TENSION CONTROL OF WEBS - A REVIEW OF THE PROBLEMS AND SOLUTIONS IN THE PRESENT AND FUTURE

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Abstract

Production plants with continuous moving webs have a complex structure where mechanical and electrical problems are involved. To solve the problems of this systems, it is necessary to take into account the total system to find an optimum. In other words, we have to achieve an *Integrated Design*.

A global presentation of specific demands and problems refering to tension control is given. After an excursion to the modelling of such systems, we can study the steady–state and dynamic behaviour.

In industrial plants, usually the tension is controlled either in an open loop system with a speed control of the driven rollers or the tension is controlled in a closed loop cascade control with PI or PID controllers. The optimization of the control is often done without the influence of the coupling of the rollers with the web. Under special conditions, if the parameters of the system fulfil particular conditions, such a control leads to an acceptable tension control.

Nowadays the demands on a tension control increase because of higher speed in the plant. In many cases the limits of the cascade control are reached and new solutions are demanded. The goal in the future is to realize non–interacting, decentralized control loops. In the control science, the state space control is an effective tool to solve complex problems and to improve the dynamic behaviour of the control. As a state space control of the total system is complex and often unpractical in industrial plants, decentralized control methods are discussed. As the measurement of the tension causes sometimes more problems than solutions, observers which estimate the web forces are used.

Nevertheless, some problems of tension control cannot be solved by using this methods. In the reality, we do not have linear systems. Therefore some new methods as *Fuzzy Control* and *Neural Networks* are discussed which may be able to solve such non–linear problems.

NOMENCLATURE

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

$\underline{A}$	System matrix of the state space control
A_0	Area of the web
$\underline{B}$	Input matrix of the state space control
$\underline{C}$	Output matrix of the state space control
d	Damping factor
E	Modulus of elasticity
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
$\underline{H}$	Gain vector of the observer
J	Criterion function of state space control
$\underline{K}$	Optimal controller gain vector
k_{en}	Equivalent gain of the speed control
k_m	Equivalent gain of the current or torque control
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
r_k	Radius of the roller No. k
s	Laplace operator
T_e	Equivalent time constant of the current control
T_{en}	Equivalent time constant of the speed control
T_{jk}	Time constant of the web between the rollers No. j and k
T_{int}	Time constant of the integrator in the reference path
T_N	Reference time constant of the web ($T_N = L_N/V_N$)
$T_{\Theta Nk}$	Time constant of inertia of roller and drive No. k
$\underline{u}$	Input vector of the state space control
v_k	Velocity of the web in the section No. k
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
ϵ_{jk}	Strain in the web between the rollers No. j and k
ϵ_N	Normalized strain
ρ	Density of the web
Ω_0	Eigenfrequency of the system
Ω_d	Characteristic frequency of the Symmetrical Optimum

INTRODUCTION

Nowadays, 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. There are often winders installed at the beginning and at the end of the plant.

Depending on the technological process there are different demands on the transport of the web. In paper machines we have at the beginning of the process a web which exists of about 90 % of water and therefore an auxiliary web of felt is needed during transport. After dewatering the web is able to be transported under tension. In rolling mills the web is transported under big forces to deform the web. The demands of plastic foils are quite different. During the transport of the web no plastic deformation may occur. On the other hand, in printing machines the quality of the printed picture is in the foreground. 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 system – schematically shown in Fig. 1 – the web will be processed in different stations. In these stations, called nip sections, there are driven and undriven rollers to transport and to 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 sometimes in force. A superimposed guidance system controls the total process. The winders at the beginning or the end of the system are a store of the material. But from the analytical point of view the winders are a special kind of nip section, where the process begins or ends, so that the winders are coupled with the web system only from one side. During the winding process the tension of the different layers of the material should be controlled in such a way that no strain up to plastic deformation of the material occurs [1].

A simple solution to keep constant the tension in the web is to use a dancing roller. The advantage of a dancing roller is that the tension is decoupled from the speed difference of the nip section. Furthermore, the dancing roller is able to compensate dynamic changes of the web tension caused by a winder running non-circular. But the usage of a dancing roller is limited to machines running with low-speed.

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 thus it is delayed. Only if the parameters of the system fulfil special conditions, such a control leads to an acceptable tension control.

Today the requirements on a tension control increase because of higher speed in the plant and so new solutions are required. Therefore, if the limits of the cascade control are reached, non–interacting, decentralized control loops should be used. In the control science, the state space control is an effective tool to solve complex problems and to improve the dynamic behaviour of the control. As a state space control of the complete system is complex and often unpractical in industrial plants, decentralized control methods should be used, where the state space control is designed with subsystems of low order. As the measurement of the tension sometimes causes more problems than solutions, observers that estimate the web forces can be used.

The linear optimal control methods will give us a controller which is guaranteed to be the best possibility to control the linearized model of the system. Unfortunately, the linearized model is guaranteed not to represent the system accurately, since there is no such thing in the reality as a linear system. For example, the strain in the paper of a coating machine changes during the coating and drying or the friction depends on the temperature. Another example of such disturbances is a winder running non–circular. This fact causes web flutter and big changes in the web tension. In some cases Fuzzy Logic, Neural Networks or some non–linear control systems can outperform a linear controller, sometimes even by a wide margin.

MODELLING OF THE SYSTEM

Mechanical System

To get a proper control it is necessary to have an extensive knowledge of the total system. The mechanical system is composed of the transported web and the rollers in the nip sections.

Behaviour of the web. The behaviour of the web under tension can be elastic, viscoelastic or plastic non–linear. In many cases it can be assumed that the web behaviour is elastic and thin, so that we get an uni–dimensional web system. Now, Hooke's law can be written as:

$$F_{jk} = \epsilon_{jk} \cdot EA_0 \tag{1}$$

Throughout this paper, normalized quantities are used. The normalized strain ϵ_N denotes the strain in the web if the nominal values are acting. From equation 1 we get the normalized strain of the web in the machine direction:

$$\epsilon_N = \frac{F_N}{EA_0} \tag{2}$$

There are various types of rollers to produce, transport and form the web. But all rollers are nip sections with slip and non–slip zones. Because of the non–slip zone we can assume that the speed of the web is equal to the peripheral speed of the roller [2]. During the transport of the web through the machine under dynamic changes of the stress and strain the mass has to be constant. To describe this behaviour, we can use the law of conservation of mass in a control volume which is well known in the theory of fluid dynamics.

$$\frac{d}{dt}\int_{Vol_c} \rho \cdot dVol \;=\; -\oint_{A_c} \rho \cdot V \cdot dA \tag{3}$$

Equation 3 describes on the left the temporal change of mass in the control volume, whereas on the right the difference of the input and output of the mass of the control volume is shown. The solution of equation 3 gives the following non–linear differential equation:

$$\frac{d}{dt}\left(\frac{L_{jk}(t)}{1+\epsilon_{jk}(t)}\right) \;=\; \frac{V_j(t)}{1+\epsilon_{ij}(t)} \;-\; \frac{V_k(t)}{1+\epsilon_{jk}(t)} \tag{4}$$

If we are in a steady–state, equation 4 gives the result:

$$\frac{V_k}{V_j} \;=\; \frac{1+\epsilon_{jk}}{1+\epsilon_{ij}} \tag{5}$$

Equation 5 shows that the strain ϵ_{jk} in a web is created by the relation of the output to input velocity $\frac{V_k}{V_j}$ of a web section *and* the incoming web strain ϵ_{ij}. As the strain ϵ is normally very small, the relation of the velocities is nearly 1, the difference is only some thousandth part. This fact is important if the tension of the web is controlled in an open loop via the difference of the velocities. If we do so, we need a very precise control of the speed of the drives.

Equation 4 must be considered if changes in the system are large, e.g. while the machine is starting up. If we study the steady–state or dynamic behaviour, the changes in variables are acceptably small. In this case equation 4 can be linearized. All variables then are small changes from initial steady–state values. After linearization we get the following result:

$$T_{jk}\frac{d}{dt}\left(\Delta\epsilon_{jk} - \frac{\Delta l_{jk}}{l_{jk}}\right) \;=\; \frac{\Delta v_k}{v_0} \;-\; \frac{\Delta v_j}{v_0} \;-\; \Delta\epsilon_{jk} \;+\; \Delta\epsilon_{ij} \tag{6}$$

The time constant T_{jk} is the time needed to transport the web from nip section j to section k. It depends on the average transport velocity v_0 and the length l_{jk} of the web between section j and k.

$$T_{jk} \;=\; \frac{L_{jk}}{V_0} \;=\; \frac{l_{jk}}{v_0} \cdot T_N \tag{7}$$

It should be mentioned that the *time constant* is not constant, it is a function of the variable average velocity v_0 of the machine.

