G with additive weighting functions

The structure of the PI-based observer can be expressed by the following relation

$$\begin{cases} \begin{bmatrix} \dot{\hat{x}} \\ \dot{z} \end{bmatrix} = \begin{bmatrix} A & K_I \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \hat{x} \\ z \end{bmatrix} + \begin{bmatrix} B \\ 0 \end{bmatrix} u + \begin{bmatrix} K_P \\ I_p \end{bmatrix} (y - \hat{y}) \\ \hat{y} = \begin{bmatrix} C & O_P \end{bmatrix} \begin{bmatrix} \hat{x} \\ z \end{bmatrix} \end{cases} \tag{8}$$

where $z(t) \in \Re^p$ is the integrated error $y - \hat{y}$, $K_P \in \Re^{n \times p}$ and $K_I \in \Re^{n \times p}$ represent respectively the observer gain matrices of the proportional effect and of the integral action, I and O denotes respectively the identity matrix and a square null matrix.

The objective of the H∞ optimization for the PI-observer is similar to the one described previously. The matrix to be optimized is now the matrix $\begin{bmatrix} K_P & K_I \end{bmatrix}$. Moreover a second weighting matrix $W_u(s)$ can be added on the signal, *v(t)*, provided by the observer controller for the H∞ synthesis of the PI-observer, so that the H∞ norm is minimized for the transfer function between *w(t)* and weighted outputs, i.e. *d(t)* (see (10)) and *g(t)*, where *g(t)* is defined as follows

$$g(s) = W_u(s) v(s) \tag{9}$$

The weighting matrix $W_u(s)$ shapes *v(t)* in order to avoid large control signal.

The main drawback of standard H∞ synthesis is the high order of the computed controllers, which is typically equal to the order of the plant plus the order of the weighting functions. With current model reduction techniques, the controller cannot always be reduced a posteriori while preserving stability and satisfying performances. It is therefore highly relevant, especially for industrial applications, to develop design algorithms producing fixed-order (e.g. static output feedback) controllers from the outset. After more than four decades of intensive research efforts, it turns out that, deceptively, efficient software for designing fixed-order controllers is not available. The underlying mathematical problem seems to be difficult since fixed-order controller design can be formulated as a typically nonsmooth (nondifferentiable) affine problem in the nonconvex cone of stable matrices (or, equivalently, stable polynomials). However, recent progress in nonlinear variational analysis, tailored towards solving H∞ fixed-order control problems (Burke *et al.*, 2003) paved the way for the development of nonsmooth optimization algorithms based on quasi-Newton (BFGS), bundling and gradient sampling. A MATLAB software called HIFOO (H-Infinity Fixed-Order Optimization) has been released, see (Burke *et al.*, 2006, Millstone, 2006), and uses local optimization techniques. This software has been used in this work for the observer gain matrix calculation (i.e. a zero-order error compensator for the observer).

3.2 Simulation results for web machines

The study of mechanical laws described in the previous section highlights that the determination of web velocity implies information concerning friction torques. In web handling systems, friction is usually assumed to be the sum of dry friction and viscous friction for driven rolls. In the case of our experimental setup, these friction torques have been identified by a third-order least-square function for the driven rolls whose constant is the dry friction torque (Koç, 2000). Unfortunately they strongly depend on lubrication, wear, etc. In addition to these wide uncertainties on frictions, the main issue of the linear model is that the dry friction torque cannot be directly taken into account in the state space model.

These mechanical constraints, added to the linearization of the system, lead to three issues to check the observer efficiency in an industrial context. The first is to evaluate the quality of tension estimates when various friction torques are applied on each master roll. The second issue concerns losses torques which are badly evaluated by a perturbation estimator, i.e. an error is committed on the inputs of the PI-observer. Finally, the last issue concerns the evolution of the model for working points widely different from web and tension nominal set points used for linearization.

Fig. 6 proposes some initial results to answer these questions. It is assumed that perturbation observers on each roll estimate precisely the friction torques, so that no error exists on the tension observer inputs. Furthermore, two types of friction are applied on the traction rolls: friction corresponding to those of our experimental setup (Fig. 6 (a)) and twice this quantity (Fig. 6 (b)). It can be easily observed that the efficiency of the observer to estimate web tension T_3 does not depend on friction characteristics of the web handling system since they are properly estimated.

