SENSORLESS TENSION CONTROL OF WEBS

by

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Abstract

Production plants with continuous moving webs have a complex structure where mechanical, electrical and control problems are involved. To solve the problems of these systems, it is necessary to take the entire system into account.

In many processing machines in the plastic–, textile– and paper industry only the speed of the roller is controlled. The web tension is a function of the speed relation. The disadvantage of only controlling the speed is that the changes in the tension of the web during the technological process cannot be controlled. Therefore some nip sections are equipped with a sensor to measure the tension so that a closed loop control of the web tension can be used.

The sensor is a roller which is able to measure the web tension by transforming the mechanical signal to an electrical signal. But each roller in the plant is able to cause problems in the lateral control of the web or generate web wrinkling. Therefore it would be better to get the web tension sensorless. This would save problems and money.

In this paper observers to estimate the web tension are discussed. But there are some problems to realize observers in plants with continuous moving webs. The first problem is that all rollers and drives are coupled in the plant. Therefore, we have to design decentralized observers. The second problem are unknown and sometimes nonlinear parameters in the plant or not measurable inputs, for example disturbances that change while the process is running. Therefore observers have to be designed to estimate the tensions without a steady–state error.

NOMENCLATURE

Unnormalized quantities are written in capital letters whereas normalized quantities are written in small letters.

$\underline{A}$	System matrix of the state space control
$\underline{B}$	Input matrix of the state space control
$\underline{C}$	Output matrix of the state space control
$\underline{e}$	Error in the observer
F_N	Reference force in the web
f_{jk}	Web force between the rollers No. j and k
f_{jk}^*	Reference web force between the rollers No. j and k
$\hat{f}_{jk}$	Estimated web force in the observer
$\underline{H}$	Gain vector of the observer
$\underline{K}$	Optimal controller gain vector
L_N	Reference length of the web
l_{jk}	Length of the web between the rollers No. j and k
m_k	Torque of the motor shaft No. k
n_k	Speed of the motor shaft No. k
s	Laplace operator
T_{jk}	Time constant of the web between the rollers No. j and k
T_N	Reference time constant of the web ($T_N = L_N/V_N$)
$T_{\Theta N}$	Time constant of inertia of roller and drive
$\underline{u}$	Input vector of the state space control
v_i	Velocity of the web in the section No. i
v_0	Average velocity of the web
V_N	Reference velocity of the web
$\underline{x}$	State vector of the state space control
$\underline{y}$	Output vector of the state space control
$\underline{z}$	Disturbance vector
ϵ_{jk}	Strain in the web between the rollers No. j and k
ϵ_N	Normalized strain

INTRODUCTION

Production plants with continuous moving webs are driven by a large number of electrical machines which are controlled by different control loops. The web, for example paper, plastic, textile or metal, has to pass through several processing stations. All sections of the continuous process are coupled by the web.

Depending on the technological process, there are different demands on the transport of the web. But in every case, the transport of the web through processes has to be successful without material defects and losses under a definite tension which has to be changeable in separate sections of the processing machine.

Production plants with continuous moving webs have a complex structure where mechanical and electrical problems are involved. In the mechanical system – schematically shown in Fig. 1 – the web is processed in different stations. In these stations, there are driven and undriven rollers to transport and process the web. The web forces must be kept on a desired value within close limits depending on the technological process. The rollers are driven by electrical motors and are controlled in current, speed and occasionaly in force. The winder is a store of the material.

A simple solution to keep the tension constant in the web is to use a dancing roller [1]. Another simple solution is to control only the speed of the driven rollers of the system. The web forces are controlled in an open loop as a function of the speed difference of the rollers. The disadvantage of this method is that changes in the strain of the web, e.g. during coating or printing, cannot be controlled.

Therefore, some nip sections are equipped with load cells to measure the tension so that a closed loop control of the web forces is possible. The disadvantage of the load cells is the random disturbance of the output, so that the signal must be smoothed and therefore it is delayed.

Today the requirements on a tension control increase because of higher speed in the plant and so new solutions are required. Therefore, non–interacting, decentralized control loops and observers should be used to improve the dynamic behaviour of the control. As a state space control and an observer of the complete system are complex and often unpractical in industrial plants, decentralized control methods should be used, where the state space control and decentralized observers are designed with subsystems of low order [2], [6].

Throughout this paper, normalized quantities are used (see table 1).

OBSERVERS

Generally, an observer is a feedbacked model of the system which estimates the controlled variables $\underline{x}$ from well measurable inputs $\underline{u}$ and outputs $\underline{y}$ of the system [3]. An example of an observer is given in Fig. 2. The observer is a parallel model of the system which is driven from the inputs $\underline{u}$ of the system. If the parameters $\underline{A}, \underline{B}, \underline{C}$ of the system and the observer are identical, the estimated state values $\underline{\hat{x}}$ are equal to the real state values $\underline{x}$ of the system. But in real plants, not all parameters of the system are exactly known. Therefore we have a difference between the outputs $\underline{y}$ of the system and the outputs $\underline{\hat{y}}$ of the observer, called error $\underline{e}$. If the error $\underline{e}$ is feedbacked by the matrix $\underline{H}$, the steady–state error is to zero, if no disturbances $\underline{z}$ are acting in the system. If there are disturbances, we need additional integrators in the observer. The steady–state outputs $\underline{\hat{z}}$ of the integrators are the estimated disturbances. In this case, we have designed a disturbance–observer. Measurable controlled values can be used as inputs of the observer, this leads to a reduced–observer.

Observer of the Total System

The basic equations of an observer, described in state space, are:

$$\begin{aligned} \dot{\hat{\underline{x}}} &= \underline{A}\cdot\hat{\underline{x}} + \underline{B}\cdot\underline{u} + \underline{H}\cdot(\underline{y} - \hat{\underline{y}}) \\ \hat{\underline{y}} &= \underline{C}\cdot\hat{\underline{x}} \end{aligned} \tag{1}$$

After a simple transformation, equation 1 can be written as:

$$\begin{aligned} \dot{\hat{\underline{x}}} &= (\underline{A} - \underline{H}\,\underline{C})\cdot\hat{\underline{x}} + \underline{B}\cdot\underline{u} + \underline{H}\cdot\underline{y} \\ \hat{\underline{y}} &= \underline{C}\cdot\hat{\underline{x}} \end{aligned} \tag{2}$$

The gain $\underline{H}$ defines the dynamic behaviour of the observer and is calculated with pole placement or riccati–equation similarly to the gain $\underline{K}$ of the state space control. The dynamic of the observer should be faster than that of the controlled system. The definition of the error $\underline{e}$ is:

$$\underline{e} = \underline{x} - \hat{\underline{x}} \tag{3}$$

The controlled system is described with the following state equations:

$$\begin{aligned} \dot{\underline{x}} &= \underline{A}\cdot\underline{x} + \underline{B}\cdot\underline{u} \\ \underline{y} &= \underline{C}\cdot\underline{x} \end{aligned} \tag{4}$$

From the equations 1 and 4 the differential equation of the error is given:

$$\dot{\underline{e}} = (\underline{A} - \underline{H}\cdot\underline{C})\cdot\underline{e} \tag{5}$$

The equation 5 is homogeneous and the error runs asymptotical to zero if the eigenvalues of the matrix $(\underline{A} - \underline{H}\cdot\underline{C})$ have negative real components. As mentioned above, an error exists if there are disturbances acting on the system. In this case, a disturbance–observer is necessary.