To achieve the linear signal–flow graph, we have to transform equation 6 into the frequency range. The result is:

$$sT_{jk}\left(\Delta\epsilon_{jk} - \frac{\Delta l_{jk}}{l_{jk}}\right) = \frac{\Delta v_k}{v_0} - \frac{\Delta v_j}{v_0} - \Delta\epsilon_{jk} + \Delta\epsilon_{jk} \qquad (8)$$

The second term in the brackets on the left in the equations 6 and 8 describes a change of the length of the web between section j and k. This occurs when we use a dancing roller. So we have to distinguish between two cases.

Case 1: System with dancing roller.
The transfer function will be:

$$\frac{\Delta l_{jk}}{l_{jk}} = \left(\frac{\Delta v_j}{v_0} - \frac{\Delta v_k}{v_0} - \Delta\epsilon_{ij}\right)\frac{1}{sT_{jk}} + \Delta\epsilon_{jk}\,\frac{1+sT_{jk}}{sT_{jk}} \qquad (9)$$

The change of the length Δl_{jk} depends on the difference of the velocities Δv_j and Δv_k. Its time behaviour is **integral**. The strain $\Delta\epsilon_{jk}$ is not a function of the speed difference. It depends on the force which acts on the dancing roller.

Case 2: System without dancing roller.
Here, $\Delta l_{jk} = 0$ and the transfer function will be:

$$\Delta\epsilon_{jk} = \left(\frac{\Delta v_k}{v_0} - \frac{\Delta v_j}{v_0} + \Delta\epsilon_{ij}\right)\frac{1}{1+sT_{jk}} \qquad (10)$$

The change of the strain $\Delta\epsilon_{jk}$ depends on the difference of the velocities Δv_j and Δv_k. The time behaviour is a first order lag element, v_0 is the variable average velocity of the machine.

With equations 9 and 10 we get two fundamentally transfer functions as shown in Fig. 2. It should be remarked that in all signal–flow graphs the sign Δ is omitted. All values are the changes from initial steady–state values.

Behaviour of the roller. If we assume to have a stiff mechanical coupling of the drives and rollers, we can add the moment of inertia of the drive and roller to a resultant moment of inertia Θ_{Nk}. After normalization we get the well known equation:

$$T_{\Theta Nk}\,\frac{dn_k}{dt} = \Delta m_k - \Delta m_{wk} \qquad (11)$$

The load torque Δm_{wk} is given from the forces acting on both sides of the motor shaft.

$$\Delta m_{wk} = (\Delta f_{kl} - \Delta f_{jk})\,r_k \qquad (12)$$

Electrical Drives

The rollers are driven by electrical motors. This can be dc or ac motors. The dynamic behaviour of dc motors is simple. If the flux is constant, the speed is proportional to the voltage of the armature. The variable voltage is generated by an ac – dc converter. The current i_k of the armature is proportional to the torque m_k and controlled in a closed loop.

The dynamic behaviour of an ac motor is more complex. To change the speed, we need a variable voltage and frequency which are produced by an inverter. If we have a field–oriented control of voltage, current and flux we can assume that the dynamic behaviour is nearly the same as that of a current controlled dc motor. Therefore a simple transfer function of first order is often used to describe the electrical drives, independent of the kind of the machines. In doing so, a lag element is obtained as equivalent function of the controlled current or torque.

$$\frac{m_k}{m_k^*} = \frac{k_m}{1 + sT_e} \tag{13}$$

k_m is the gain and T_e the equivalent time constant. Depending on the quality of the control, the value of T_e is between 1 to 10 ms [3], [4].

Signal–flow Graph Of The System

Now we are able to design the linear signal–flow graph of the total system, here without a dancing roller. With the equations 2, 10, 11 and 12 we get the block diagram as shown in Fig. 2.

ANALYSIS OF THE SYSTEM

Controllability Of The Tension

The driving motors and the rollers are coupled to each other by the web forces. That is shown in Fig. 2. This causes the propagation of disturbances in the system in the direction of the transport of the web and contrary to that direction. This fact forms a multi dimensional system. To understand the control direction of the web forces, let us look at the subsystem of third order in Fig. 2. The tension f_{34} is generated by the speed v_4 and the strain ϵ_{23}. If we assume that the speeds v_3, v_5 and the strain ϵ_{23} are constant, we get the following transfer function:

$$\frac{\Delta f_{34}}{\Delta v_4} = \frac{1}{v_0\ \epsilon_N} \frac{1}{1 + sT_{34}} \tag{14}$$

But a change of the speed v_4 causes also a change of the tension f_{45}. The transfer function in that case is:

$$\frac{\Delta f_{45}}{\Delta v_4} = -\frac{1}{v_0\ \epsilon_N} \frac{1}{1 + sT_{45}} \frac{sT_{34}}{1 + sT_{34}} \tag{15}$$

In case of steady–state, equation 14 leads to the result:

$$\frac{\Delta f_{34\infty}}{\Delta v_4} = \frac{1}{v_0 \ \epsilon_N} \tag{16}$$

Equation 15 gives the result:

$$\frac{\Delta f_{45\infty}}{\Delta v_4} = 0 \tag{17}$$

Equation 17 shows that only dynamic changes of the tension f_{45} are possible. This fact can be explained. Let us assume a positive step of the speed v_4 occurs. The tension f_{34} then increases, whereas the tension f_{45} decreases in the first time. But during running the increasing tension f_{34} is transported into section 4–5 and the decreasing of tension f_{45} will be cancelled.

From this fact we can see that we have to control the web tension only with the following drive.

Standstill Of The Machine

In the signal–flow graph there is the gain $\frac{1}{v_0}$ (see Fig. 2). In the case of standstill the average velocity v_0 is zero. This fact leads to an infinite gain. But we have to remember that the time constant T_{jk} is also a function of v_0. If we shift the gain $\frac{1}{v_0}$ into the lag element $\frac{1}{1+sT_{jk}}$ we can transform the lag element as follows:

$$\Delta\epsilon_{jk} = [(v_k - v_j) - v_0 \ \Delta\epsilon_{jk}] \ \frac{1}{s \ l_{jk} \ T_N} \tag{18}$$

If v_0 is zero, equation 18 has the result:

$$\Delta\epsilon_{jk} = (v_k - v_j) \frac{1}{s \ l_{jk} \ T_N} \tag{19}$$

In standstill the structure of the web dynamic has changed. The time response is **integral**. Because there is no transport of material from one section to the other the tension increases if there is no limitation of the speed v_k by the control. As we will see later, in this case there is also no damping in the web (equ. 27). In Fig. 3 the signal–flow graph in the case of standstill is shown.

Dynamics Of A Subsystem

To study the dynamics of the system it is advisable to look at a subsystem of third order, marked in Fig. 2. The transfer function of such a system, in which v_j and v_l are constant, is:

$$\frac{\Delta v_k}{\Delta m_{mk}} = \frac{v_0 \ \epsilon_N \ (1 + sT_{ij}) \ (1 + sT_{jk})}{N} \tag{20}$$

The denominator N of equation 20 is of the third order.

$$N = 1+s(v_0\epsilon_N T_{\Theta Nk}+T_{ij}+T_{jk})+s^2[v_0\epsilon_N T_{\Theta Nk}(T_{ij}+T_{jk})]+s^3 v_0\epsilon_N T_{\Theta Nk}T_{ij}T_{jk} \tag{21}$$

The denominator N can have three real poles or one real pole and one complex pair of poles. So we get three cases.

<u>Case 1</u>:

If the following condition is valid

$$T_B \ << \ v_0 \ \epsilon_N \ T_{\Theta Nk} \tag{22}$$

we get three real poles.
The time constant T_B is calculated as:

$$T_B \ = \ \frac{l_{ij} \ l_{jk}}{l_{ij}+l_{jk}} \ \frac{T_N}{v_0} \tag{23}$$

T_B is the time constant of the paralleling of the web length on the left and right side of the roller k. If the condition 22 is true the transfer function in equation 20 has changed to:

$$\frac{\Delta v_k}{\Delta m_{mk}} \ = \ \frac{v_0 \ \epsilon_N}{1+s \ v_0 \ \epsilon_N \ T_{\Theta Nk}} \tag{24}$$

The third order system has changed to a simple lag element.