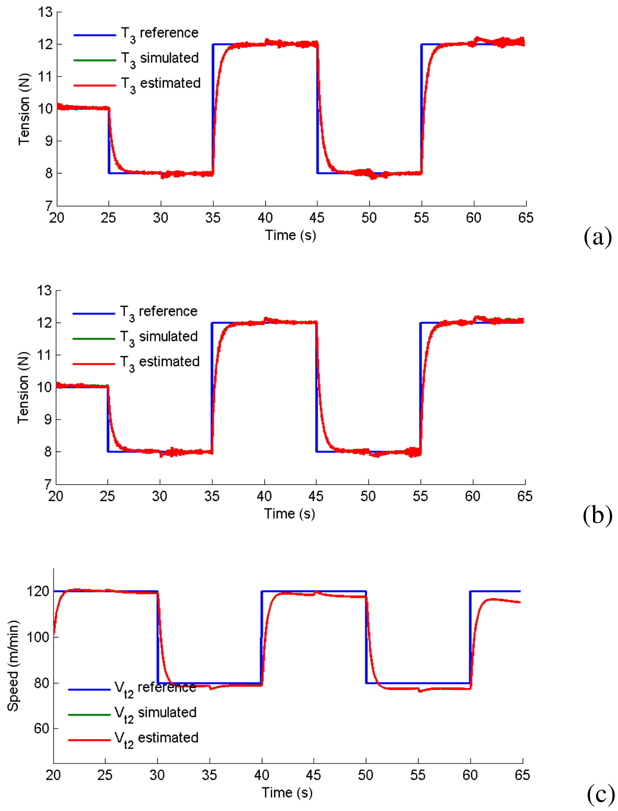
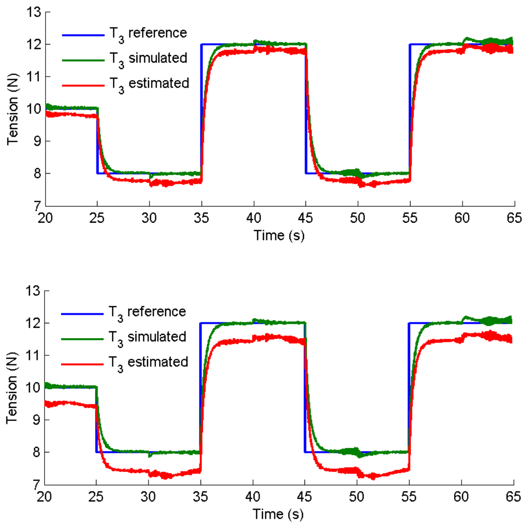


Fig. 6. Estimation of T_3 for various friction torques. (a) Identified friction model. (b) Twice the identified model. (c) Speed reference

In addition to various friction torques, step changes are alternatively applied in web speed and tension references, so that the working points of the system is significantly different from the nominal set points used for model linearization (Fig. 6 (c) shows speed reference). The observer is calculated for a nominal web speed V_0 of 100 m/min and a nominal web tension T_0 of 10 N. The simulations prove that the observer works for a wide range of working points around the nominal points. So the estimation of T_3 depends neither on the working points nor on the friction characteristics of each roll.

Finally, errors on the friction estimations have been added to the results proposed in Fig. 7. Fig. 7 (a) assumes that 90% of the effective friction torques have been estimated, and only 75% in Fig. 7 (b). It can be observed that the error in the estimation of T_3 increases dramatically with the error on friction estimations at the inputs of the observer. These simulations highlight a very important point concerning tension observer in industrial unwinder – winder systems: the assumptions of negligible friction or perfectly-modeled friction are not enough to provide efficient and accurate tension estimates. These mechanical perturbations need to be known precisely at each point in time. The Kalman filter in the next section presents a mean to take directly into account these frictions in the observer synthesis without external perturbation estimators.



(a)

(b)

Fig. 7. T_3 for various friction estimation errors. (a) 10% mistake. (b) 25% mistake