Decentralized Observer

As a state space control of the total system is complex and often unpractical in industrial plants, decentralized control methods should be used, where the state space control and the observers are designed with subsystems of low order [4]. The decentralized observer has to estimate the substate values $\hat{\underline{x}}_i$ only from the input $\underline{u}_{Si}$ and the output $\underline{y}_{Mi}$ of the subsystem number i. This fact is shown in Fig. 3. The state equations of the decentralized observer No. i reads as follows:

$$\begin{aligned} \dot{\hat{\underline{x}}}_i &= \underline{A}_{ii}\cdot\hat{\underline{x}}_i + \underline{B}_{Si}\cdot\underline{u}_{Si} + \underline{B}_{Ki}\cdot\underline{u}_{Ki} + \underline{H}_i\cdot(\underline{y}_{Mi} - \hat{\underline{y}}_{Mi}) \\ \hat{\underline{y}}_{Mi} &= \underline{C}_{Mi}\cdot\hat{\underline{x}}_i \end{aligned} \tag{6}$$

in which $\underline{u}_{Si}$ and $\underline{y}_{Mi}$ are respectively the measurable in– and output of the observer and $\underline{u}_{Ki}$ is the input vector of the coupling values. To get a homogeneous differential equation of the error, we have to feed all coupling values into the observer. That means, all these values must be measurable. But this is not possible in real systems . Therefore we try to replace the coupling vector $\underline{u}_{Ki}$ with an approximation $\underline{\delta}_i$. The approximation $\underline{\delta}_i$ is calculated from measurable values of the subsystem. With $\underline{u}_{Ki} \longrightarrow \underline{\delta}_i$ the new state equations of the decentralized observer are:

$$\begin{aligned} \dot{\hat{\underline{x}}}_i &= \underline{A}_{ii} \cdot \hat{\underline{x}}_i + \underline{B}_{Si} \cdot \underline{u}_{Si} + \underline{B}_{Ki} \cdot \underline{\delta}_i + \underline{H}_i \cdot (\underline{y}_{Mi} - \hat{\underline{y}}_{Mi}) \\ \hat{\underline{y}}_{Mi} &= \underline{C}_{Mi} \cdot \hat{\underline{x}}_i \end{aligned} \tag{7}$$

The differential equation of this observer is:

$$\dot{\underline{e}}_i = (\underline{A}_{ii} - \underline{H}_i \cdot \underline{C}_{Mi}) \cdot \underline{e}_i + \underline{B}_{Ki} \cdot (\underline{u}_{Ki} - \underline{\delta}_i) \tag{8}$$

Equation 8 is inhomogeneous, as there is a difference between $\underline{u}_{Ki}$ and $\underline{\delta}_i$. Therefore we try to minimize the difference and get the difference to zero in the steady–state. If we do so, equation 8 is asymptotical homogeneous and no steady–state error occurs.

Approximation With Disturbance Model

The principle method is simple. The subsystem is extended with the disturbance model and the decentralized observer is calculated with the extended system. This system is shown in Fig. 4. The problem is to find a practicable disturbance model.

To minimize the problems, a homogeneous differential equation of the disturbance model is proposed.

$$\begin{aligned} \dot{\underline{\xi}}_i &= \underline{\Psi}_i \cdot \underline{\xi}_i \\ \underline{u}_{Ki} &= \underline{\Phi}_i \cdot \underline{\xi}_i \end{aligned} \tag{9}$$

in which $\underline{\Psi}_i$ is the dynamic matrix, $\underline{\Phi}_i$ the output matrix, $\underline{\xi}_i$ the state value and $\underline{u}_{Ki}$ the output of the disturbance model. The state equations of the extended system are:

$$\begin{aligned} \dot{\hat{\underline{x}}}_i &= \underline{A}_{ii} \cdot \hat{\underline{x}}_i + \underline{B}_{Si} \cdot \underline{u}_{Si} + \underline{B}_{Ki} \cdot \underline{\Phi}_i \cdot \underline{\xi}_i + \underline{H}_i \cdot (\underline{y}_{Mi} - \hat{\underline{y}}_{Mi}) \\ \hat{\underline{y}}_{Mi} &= \underline{C}_{Mi} \cdot \hat{\underline{x}}_i \end{aligned} \tag{10}$$

$$\begin{aligned} \dot{\hat{\underline{\xi}}}_i &= \underline{\Psi}_i \cdot \hat{\underline{\xi}}_i + \underline{H}_{\xi i} \cdot (\underline{y}_{Mi} - \hat{\underline{y}}_{Mi}) \\ \hat{\underline{u}}_{Ki} &= \underline{\delta}_i = \underline{\Phi}_i \cdot \hat{\underline{\xi}}_i \end{aligned} \tag{11}$$

To get an asymptotical homogeneous differential equation of the error and a practicable disturbance model, we have chosen the following special model:

$$\begin{aligned} \underline{\Psi}_i &= \underline{0} \\ \underline{\Phi}_i &= \underline{I} \end{aligned} \qquad (12)$$

This leads after an algebraic manipulation of equation 11 to the differential equation:

$$\dot{\hat{\underline{\xi}}}_i = \dot{\hat{\underline{\delta}}}_i = \underline{H}_{\xi i} \cdot (\underline{y}_{Mi} - \hat{\underline{y}}_{Mi}) \qquad (13)$$

We can see from equation 13, that we have to extend the decentralized observer with an integral feedback of the difference of the measurable and estimated outputs $\underline{y}_{Mi}$ and $\hat{\underline{y}}_{Mi}$. With this difference the steady-state value of the coupling value $\underline{u}_{Ki}$ is reconstructed.

I have to point out that the theorem of separation is not valid, if we use decentralized observers. That means that the dynamic of the controlled system depends also on the dynamic of the observers. In the case of a total observer the separation is valid.

DECENTRALIZED OBSERVER TO ESTIMATE THE WEB FORCES

Linear Signal–flow Graph of the Total System

The linear signal–flow graph of a total system is shown in Fig. 1. The technological system consists of drives, rollers and web sections [5]. The separation into subsystems should be close to the technology. Therefore, the subsystem was designed in this manner, as shown in Fig. 1 and explained in [6].

Example with two Subsystems

In the same manner, a second subsystem is added. The tension control of these subsystems is done with two decentralized, reduced observers. Each subsystem is of the third order, each observer of the second order. The reduction is possible, if we measure the current or torque of the electrical drive. In doing so, we get the principle structure of the sensorless control shown in Fig. 5. The controllers work with the estimated web forces $\hat{f}_{23}$ and $\hat{f}_{34}$.