In real machines the condition 22 is fulfilled, the smaller the length and the modulus of elasticity of the web and the bigger the mass of inertia and the velocity of the machine will be.

The modulus of elasticity is small for webs of rubber, plastic and textile. As we will see later, in case 1 we will not have problems with simple control units.

<u>Case 2</u>:

If the condition 22 is not valid or if we write

$$T_B \ >> \ v_0 \ \epsilon_N \ T_{\Theta Nk} \tag{25}$$

the third order system remains and we get one real pole and an oscillating second order system.

In real machines the condition 25 is fulfilled the bigger the length and the modulus of elasticity of the web and the smaller the mass of inertia and the velocity of the machine will be.

The modulus of elasticity is big for webs of paper and steel.

In case 2 we will have problems with simple control units if we do not include special conditions as we see later.
The natural frequency Ω_0 can be calculated:

$$\Omega_0 = \frac{1}{\sqrt{\frac{l_{jk}}{2} \epsilon_N T_{\Theta Nk} T_N}} \tag{26}$$

The damping is:

$$d = \frac{3}{8} v_0 \sqrt{\frac{2\epsilon_N}{l_{jk}} \frac{T_{\Theta Nk}}{T_N}} \tag{27}$$

The damping depends on the average velocity v_0 of the machine. In the case of standstill there is no damping in the web. This is the worst case of a control. On the other hand the natural frequency does not depend on the velocity.

Case 3: System without a web.
No web is in the machine during the drawing of the web or if the web is torn off. In this case the transfer function will be very simple:

$$\frac{\Delta v_k}{\Delta m_{mk}} = \frac{1}{s T_{\Theta Nk}} \tag{28}$$

Only the moment of inertia is acting on the drive. Fig. 4a shows the frequency characteristics of the three cases discussed above.

SPEED CONTROL WITH PI CONTROLLERS

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 difference and the steady–state of the tension results from equation 5. The first step to design the controller is to test whether the system is able to oscillate or not while you use the equations 22 or 25.

Non–oscillating System

In the case of a non–oscillating system the design of the controller can be done by using the well known Symmetrical Optimum (SO) [5].
The gain of the PI controller will be:

$$K_n = \frac{T_{\Theta Nk}}{2 T_{\sigma n} k_m} \tag{29}$$

$T_{\sigma n}$ is the sum of all small time constant in the speed control:

$$T_{\sigma n} = T_e + T_{dn} \tag{30}$$

T_{dn} is the smoothing time constant of the speed measuring.
The integral–action time of the speed controller is:

$$T_{nn} = 4 \cdot T_{\sigma n} \tag{31}$$

Oscillating System

Control without decoupling. In the case of an oscillating system we have to design a fast speed control to get proper results. But what is fast? It depends on the natural frequency of the controlled system. A useful condition is the following equation:

$$\Omega_d = (5...10)\, \Omega_0 \tag{32}$$

Ω_d is the characteristic frequency of the Symmetrical Optimum.

$$\Omega_d = \frac{1}{2\, T_{\sigma n}} \tag{33}$$

Equation 32 means that the frequency of the open loop speed control should be 5 to 10 times higher than the natural frequency of the system. If this can be achieved the results of the PI controlled system are time responses without oscillations like in the case of a non–oscillating system. If you cannot fulfil equation 32 because of limitations in the control, e.g. you need more smoothness in the measured speed because of mechanical problems, you will have oscillations in the time response which causes disturbances in the plant. It makes no sense to change the parameters of the PI controllers to reduce the oscillations. In doing so you will get a poor dynamic of the control. In the next section a better solution is discussed. Fig. 4b shows some calculated results of the control for the cases discussed above, Fig. 10a shows the measured forces with a speed control [2].

Control with decoupling. The forces f_{ij} and f_{jk} acting on the left and right side of the roller j (see Fig. 2) are the coupling values of the system. If it would be possible to cut this coupling, we would have no problems with oscillations in the system. How can we achieve this? Of course, we cannot cut the web, but we can cut the effect of the coupling by compensating the web forces in the control [6]. The idea is very simple. To do this, we have to add the inverse forces to the input of the current controller. But the load cells to measure the forces in the web have mostly a poor dynamic because of the need of smoothing filters. In this case the compensating works very poorly.

So it is better to estimate the difference of the forces with an observer. The inputs of the observer are the current i_j ore torque m_j of the electrical motor and the speed n_j of the drive. The output is the difference $f_{jk} - f_{ij}$ of the web forces. The only parameter to be calculated is the time constant T_{obs} of the observer.

$$T_{obs} < \frac{\Omega_d}{5\, \Omega_0^2} \tag{34}$$

Fig. 5 shows two structures of the simple first order observer. The advantage of the decoupling is that we can use the well known cascade control with PI controllers in any case independent of the behaviour of the system. This kind of decoupling was applied in coating machines with success. In Fig. 6 the effectiveness of such a control is shown. On the top there is shown a step response of the speed and below are measured speed responses caused by a change of the force f_{34}. The decoupling with observer is nearly perfect. [6].

TENSION CONTROL WITH PI CONTROLLERS

The disadvantage of only controlling the speed is that the changes in the strain of the web during coating or printing 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 force can be used. The tension control is designed in a cascade structure. The inner circuit is the current control, the next the speed control and the outer circuit is the tension control. If the speed control is done properly we can build up a first order equivalent element of the speed control.

$$\frac{n_k}{n_k^*} = \frac{k_{en}}{1 + sT_{en}} \tag{35}$$

with the equivalent time constant of the SO controlled speed control:

$$T_{en} = 4 \cdot T_{\sigma n} \tag{36}$$

The gain k_{en} usually has the value of 1.
To reduce the oscillations in the measured forces we need a smoothing filter with the time constant T_{df}. The value of this parameter is about 100 to 500 ms. If we proceed in the same manner as in the speed control we get the sum of the small time constants $T_{\sigma f}$ of the tension control.

$$T_{\sigma f} = T_{en} + T_{df} \tag{37}$$

After this simplification we get the following equivalent transfer function of the tension to be controlled:

$$\frac{f_{jk}}{n_k^*} = \frac{1}{v_0\ \epsilon_N} \frac{1}{(1 + sT_{jk})\ (1 + sT_{\sigma f})} \tag{38}$$

The gain of the PI-controller designed to the rules of SO will be:

$$K_f = \frac{T_{jk}\ v_0\ \epsilon_N}{2\ T_{\sigma f}\ k_{en}} = \frac{l_{jk} T_N\ \epsilon_N}{2\ T_{\sigma f}\ k_{en}} \neq f(v_0) \tag{39}$$

The integral–action time of the tension controller is:

$$T_{nf} = 4 \cdot T_{\sigma f} \tag{40}$$

It is to be noted that all parameters of the PI controller are not functions of the average velocity v_0 of the machine. Because of the fact that the smoothing time constant of the load cell is relatively large, the dynamic of such a tension control is often poor with large transient response times. Because of the PI controller we get no steady–state errors of the tension. So, this kind of control very often is used to get a precise steady–state value. Fig. 10b shows the results of such a cascade control of the web tension.

STATE SPACE CONTROL

Introduction

Currently the requirements on a tension control increase because of higher speed in the plant and new solutions are required. Therefore, if the limits of the cascade control are reached, non–interacting, decentralized control loops should be used. In the control science, the state space control is an effective tool to solve complex problems and to improve the dynamic behaviour of the control [7]. As a state space control of the complete system is complex and often unpractical in industrial plants, this control is transformed into a so–called *Cascade state space control.* This gives us the advantages of both, the state space control and the advantageous cascade structure of the control.

In the state space control we operate with *state values.* This are all outputs of a store. A store in our case is an integrator or a lag element. Real state values in a tension control are the current, the speed and the strain or tension. The system to be controlled is described with state equations:

$$\begin{aligned} \underline{\dot{x}} &= \underline{A} \cdot \underline{x} + \underline{B} \cdot \underline{u} \\ \underline{y} &= \underline{C} \cdot \underline{x} \end{aligned} \tag{41}$$

The matrix $\underline{A}$ is called system matrix and describes the steady–state and dynamic behaviour of the system. The matrix $\underline{B}$ is the input matrix and describes the effect of the inputs while the matrix $\underline{C}$ defines the measurable outputs of the system. The vector $\underline{x}$ describes the state values, vector $\underline{y}$ the measurable outputs and vector $\underline{u}$ the inputs of the system.
The optimal control is the linear constant feedback law

$$\underline{u} = -\underline{K} \cdot \underline{x} \tag{42}$$

where $\underline{K}$ is the optimal control gain of linear time invariant multivariable systems. Fig. 7a shows the configuration of the state space control.