4. KALMAN FILTERING

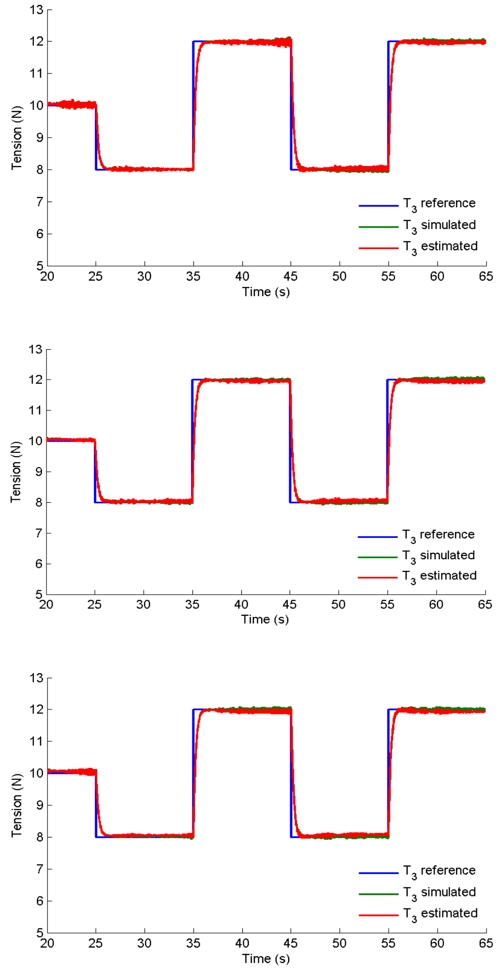
In this case, the state space representation used is slightly different because friction is directly estimated by the Kalman filter. First a linearization at the nominal speed set point of the identified friction model is directly taken into account in the speed dynamics of the filter. Then all the other losses, i.e. dry friction and other random variations, are compensated and estimated by the observer thanks to an additional state (Gassmann, 2007). This new state is chosen as follows

$$\frac{dC_{rk}}{dt} = 0 \tag{10}$$

where k represents one the three master rolls. The principal advantage of this approach compared to the PI-observer is that it appears as fully friction-independent.

Fig. 8 shows the efficiency and the accuracy of the Kalman filter to estimate the unknown web tension T_3 whatever the friction applied to each roll. Notice that the nominal web speed set point used for model linearization is the one corresponding to the constant reference (V_0 = 100 m/min) for the following simulations.

Another result concerning the Kalman filter is presented in Fig. 9. The observer is calculated for a nominal web speed of 100 m/min and a nominal web tension of 10 N. Then step changes in references are applied alternatively on tensions and speed. A large difference between the nominal set point used for linearization and the working point has no influence on estimate precision when this difference concerns only the web nominal set point or tension nominal set point (Fig. 9 between time 25 and 50s, 55 and 70s). On the contrary, when there is a huge difference at the same time (Fig. 9. between time 50 and 55s, 70 and 80s), tension estimate presents an offset. A short analysis of relation (7) can easily prove that the main reason of this offset comes from the error committed on the speed nominal set points. This sensitivity to web velocity has already been observed in the case of the study of slippage between web and roll (Shin, 2000). A direct consequence of this dependence is the requirement of control strategies which ensure efficient speed reference tracking. To face this issue, the use of techniques based on linear models, such as LPV or multi-models, are under study.



(a)

(b)

(c)

Fig. 8. Estimation of T_3 for various friction torques. (a) Without friction. (b) With the identified friction. (c) Twice the identified friction

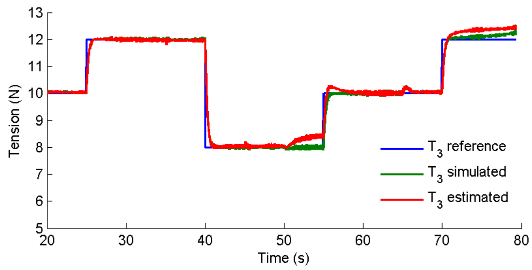
5. CONCLUSION

This paper has focused on a cost-effective method of estimating tension in web handling systems based on observer theory. This method presents the advantage of limiting the number of load sensors and dancers in the line. Two kinds of approaches have been tested and discussed for parameter variations, friction in particular.

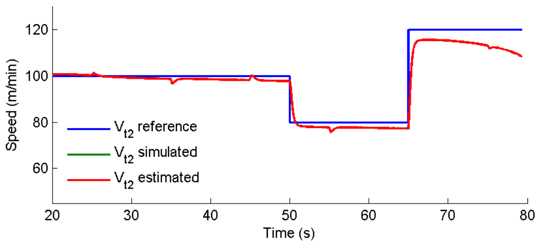
The first approach is a H∞-based PI-observer which ensures disturbance rejection. A perturbation observer which has not been presented in this paper is necessary to provide efficient friction estimations on each master roll. The observer has been tested for various frictions applied on each roll and various tension and speed working points different from the nominal set points used in the linearization. Thus it has been shown that these frictions have to be precisely known at each instant in order to achieve good tension estimation accuracy.

The second approach consists in a Kalman filter. This second estimator takes directly into account a linearized friction model in the state space representation and estimates all the other losses, e.g. dry friction, thanks to an additional state. It presents very interesting results for friction variations but has the drawback of being more dependent on the web and tension nominal set points than the PI-observer.

Further studies will investigate the synthesis of LPV or multimodel observers in order to face the nonlinearities and working variations.



(a)



(b)

Fig. 9. (a) Estimation of T_3 for various tension and speed references around their nominal set points. (b) Speed reference

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