The coupling input of subsystem No. 3 and the coupling output of subsystem No. 4 is the web force f_{34}, whereas the coupling inputs of subsystem No. 4 and the coupling outputs of subsystem No. 3 are the speed v_3 and the strain ϵ_{23} (Fig. 1). So we get the following vectors and matrices analogous to equation 6:

$$\underline{u}_{K3} = [\ f_{34}\ ] \tag{14}$$

$$\underline{B}_{K3} = \begin{pmatrix} 0 \\ 1/T_{\Theta N} \\ 0 \end{pmatrix} \tag{15}$$

$$\underline{u}_{K4} = [\ v_3 - v_0\epsilon_{23}\ ] \tag{16}$$

$$\underline{B}_{K4} = \begin{pmatrix} -1/l_{34}T_N\epsilon_N \\ 0 \\ 0 \end{pmatrix} \tag{17}$$

The reduced decentralized observers with disturbance model are designed analogous to the equations 10 and 13. The parameters of the gain vector $\underline{H}$ and the disturbance model are calculated with the riccati–equation. The working characteristic data is equal to those of our experimental plant. Fig. 6a shows the decentralized observer No. 3 and Fig. 6b the decentralized observer No. 4. The disturbance models are simple integrators. The outputs $\hat{\xi}_3$ respectively $\hat{\xi}_4$ are equivalent to the coupling inputs f_{34} respectively $v_3 - v_0\epsilon_{23}$ in case of steady–state. The dotted feedback in Fig. 6b can be neglected, if the value of the product $h_{41} \cdot \epsilon_N$ is very small. To show how the observer works, two cases are considered.

<u>Decentralized observer without disturbance model</u> The controllers are designed to the method of decentralized decoupling [6]. To recognize the error of the observers, in the following examples the measured web forces are feedbacked to the controllers. So, the observers are running parallel to the system to be controlled. The step responses of the web forces f_{23} respectively f_{34} are shown in Fig. 7. The estimated web forces $\hat{f}_{23}$ respectively $\hat{f}_{34}$ are identical with the measured web forces f_{23} respectively f_{34} in the relevant subsystem. But the observer No. 3 cannot estimate the web force $\hat{f}_{23}$ without an error, if a change of the force in the subsystem No. 4 is active (Fig. 7b). On the other hand, the estimated web force $\hat{f}_{34}$ in observer No. 4 is wrong, if the control of subsystem No. 3 is active (7a). This is the consequence of neglecting the coupling values. To improve the observers, we need a disturbance model.

<u>Decentralized observer with disturbance model</u> Now the observers are designed with disturbance models. Fig. 8 shows that both observers are able to estimate the web forces without a steady–state error in any case of excitation of the controlled systems. However, dynamic errors occur as seen

especially in Fig. 8b of the estimated force $\hat{f}_{23}$. These dynamic errors can be minimized by a reduction of the time constant T_{ξ_3} in observer No. 3. But the reduction of the time constant is limited in real plants due of noisy inputs of the observers.

Changes of Parameters

In the chapters above we have seen, that decentralized observers with disturbance models are able to estimate the web forces without the knowledge of the coupling values. The requirement is that all parameters of the observers are identical with these of the system to be controlled.

But there are unknown parameters in the plant or not measurable inputs $\underline{z}$ (Fig. 2) which change while the process is running. If the disturbance inputs $\underline{z}$ are not measurable, the observer is not able to know these inputs and we will get an error in the estimated outputs $\hat{\underline{y}}$. Normally in such cases an integrator is used in the observer to estimate the steady–state value $\hat{\underline{z}}$ [3], [4].

In the case of continuous moving webs there are two dominant unknown parameters causing errors in the estimated web forces. Unfortunately these two parameters, the friction f_r and the web modulus of elasticity ϵ_N are acting on the same place at the balance of the torques in the system as shown in Fig. 9. As we have only one speed error $\underline{\epsilon}$ in the observer (Fig. 6), we cannot estimate two parameters. If we would add one integrator more to estimate the second unknown parameter, we get an instable observer.

Change of the modulus of elasticity To see the effect of a change of unknown parameters, first we change the modulus of elasticity ϵ_N. The amount of the change in this example is:

$$\epsilon_N = 0.5 \cdot \epsilon_{Nobs} \tag{18}$$

The step responses of the web forces appear in Fig. 10. As shown in Fig. 10a, the observer No. 3 is not able to estimate the web force $\hat{f}_{23}$ without a steady–state error. The steady–state value of the web force is only 0.5.

But the observer No. 4 estimates the web forces without a steady–state error in spite of different moduli of elasticity in the system and observer. The reason of this fact is that the disturbance integrator in observer No. 4 acts at the balance of the speeds $\hat{v}_4 - v_3$ (Fig. 6b). Therefore the steady–state error can be compensated. The disturbance model of observer No. 3 acts at the balance of the torques and is not able to compensate the error (Fig. 6a).

Change of the friction An other situation is given, if the friction in the plant is changing as shown in Fig. 11. The friction changes with a step from the normalized value 0 to 1. As shown in Fig. 11a, the observer No. 3 is able to estimate the web forces without a steady–state error. Here, the disturbance integrator acts at the balance of the torques, this is the same place as the friction acts (Fig. 6a and Fig. 9). The friction is compensated.

On the other hand, the observer No. 4 estimates the web forces $\hat{f}_{34}$ with a big steady state error. Here, the disturbance integrator acts at the balance of the speeds and cannot compensate the friction (Fig. 6b and Fig. 9).

We can see from these examples that the disturbance models of the decentralised observers are able to compensate the coupling inputs as well as changes of parameters. So, the disturbance model of observer No. 3 is able to compensate the friction, whereas the disturbance model of observer No. 4 compensates the modulus of elasticity. But it is impossible to use both disturbance models in each observer, because there is only one speed error $v_j - \hat{v}_j$. Therefore we have to use additional methods to compensate both the friction and the modulus of elasticity.

Realized Sensorless Tension Control

Because of the problems discussed above, we suggest to design a sensorless tension control as shown in Fig. 12. The inner structure of all decentralized observers is similar to Fig. 6b. The advantage of this structure is that the observer is able to estimate the incoming strain ϵ_{ij} and the modulus of elasticity ϵ_N. These parameters often are unknown and changing during processing in real plants. To decouple the observers, it is necessary to put in the tension f_{jk} of the following system. This can be done with the estimated tension $\hat{f}_{jk}$. It is advisable to put in also the speed v_i, so that the observer works with an input control to improve the dynamic behaviour. To design a sensorless tension control we only have to measure the torque or current and the speed of the relevant electrical drives. This values are also needed to control the system. No additional values are necessary. The inputs to the tension controllers are the relevant measured speed v_i and the estimated web force $\hat{f}_{ij}$. A control in this manner is able to get the tension sensorless without a steady–state error, even if the modulus of elasticity is unknown or nonlinear.

A simulated control is shown in Fig. 13. The modulus of elasticity ϵ_N was changed referring to equation 18. The suggested structure of the observer is not strictly a decentralized structure as we have a communication between the observers. But if we compare the results of the strictly decentralized observer in Fig. 8 to Fig. 13, we get a significant improvement of the dynamic behaviour.

But the observers are not able to estimate the tension without an error if a **friction** exists. The friction must be compensated with other methods. The friction mostly depends on the speed and the temperature. In our experience, if a plant is running for a while, the friction depends only on the speed. The dependence of the friction versus speed can be measured in different ways or with the method discussed later. New investigations try to estimate the friction with neural networks.

The accuracy of the observer depends on the accuracy of the measurement of the speed and torque or current and the compensation of the friction. Today it is not a problem to measure the speed and current with high accuracy.

So the accuracy of the estimated tension depends mainly on the compensation of the friction.

Advantage of a Sensorless Tension Control

The advantage is to save the measuring equipment, e.g. additional rollers which causes oscillations in the draw and negative influence to the surface of the web. It is not necessary to measure additional values. All needed inputs to the observer are needed to the control as well. So observer can be installed without changing the plant.

On the other hand, an observer is a measuring equipment without big smoothing filters, so that a control with higher dynamics can be designed. Fig. 14a shows the control with sensors, Fig. 14b the control with observers. The decoupling is much better with observers than with sensors.