$\underline{K}$ is usually calculated with the *Quadratic Criterion Function* and the *Matrix Algebraic Riccati Equation.* The quadratic criterion function can be described as:

$$J = \int_0^\infty [\, \underline{x}^T \, \underline{Q} \, \underline{x} \, + \, \underline{u}^T \, \underline{R} \, \underline{u} \,] \, dt \tag{43}$$

The matrix $\underline{Q}$ is the valuation of the state values in the control while the matrix $\underline{R}$ is the valuation of the inputs of the control. In practice this matrices should be in diagonal form. With the choice of $\underline{Q}$ and $\underline{R}$ the engineer is able to design the quality of the control.

The feedback gain $\underline{K}$ is calculated with the Matrix Riccati Equation:

$$\underline{P}\,\underline{A} + \underline{A}^T\,\underline{P} - \underline{P}\,\underline{B}\,\underline{R}^{-1}\,\underline{B}^T\,\underline{P} + \underline{Q} = \underline{0} \tag{44}$$

The matrix $\underline{P}$ is calculated from equation 44 and the optimal gain $\underline{K}$ is derived from:

$$\underline{K} = \underline{R}^{-1}\,\underline{B}^T\,\underline{P} \tag{45}$$

Meanwhile there are a lot of efficient software tools to transform the system from the signal–flow graph or transfer function discription to the state space description corresponding to equation 41 and to solve the equations 43, 44 and 45.

The closed loop behaviour of the state space control can be derived if we combine the equations 41 and 42:

$$\begin{aligned} \dot{\underline{x}} &= (\underline{A} - \underline{B}\,\underline{K}) \cdot \underline{x} + \underline{B} \cdot \underline{w} \\ \underline{y} &= \underline{C} \cdot \underline{x} \end{aligned} \tag{46}$$

The vector $\underline{w}$ describes the reference inputs of the control. The matrix product $\underline{B}\,\underline{K}$ must be of the same order as the matrix $\underline{A}$. That means all states must be feedbacked in the control. The advantage of this control is that we are able to change the system behaviour by the gain $\underline{K}$. There are no limitations, an oscillating system or even an unstable system can be controlled with satisfaction.

Cascade State Space Control

Each state space control can be transformed into a cascade structure with an equal behaviour of the control. This gives us the advantages of both, the state space control and the advantageous cascade structure of the control. As the feedback of the state space control is a gain, we can transform the common feedback of the states into a cascaded feedback of all separated states. This leads to cascaded circuits with P controllers. To achieve no steady–state errors, the main control value, e.g. the tension, is feedbacked with an integrator. This leads in the cascade state space control to an PI controller with a delay in the reference input. The structure of a cascade state space control is shown in Fig. 8. The parameters of the P and PI controllers are calculated with the equations 43, 44 and 45.

OBSERVERS

As mentioned above in a state space control we have to feedback all state values. Unfortunately often in a real plant not all state values can be measured or the quality of the measurement is poor. In these cases we can use observers [8].

An observer is a feedbacked model of the system which estimates the state values $\hat{\underline{x}}$ from well measurable inputs and outputs of the system. The feedback is fed by the error $(\underline{y} - \hat{\underline{y}})$ of the system and the model. The basic equations of an observer in state space are:

$$\begin{aligned} \dot{\hat{\underline{x}}} &= \underline{A} \cdot \hat{\underline{x}} + \underline{B} \cdot \underline{u} + \underline{H} \cdot (\underline{y} - \hat{\underline{y}}) \\ \hat{\underline{y}} &= \underline{C} \cdot \hat{\underline{x}} \end{aligned} \tag{47}$$

The feedback gain $\underline{H}$ is calculated similarly to the gain $\underline{K}$ of the state space control and gives the dynamic of the observer. Fig. 7b shows the structure of an observer with an integrator. The integrator compensates the errors caused by disturbances. From the point of view of control, such an observer is a high dynamic measuring device with no steady–state error.

DECENTRALIZED CONTROL

Introduction

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 is designed with subsystems of low order. To design a decentralized control we have to separate the total system into subsystems. As shown in Fig. 9 the subsystem exists of the roller, the electrical drive and the web section on the left side of the roller. The separation in this manner comes close to the technological system which exists of drives, rollers and web sections.

Each subsystem can be controlled with a low order state space control as mentioned above. But if we design the controller with the isolated subsystem, we get significant deteriorations of the dynamic behaviour in the total system as shown in Fig. 10b,c. Because of the influence of the coupling quantities, oscillations occur and the forces of the neighbouring subsystems have large dynamic changes too. This is the consequence of the neglect of the quantities of coupling during the design of the control.

To get a proper dynamic behaviour the quantities of coupling must be taken into account. To do this, there are three possibilities:

- the design of decoupling networks
- the use of so called equivalent terminating models
- the decentralized decoupling.

The first possibility requires the design of a special decoupling network and presupposes the measurement of the quantities of coupling.

The second possibility requires the design of a low order equivalent model of the controlled neighbouring subsystems. If we only have a few subsystems (less then three or four) this method is successful and gives equivalent results like method three. But if the number of subsystems increases this method is not recommended because of many iterations during the design of the control [9].

The third possibility avoids this disadvantages and is explained now.

Decentralized Decoupling

This method was introduced at IWEB2 [10]. The goal of the method is to design a controller which minimizes the influence of the remaining system. The state space controller has two functions:

- to guarantee the desired dynamic and stability of the total system and
- to minimize the influence of the remaining system.

The solution to design such a controller is to consider the sensitivity of the eigenvalues.

The advantage of this method is that no measurements of the quantities of coupling are required. It is only necessary to know where the quantities of coupling are active in the subsystem. The designed control is robust against changes of the parameters in a wide area [10].

EXPERIMENTAL RESULTS OF LINEAR CONTROL

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

Results

Fig. 10 shows a comparison of the measured step responses of the web forces. Fig. 10a shows a system, where only the current and speed are controlled. The forces are in an open loop control. Fig. 10b shows a closed loop control of the forces with a cascade control of current, speed and force with PI controllers. Both control systems are state of the art in real plants. Fig. 10c shows a state space control without decoupling. As shown in Fig. 10d the quality of the control is improved by the decentralized decoupling control. Nearly no changes occur in the neighbouring subsystem (force F_{34}). You can also see the advantage of an observer. The estimated force $\hat{F}_{23}$ is smoother than the measured force F_{23}. Another advantage of the new control is the fact that no new investigations or changes in the mechanical systems are necessary. Only a new control needs to be designed [11].

Large Systems

If the numbers of the subsystems increases, the decoupling of the decentralized control decreases. Another disadvantage is, that a very good decoupling causes a bigger transient response time of the controlled system. If we have large systems and we want to decouple each subsystem very well, it is advisable to use a combination of decoupling networks and decentralized observers. From the observers we get the coupling quantities and state values so that no measurements of the strains or forces are necessary [12].

FUZZY CONTROL

General Survey

The linear optimal control methods will give us a controller which is guaranteed to be the best possible to control the linearized model of the system. Unfortunately, the linearized model is guaranteed not to represent the system accurately, since in the reality there is no such thing as a linear system. For example, the strain in the paper of a coating machine changes during the coating and drying or the friction depends on the temperature. In some cases Fuzzy Logic can outperform a linear controller, sometimes even by a wide margin.

A Fuzzy controller is in principle a non–linear P controller. To find the setting of the Fuzzy controller it is not necessary to have a mathematical description of the process. But you must have a good physical knowledge of the process. The rules of a Fuzzy controller are made with *if...than* conditions. This way of thinking is close to that of people. In the conventional control the process is modelled, but in Fuzzy control the expert is modelled. This fact may be the explanation why some difficult problems are solved better and in a shorter time with Fuzzy control as by a conventional non–linear control.

There are three steps to design a Fuzzy control.

Step 1 is the so called *fuzzyfication.* This is done with *membership functions.*
Step 2 is to create the rules with *if...than* conditions and
Step 3 is the *defuzzification* to get a definite output of the controller.

Unfortunately there are no rules like criterion functions to find an optimal Fuzzy controller. Usually you have to find the optimum with the try and error method. Nevertheless in many cases the Fuzzy control is a method to get better results [13], [14], [15], [16].