DECENTRALIZED OBSERVER TO ESTIMATE THE FRICTION

The described observers are able to identify online the changing parameters, for example the friction dependent on the speed, temperature or web force. The identified parameters can be used to get a family of characteristics of the friction. To use the observer as an identifier, the tension must be controlled with sensors. But in this case also a poor measurement is sufficient. Fig. 15 shows the structure of such an identifier. The friction is calculated from the error of the speeds. The inputs are the speeds and the torque or current. As the tension is controlled it is enough to use only the reference inputs f^*_{ij} and f^*_{jk} of the forces . So we avoid the noisy measured inputs of the tensions. The result of a calculated friction in this manner is shown in Fig. 17. This graph can be used to compensate the friction in the decentralized observer as explained above.

EXPERIMENTAL RESULTS

Experimental investigations were made with the plant of our institute to verify the theoretical results. The plant consists of two winders and three nip sections, driven by electrical motors [7].

Fig. 16 shows the result of a sensorless tension control. The control was designed to Fig. 12. For comparison the measured tensions are added in this Figure. It is to point out, that the measured tensions are smoothed with a time constant of 200 ms, whereas the estimated tensions are smoothed with a time constant of 10 ms!

Fig. 17 shows the identified friction during a run–up of the plant from the speed zero to the maximum speed of the plant.

The results of the experiments show that a sensorless control with decentralized observers is possible in real plants and that such observers can be used as identifiers of unknown parameters in the plant.

CONCLUSION

In the paper new decentralized observers are introduced. These observers are able to estimate the web forces in a plant without a steady–state error, even if unknown parameters like modulus of elasticity or nonlinearities are effective. Using this observer, no additional undriven rollers to measure the tension are necessary in the plant. This fact reduces a lot of problems in the longitudinal and lateral mechanics and control of the web. As the accuracy of the estimated tension depends mainly on the compensation of the friction in the plant, it is advisable to reconstruct that parameter very accurately.

On the other hand, such an observer can be used to identify nonlinear parameters in the plant. Therefore this identifier is a step to a self–adaptive control in the plant.

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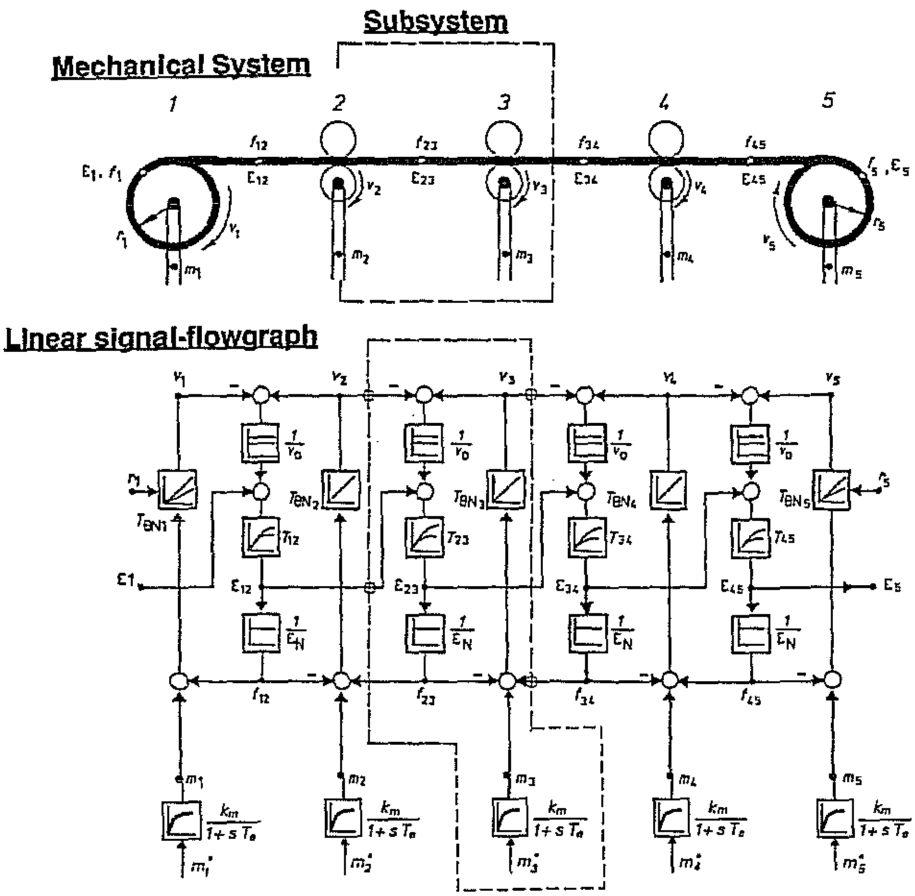


Fig. 1: Linear signal–flow graph of the total system

Unnormalized Quant.	Normalized Quant.	Reference Value
Current I	$i = I/I_{AN}$	Rated current I_{AN}
Torque M	$m = M/M_{iN}$	Rated torque M_{iN}
Speed N	$n = N/N_{0N}$	Rated speed N_{0N}
Velocity V	$v = V/V_N$	Rated velocity V_N
Length L_{ij}	$l_{ij} = L_{ij}/L_N$	Rated length L_N
Force F_{ij}	$f_{ij} = F_{ij}/F_N$	Rated force F_N