Design Of The Fuzzy Web Tension Control

The block diagram of the Fuzzy control of three subsystems is shown in Fig. 11. It should be mentioned that the design of the Fuzzy controllers was made only with a *single subsystem* without knowledge of the quantities of coupling.

In large systems it is advantageous to add decoupling networks to achieve the best results. Here the decoupling was realized with Fuzzy Logic. The design of the Fuzzy controller was made with trapezoidal membership functions for the inputs whereas the membership functions of the output are singletons. In the reference path an integrator was added to avoid steady–state errors [12].

Results Of A Large System

To compare the Fuzzy control with a conventional control, we proceeded the same as in the previous investigations. The result of such a Fuzzy control of seven subsystems is shown in Fig. 12. If we compare it with Fig. 10d we notice that the step time responses are extremely short with no oscillations and the decoupling is proper. Another advantage of the Fuzzy control is that we do not have to solve Matrix Riccati Equations; we can find the rules by try and error. On the other hand there are meanwhile a lot of useful tools to design a Fuzzy control. In systems with less then about five subsystems the Fuzzy controller can be designed without special decoupling networks.

NEURAL NETWORKS

Today more and more *Neural Networks* are being used to control non–linear systems. In the field of web tension control there are limitations of the current or torque of the electrical drives. The limitations exist in the steady–state value and in the derivation of the current because of the inverter and motor. With a Neural Network it is possible to superpose on a conventional control a self learning circuit to get a time–optimal control. [17], [18], [19].

Another example is the use of a Neural Network to learn the unknown time dependent friction of the mechanical system for a compensation.

A third example is the compensation of disturbances if a winder runs non–circular. The Neural Network is able to learn such disturbances.

We have just started our investigations in this field with simulations. Because of the success of our first results we will continue our investigations [20].

CONCLUSION

In this report, a global presentation of specific demands and problems refering to tension control is given. After an excursion to the modelling of such systems, we can make an analysis of the system and study the specific steady–state and dynamic behaviour with the help of linear signal–flow graphs and discuss the responses in the time and frequency area.

After having this knowledge of the system to be controlled, we are able to design a control. If the system fulfils special conditions we can use simple P or PI controllers for the speed and tension control.

If it is not possible to fulfil the special conditions, we should design a decoupling network or we should use the state space control. Each state space control can be transformed into a cascade structure with an equal behaviour of the control. This give us the advantages of both, the state space control and the advantageous cascade structure of the control. A state space control of the total system is not very convenient. So, a *Decentralized Control* is proposed. Here we are able to design controllers of low order and we get an optimal control of the total system. As all state variables have to be feedbacked, observers are used to estimate the bad or non–measurable state values.

The linear optimal control methods will give us a controller which is guaranteed to be the best possible to control the linearized model of the system. But if a non–linear behaviour is dominant, we can use new control philosophies as *Fuzzy Control* or *Neural Networks*. Both methods can be combined to a *Neuro Fuzzy Control*. It should be noted that you will get the best results if you combine linear and non–linear methods in the control. So the non–linear control circuit has to work only in the non–linear area of the system whereas the linear control works in the linear area. Nowadays it is no problem to realize the new control methods in a plant because most of the control systems are realized with very flexible microcomputer systems.

The new control methods give us a lot of improvements in parts of web handling, e.g. in the mechanics, drives, electronics, control systems and measurement. Let us use the well known and tested methods when possible and let us take the advantages of new methods whenever necessary to get better products, more efficiency and a better saving of our resources.

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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