Table 1: Normalized Quantities

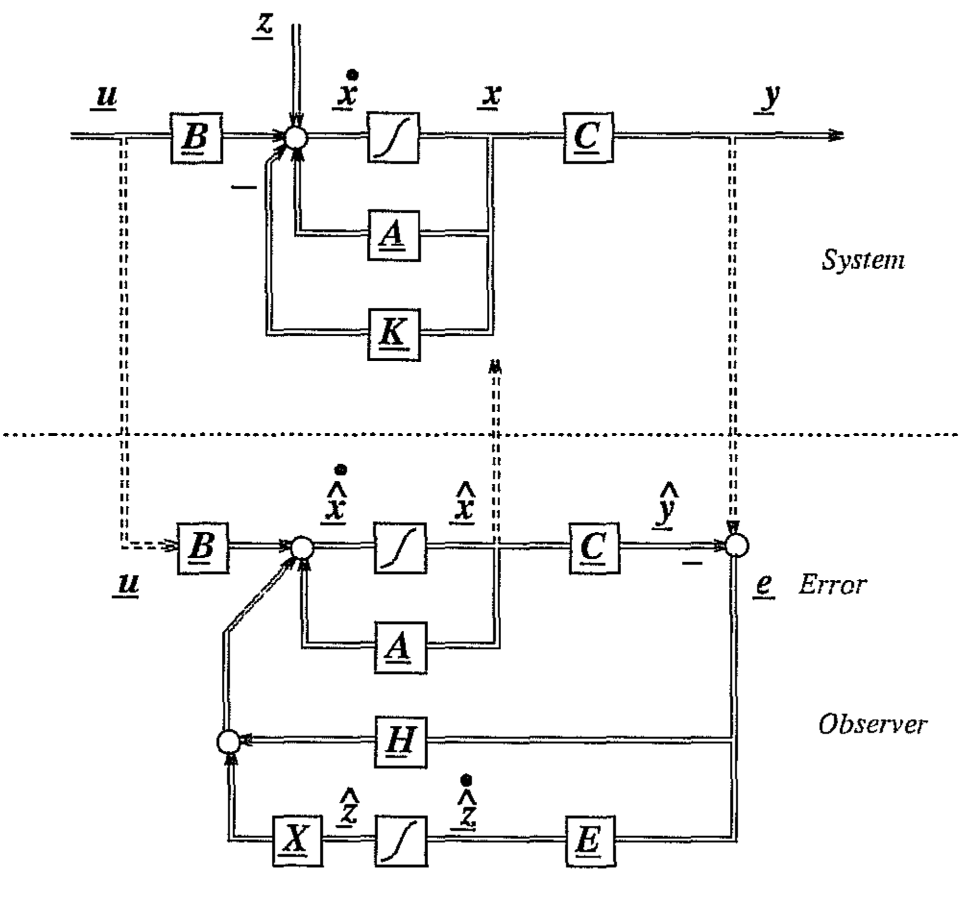


Fig. 2: State space control and observer

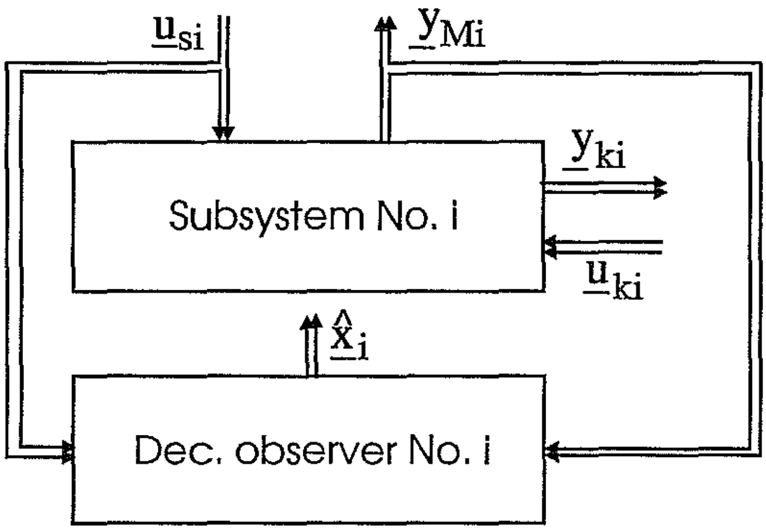


Fig. 3: Decentralized observer

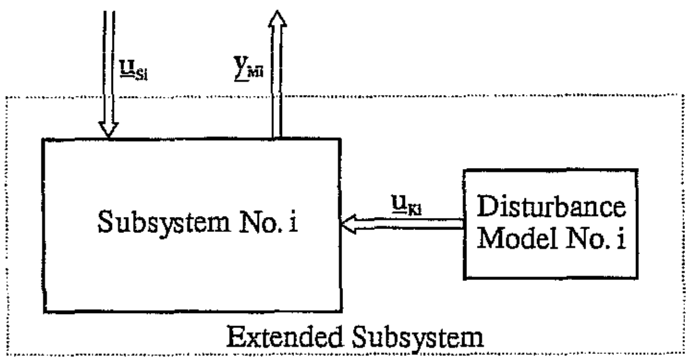


Fig. 4: Extended subsystem

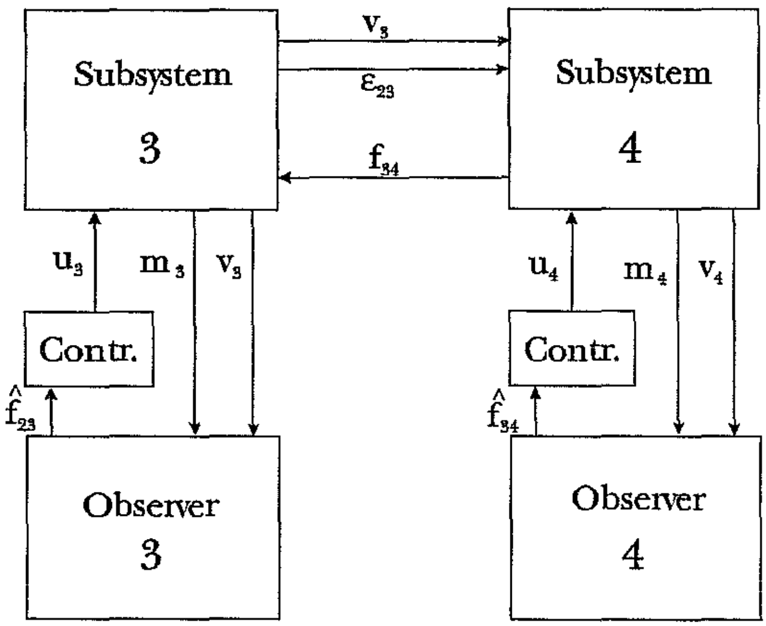
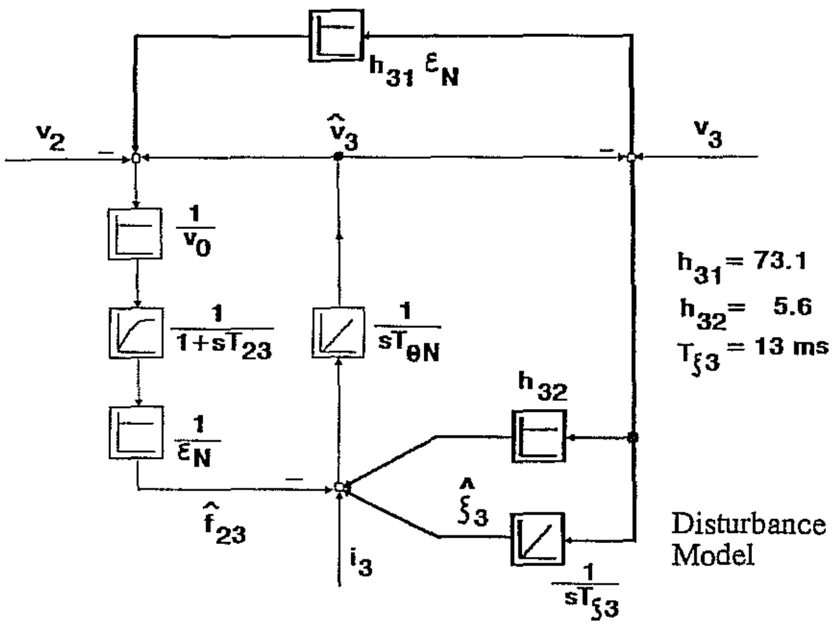
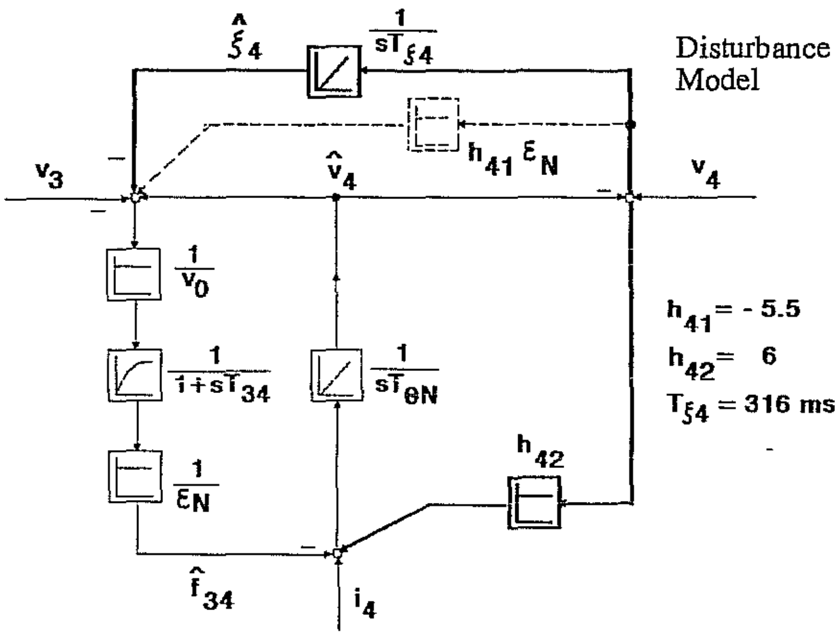