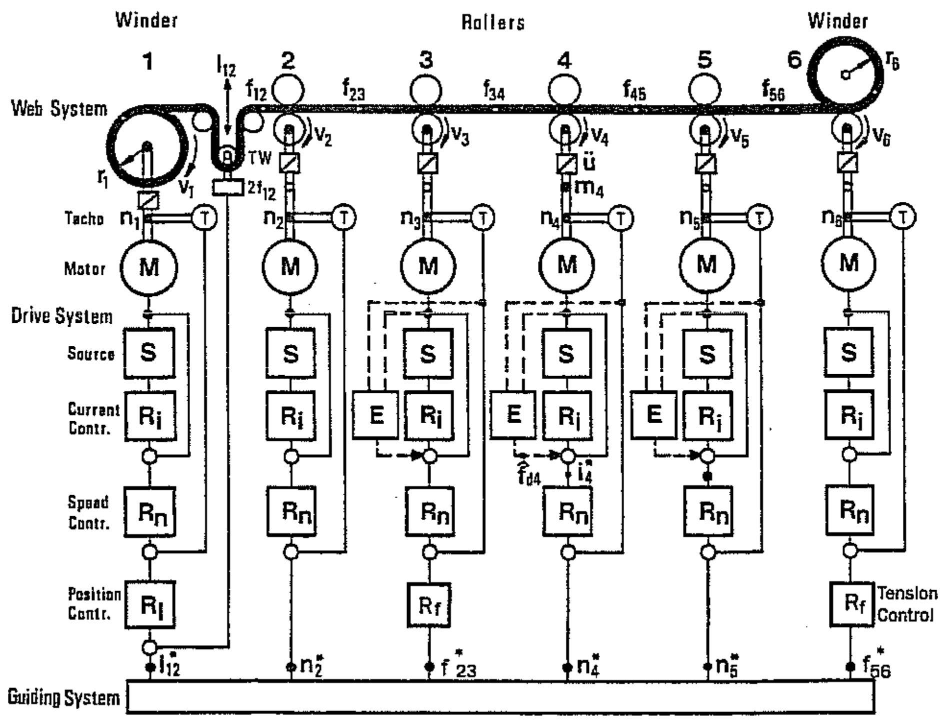


Fig. 1: Example of a processing plant

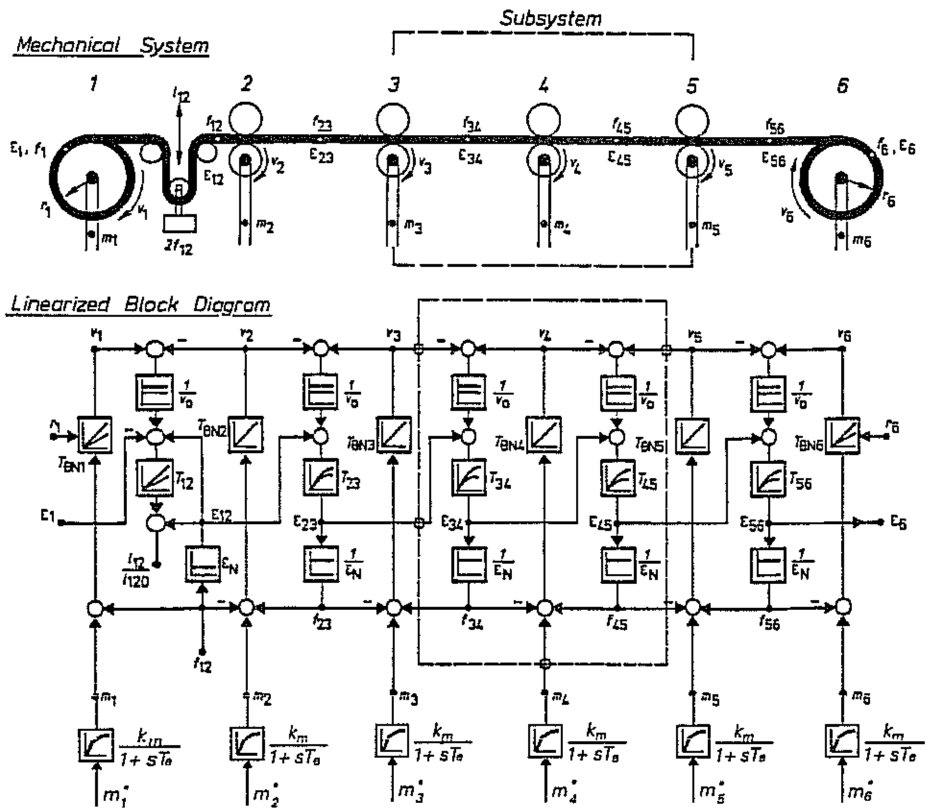


Fig. 2: Signal–flow graph of the total system

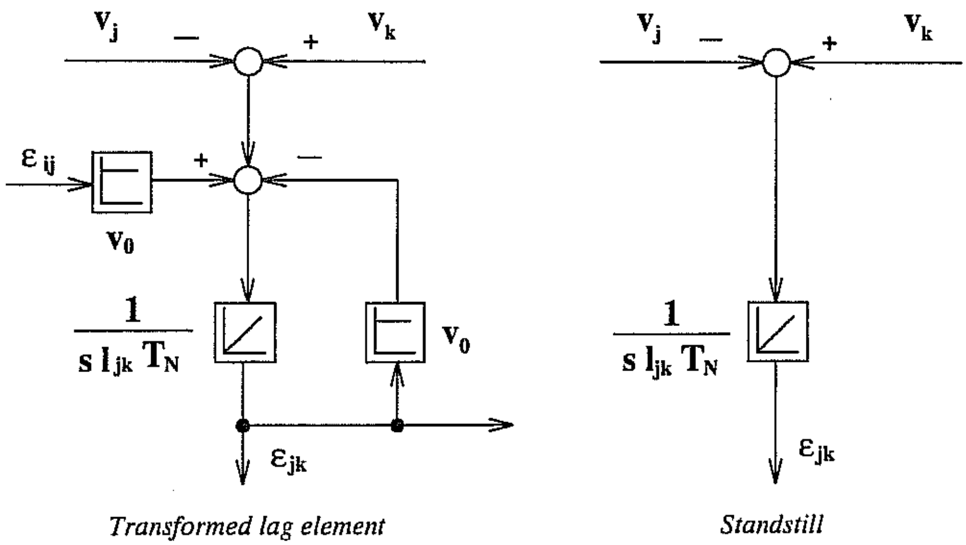


Fig. 3: Signal–flow graph at standstill

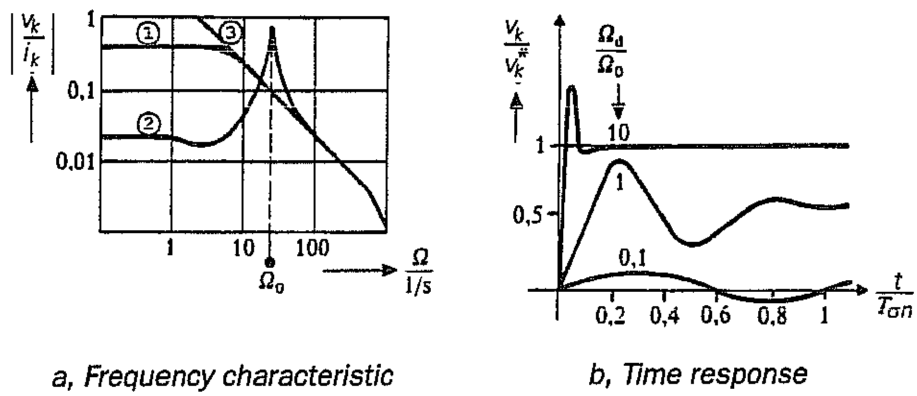


Fig. 4: Behaviour of the system

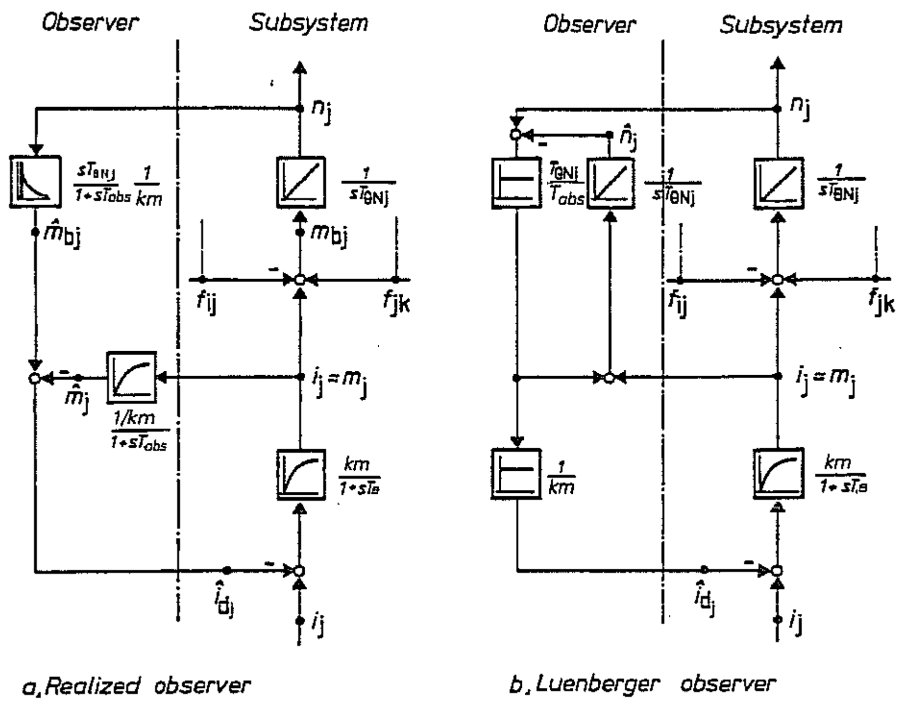


Fig. 5: Decoupling observer

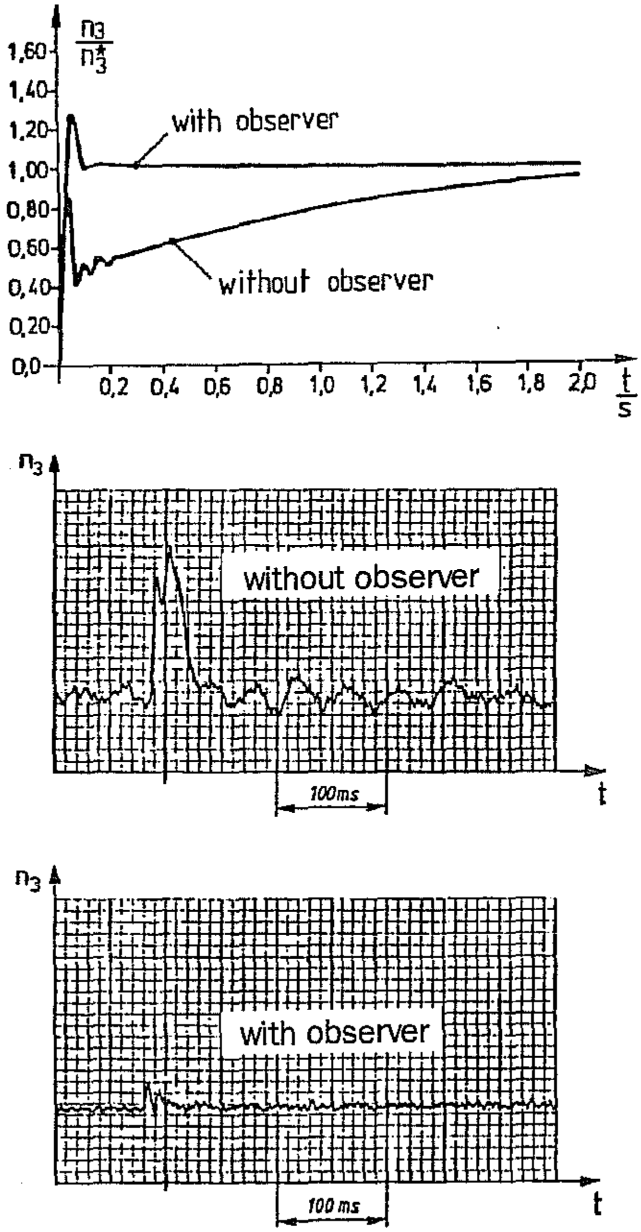


Fig. 6: Result of the decoupled speed control

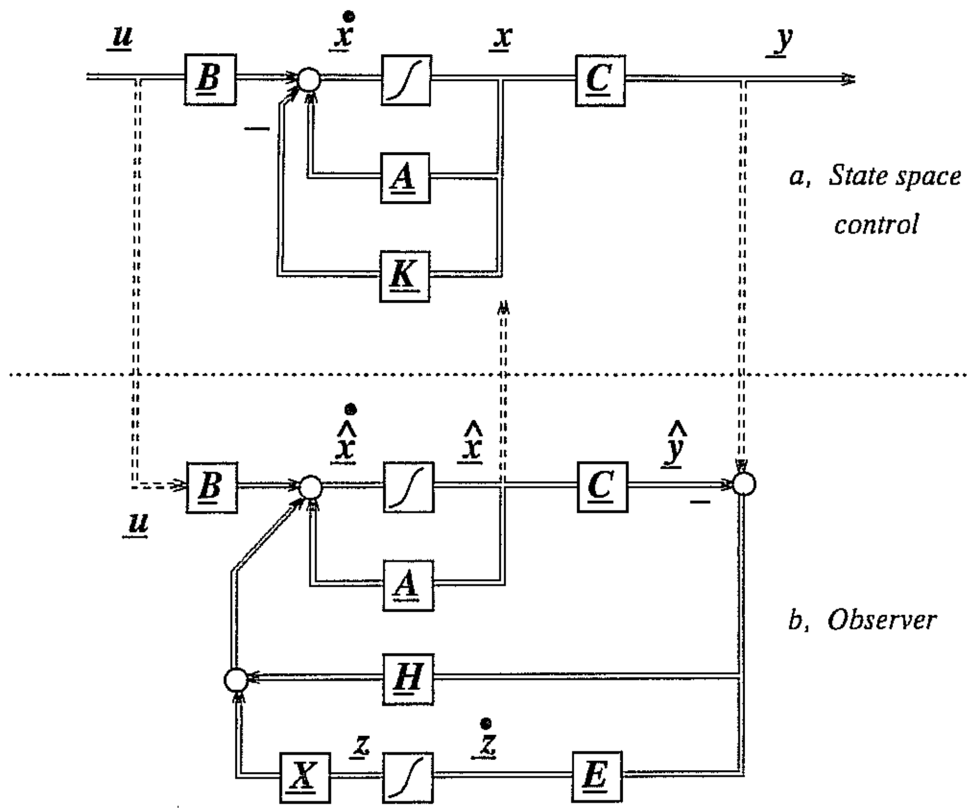


Fig. 7: State space control and observer

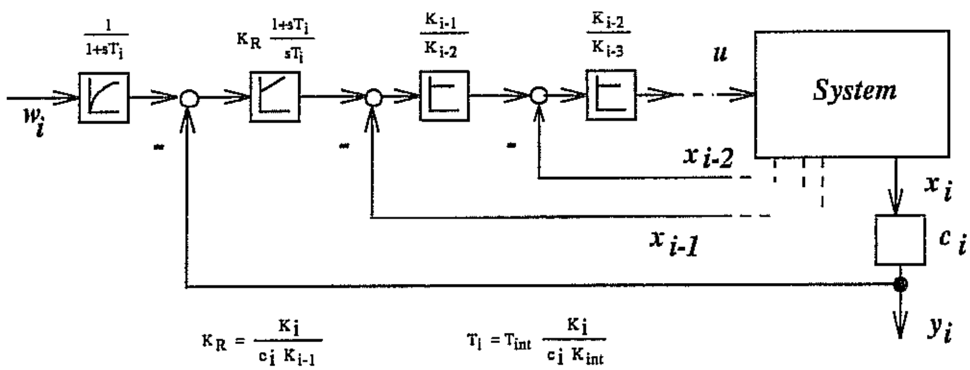


Fig. 8: Cascade state space control

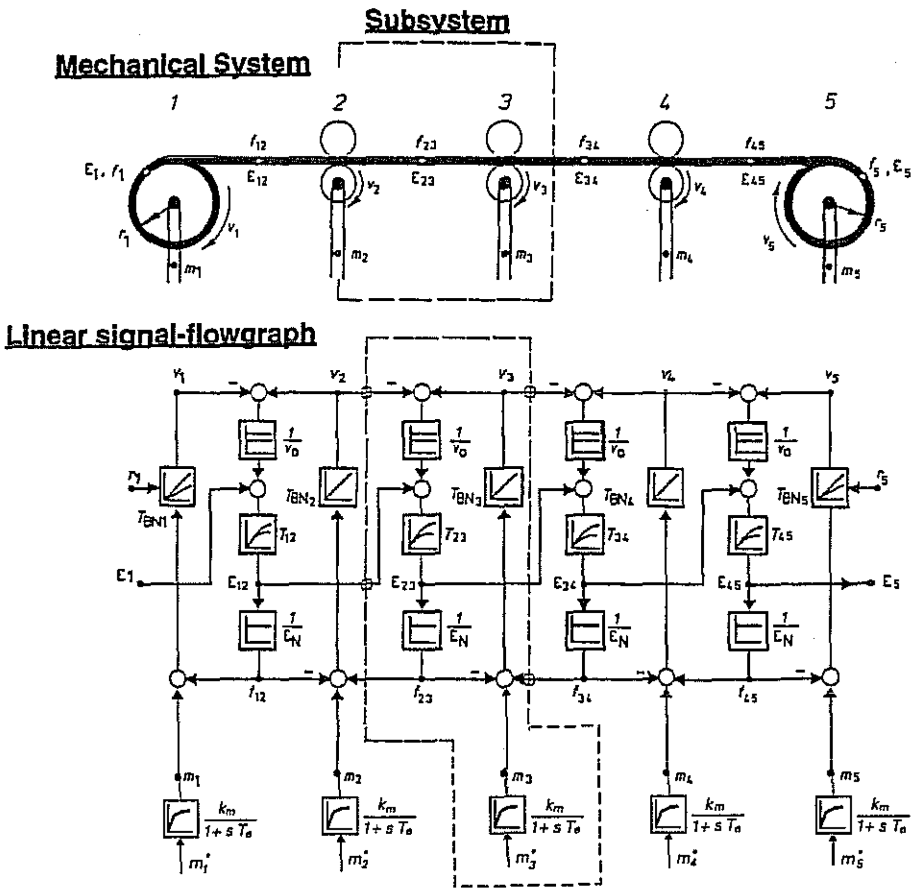
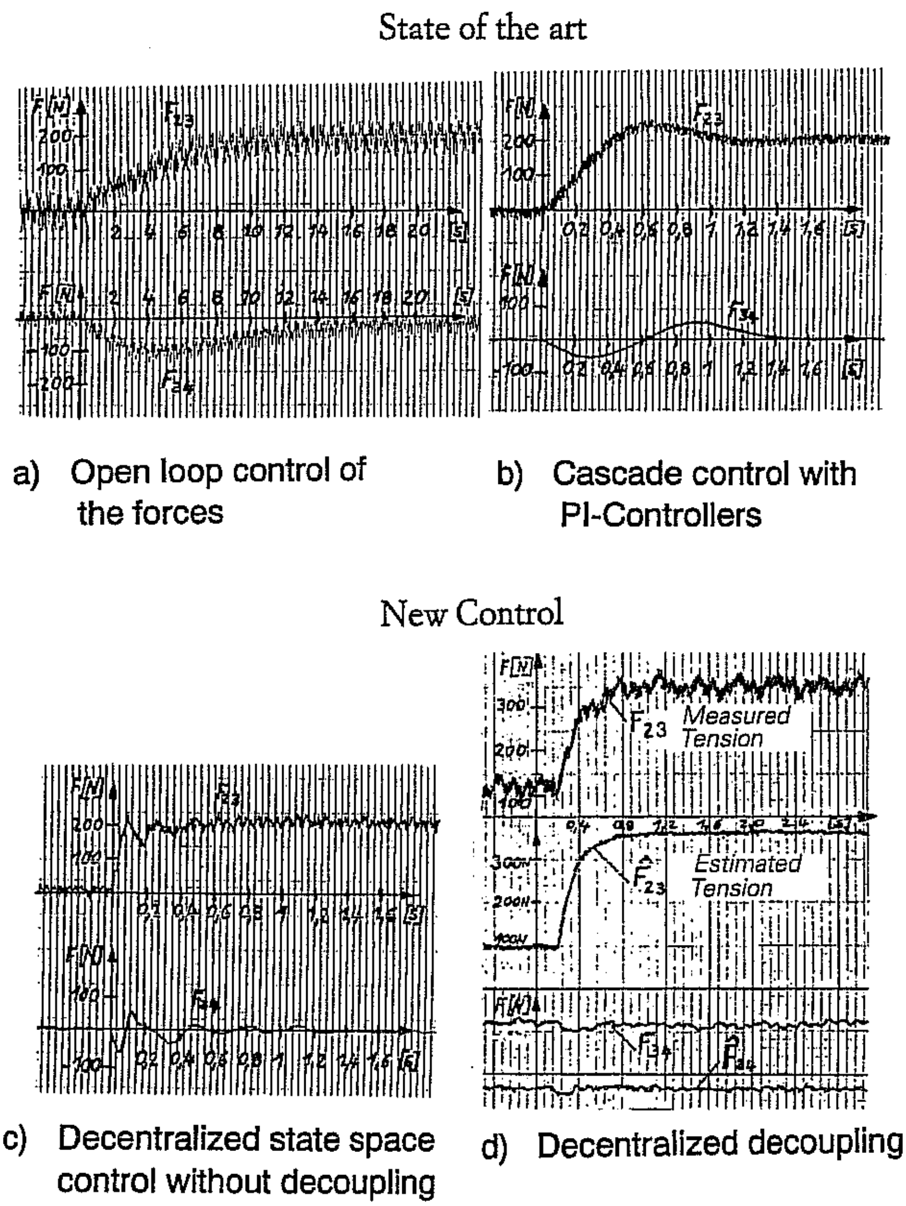