Fig. 5: Structur of a tension control with decentralized observers

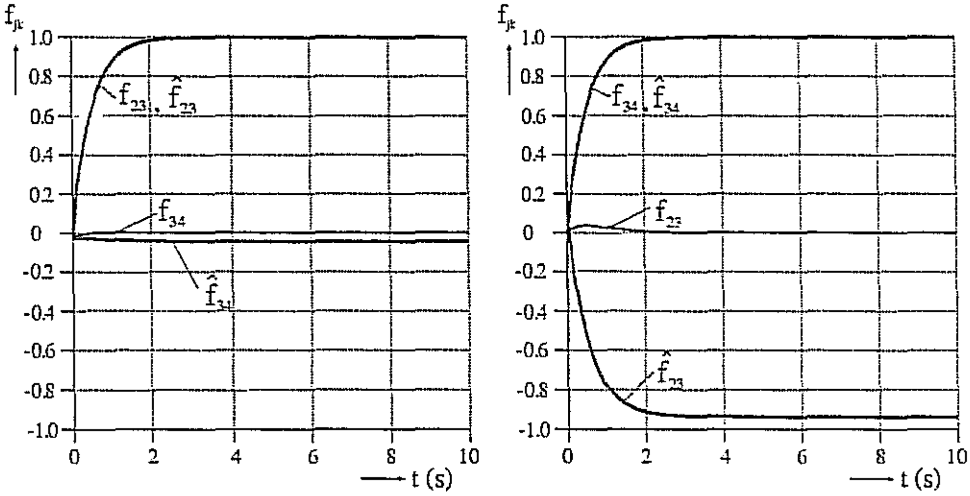


a, Dec. Observer No. 3 with Disturbance Model



b, Dec. Observer No. 4 with Disturbance Model

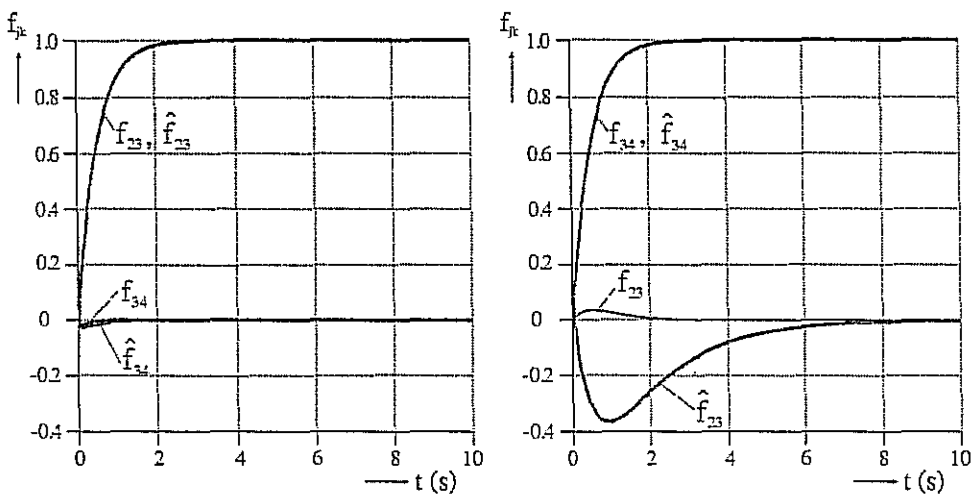
Fig. 6: Real decentralized observer with disturbance model



a, Step responses of subsystem 3

b, Step responses of subsystem 4

Fig. 7: Decentralized observer without disturbance model



a, Step responses of subsystem 3

b, Step responses of subsystem 4

Fig. 8: Decentralized observer with disturbance model

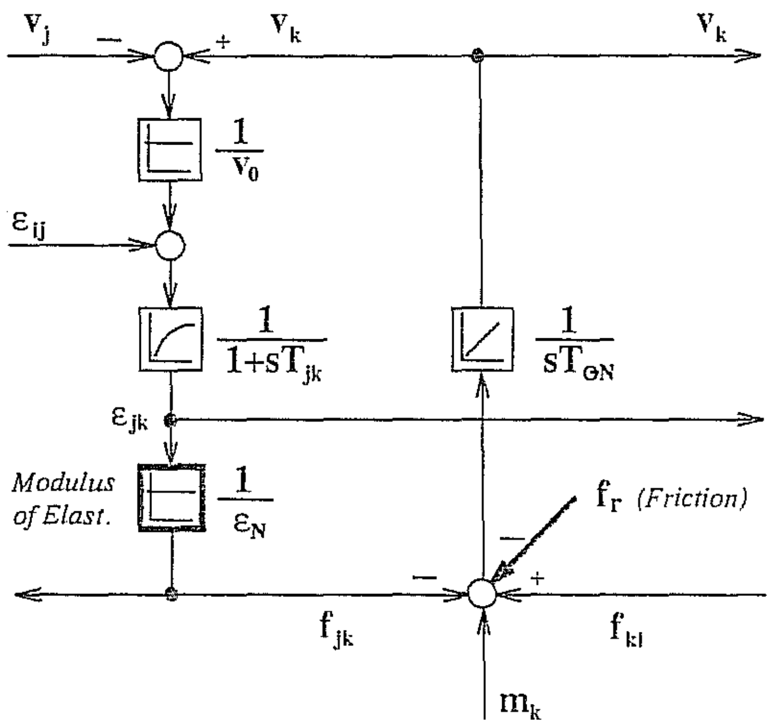


Fig. 9: Subsystem with disturbance values

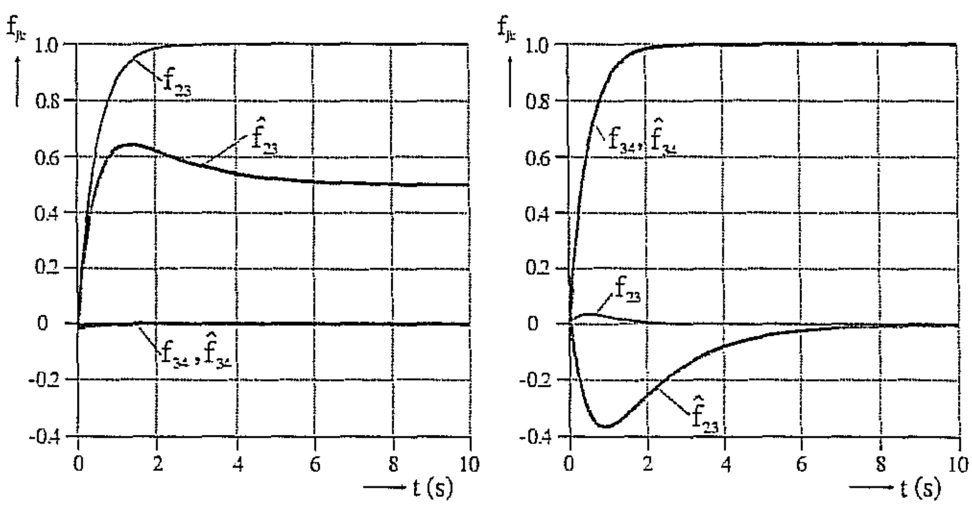


Fig. 10: Decentralized observer with change of modulus of elasticity

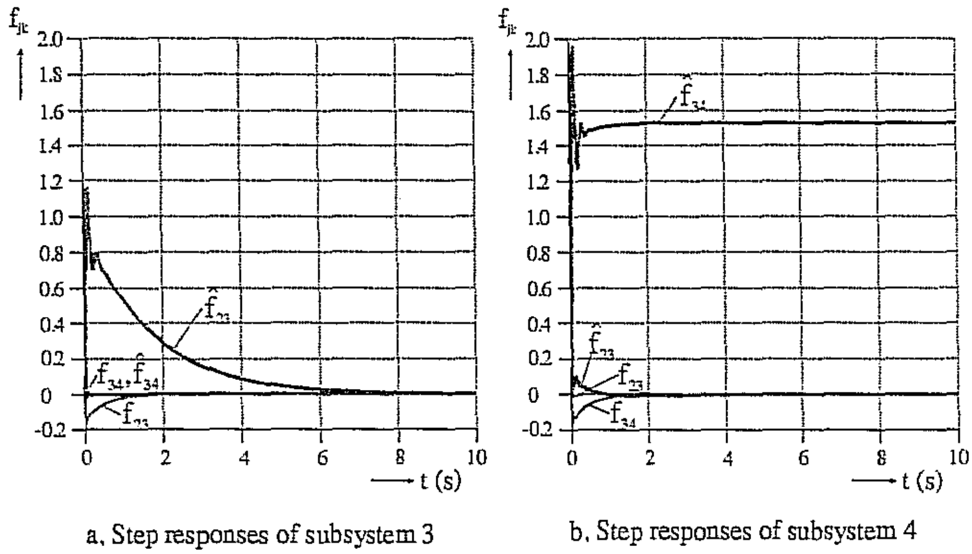


Fig. 11: Decentralized observer with change of friction

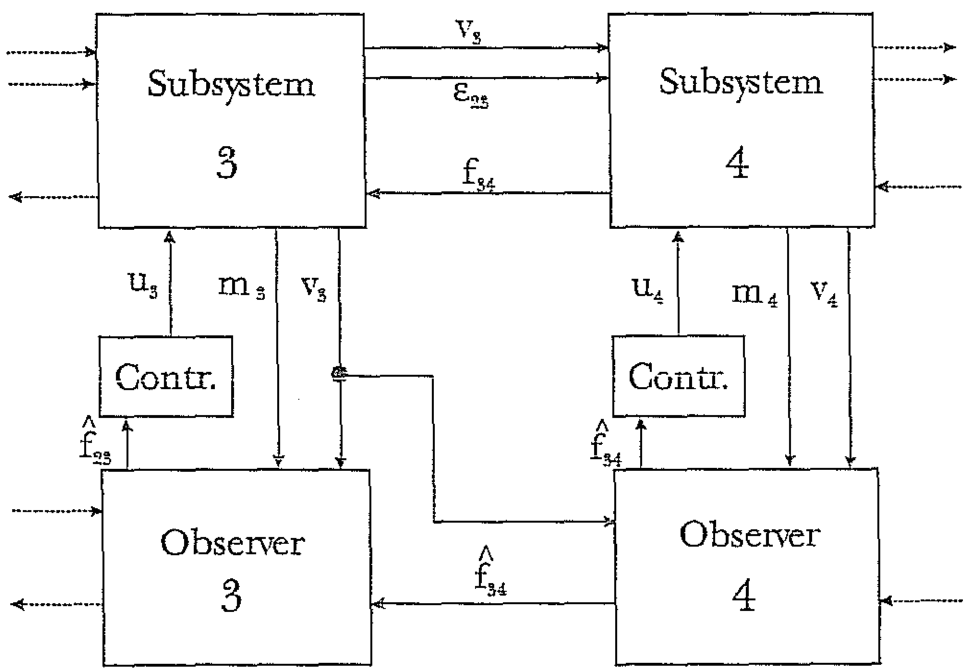
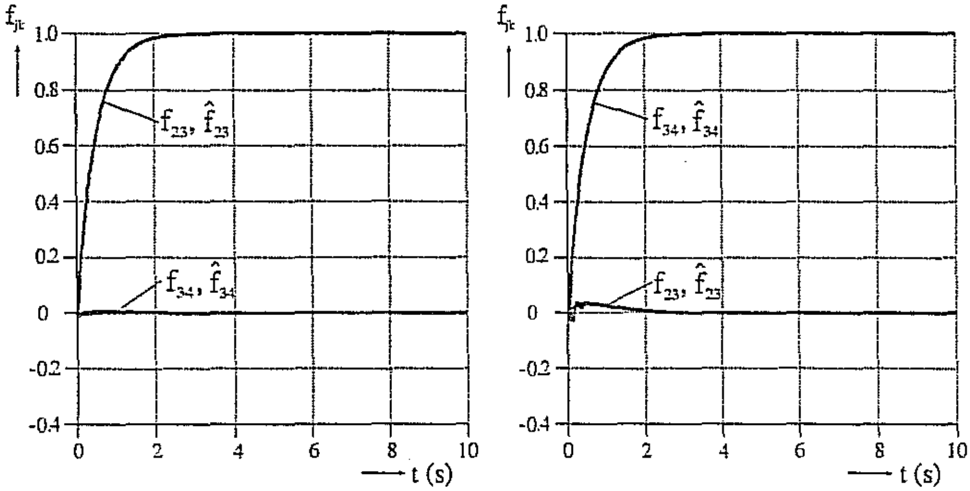


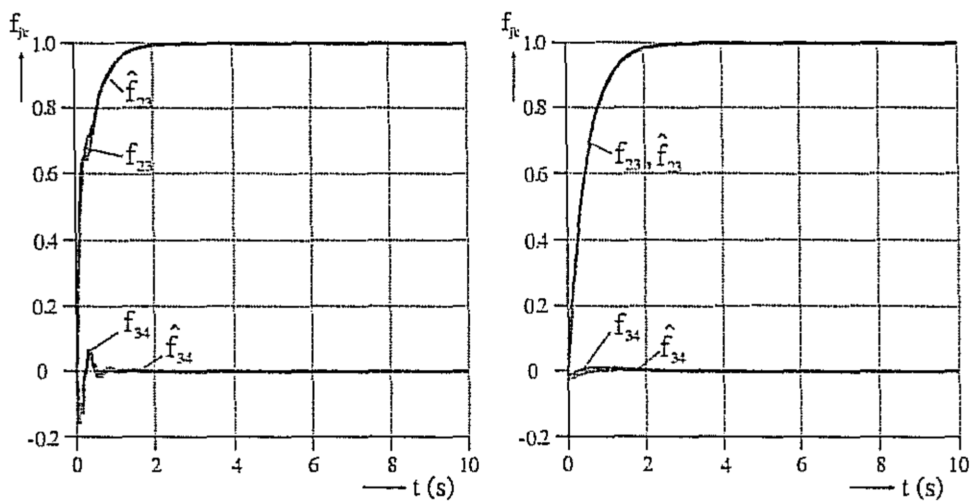
Fig. 12: Realized sensorless tension control