Fig. 9: Subsystem of the tension control



a) Open loop control of the forces

b) Cascade control with PI-Controllers

c) Decentralized state space control without decoupling

d) Decentralized decoupling

Fig. 10: Experimental results of different control strategies

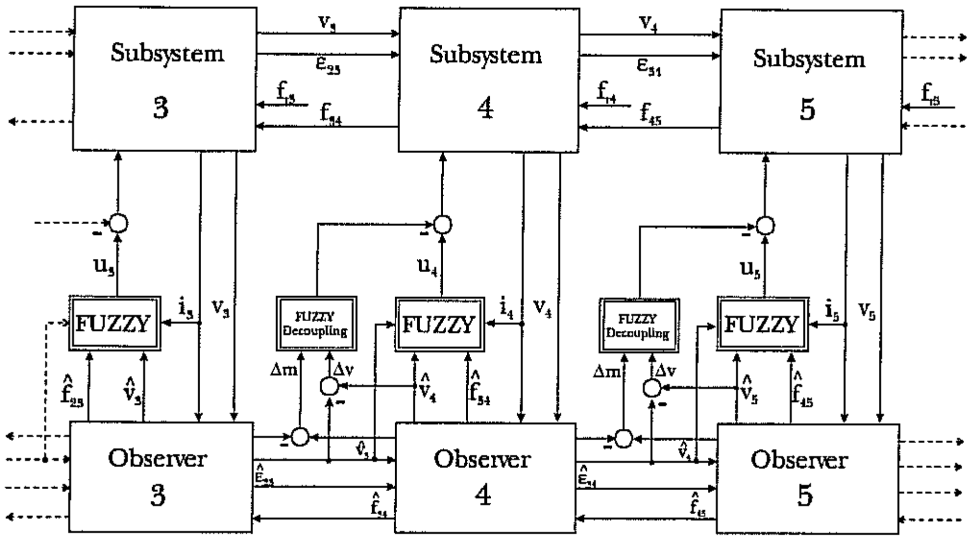
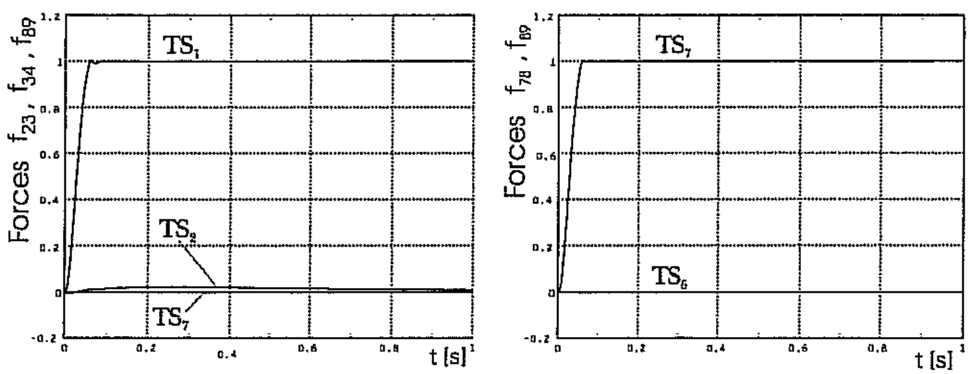


Fig. 11: Fuzzy control with decoupling



Step responses f_{23}^{*} 0 > 1

Step responses f_{89}^{*} 0 > 1

Fig. 12: Results of the Fuzzy control of a large system

Wolfermann, W.
Tension Control of Webs - A Review of the Problems and Solutions in the Present and Future
6/20/95 Keynote 9:00 - 9:50 a.m.

Question - You mentioned that the speed loop gain with has to be 5 to 10 times higher than the dominate frequency. Typical you have torsional problems with the motor shaft and the gear box that limits the gain of the speed loop so that this is not practical in most cases.

Answer - You asked what happens if we have elasticity between the motor shaft and the roller, for instance in the transmissions and clutches. Of course, the system is more complex in this case. It is not the loop gain which has to be 5 to 10 times higher, it is the characteristic frequency of the open loop of the speed control. If you cannot fulfill that condition, you have to use decoupling methods or you have to take into account these problems in the state space control. If you use only the simple cascade control with PI controller you will have problems.

Question - What hardware do you use in implementing space state controllers. Commercially available hardware?

Answer - We used an industrial control system in our experimental plant from Siemens. It's a real-time digital control system with very fast 32 bit RISC-Processors.

Question - Siemens, is this the commercial name of the product?

Answer - No, the commercial name is SIMADYN D.

Question - Second question, can you clarify your comments on why dancer is not adequate on high speed machine.

Answer - You have a limitation in the storage of the dancer roll. If you have difference between the speed on the left and right of the dancer roll, the dancer is moving down if you have a high speed machine and your dancer control is not very fast, you will reach the end of the storage. On the other hand, the dancer has a mass, this causes additional forces during moving the dancer roll. So, a dancer is used in paper or textile machines running with low speed, low speed means less than 500 m/min.

Question - You seem to be arguing against the use of tension sensors with mote/cells and I know that paper machines you don't have the measurement tension, in the steel industry I understand and I'm not familiar with printing presses, the conventional way in controlling tension in a coater is many station with low cells tending the tension. I'd appreciate your comment on that and if you are using sensors what about the dynamics of the sensors itself?

Answer - Mostly its the dynamic of the sensors which causes problems, because you have to use smoothing filters with a time constant of about 200, 300 to 500 ms. That leads to a very slow control. If you spend more money you can get sensors with a time constant of about 70 ms. The disadvantage of the measuring system is that you have an additional roll in your web system with a mass. If you remember on my picture, you will get some more peaks in the frequency response which may cause more problems in the control. My opinion is, use observers if it is possible.

Question - I'm in control business that's why I'm asking so many questions, if you had the ban width on your tension regulator in the real world I would see the torque on the motor, in other words you wouldn't have enough horse power to keep the tension regulation and you would be slamming into current limit and basically destroying your gear box the real world. No way in blazes would you get that kind of ban width on a tension regulator you would just destroy the mechanics.

Answer - Yes you are right. On simulations you are able to design a fast state space control. In the real world you have to consider the parameters of the mechanics and your control. But if you use new control methods like Neural Networks you can take into account the limitations of your mechanical and electrical system as I mentioned and you can get a time-optimal control without a loss of quality of the control. If you don't do this, you have to reduce the gain and you will get not an optimal control. Furthermore, it makes no sense to design only a fast control. You also have to increase the quality of your mechanical system.

Question - On rewind the dynamics has a system change drastically is the change in the roll. Is the state space control meaningful in this system, cause it has differences in the state buildup?

Answer - You can take into account this changing diameter to adapt the gain in your state space control.

Question - I didn't want to sense diameter. Do I have to sense diameter to do that? Do I have to measure the diameter in order to use state space?

Answer - No, you calculate the diameter with the speed of the winder and the following roller, if you have a web between the winder and roller. But if you have a slip on the roller, the calculated diameter will be wrong. If you have a slip to fix the diameter will be wrong, that's right.

Question - Most of your simulation was for step response. Have you looked at state space observer technology for frequency response during steady state operation?

Answer - Yes we have. We have an example here.

Question - Does it follow the same level of improvement that you see with the transient responses or does it take some other different analysis to get a reduction?

Answer - You can get the same results with this. We had no problems.

Question - What happens on a centralized or multistation control system in the event of a web break. Do you store all the parameters that you had and then recall them after you reestablish web to remember when the web broke or do you go back to the zero condition?

Answer - You mean the web is torn off. If you have a centralized control system with state space control, you will have problems, because your system has changed and the state values of the web are not present. But if you have a decentralized control, each subsystem is able to work. You will get only less changes in the dynamics if during the break occurs. In a digital microcomputer system you are able to store all important parameters, including the diameter so you have not to go back to zero conditions.

Question - Presumably you also have to have a web break that solve all these stations together. This is a web break not an error.

Answer - Yes, of course yes.

Thank you.