a, Step responses of subsystem 3

b, Step responses of subsystem 4

Fig. 13: Simulated sensorless tension control



a, Tension control with sensors

b, Tension control with observers

Fig. 14: Comparison of a tension control with sensors and observers

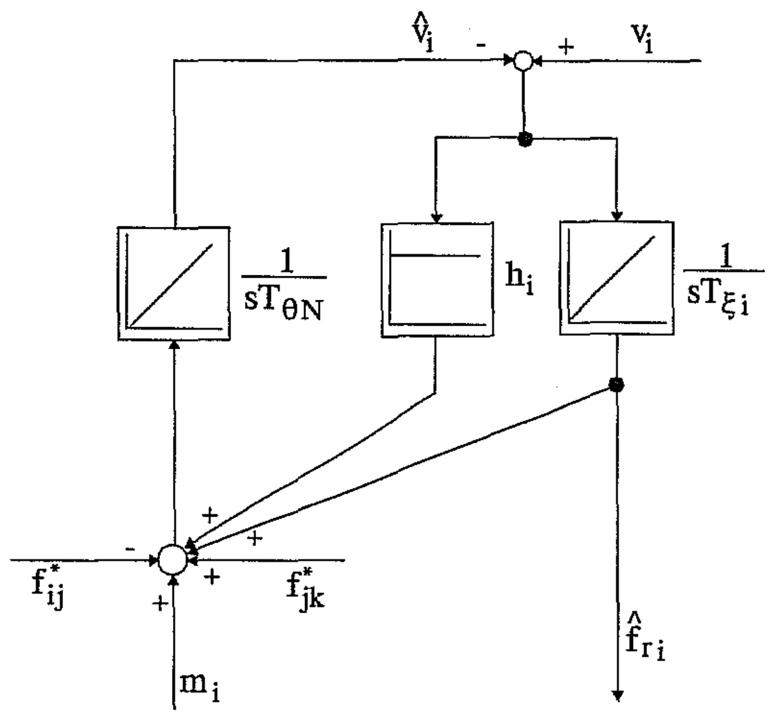
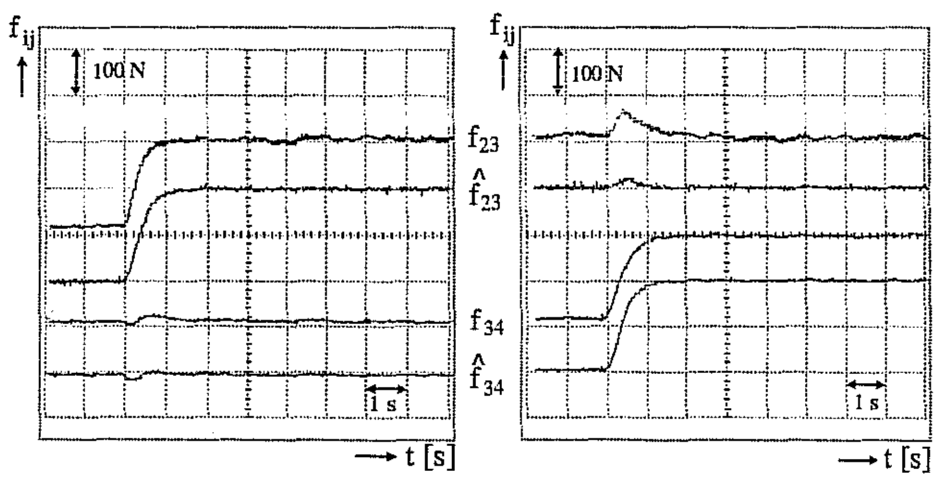


Fig. 15: Structure of the identifier of the friction



a, Measured step responses of subsystem 3 b, Measured step responses of subsystem 4

Fig. 16: Experimental results of a sensorless tension control

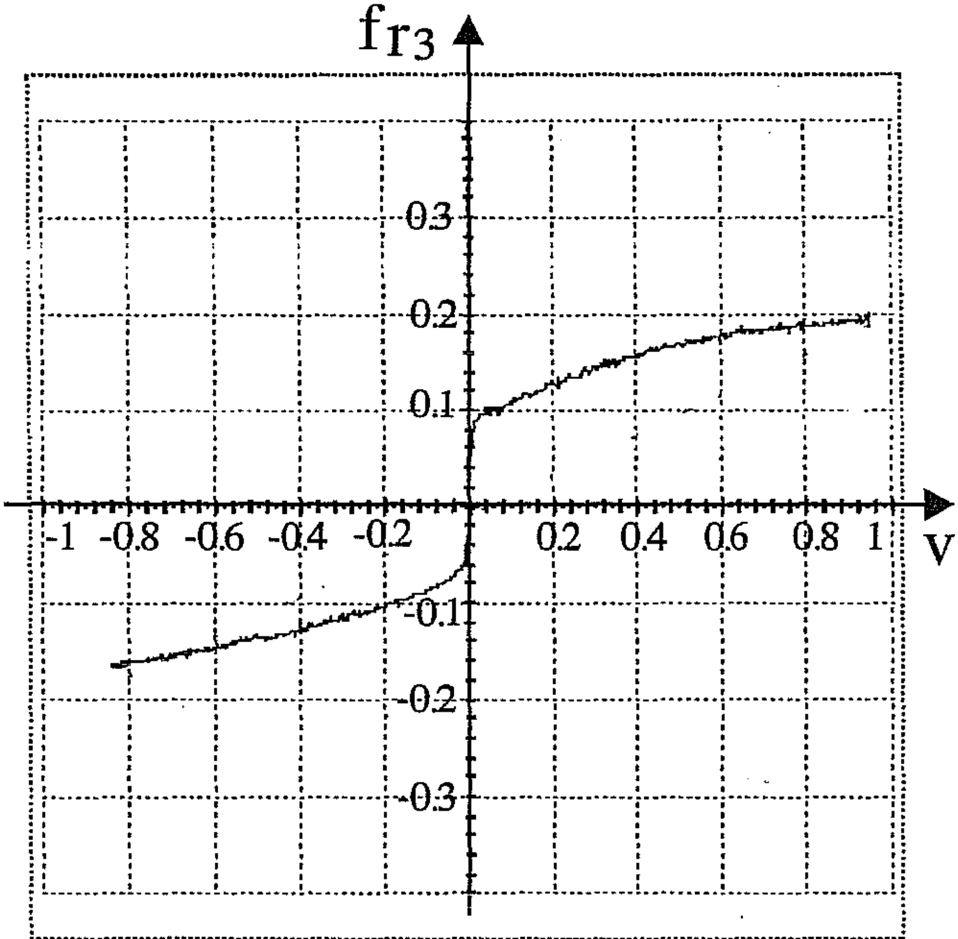


Fig. 17: Identified friction

Question - In making these changes were you able to make observations in the changes or in press or operations?

Answer - Yes.

Question - Is that the experimental data on the loop that you have?

Answer - Yes.

Question - What tension defects in your roll effects the quality of the reel at the printer? Does this tension variation influence the quality of the paper?

Answer - Yes