COMPENSATION OF DISTURBANCES IN THE WEB FORCE CAUSED BY A NON-CIRCULAR RUNNING WINDER

by

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Abstract

In many plants of the steel–, paper–, printing–, plastic– or textile industry the first section is an unwinder. But during storage and transport of the rolls, the rolls are often non–circular. If such a roll is unwinded, the radius is variable around the circumference. Therefore a changing web velocity is caused depending on the variable radius and big oscillations of the web forces are the consequence, if the winder speed is constant.

To solve the problem, it is necessary to use new methods to compensate the disturbances without additional mechanical systems. To do this, there are to solve two fundamental problems. The first is to get the unknown, nonlinear changes of the radius and the second is the design of a fast speed control of the winder which is able to compensate these changes.

Therefore a neural network is proposed to identify online the unknown, nonlinear variable radius with respect to the angle position continuously during running. The advantage of neural networks is that they do not need any information about the nonlinearities, they are able to handle unknown nonlinearities. So the neural network is like a "learning" observer.

To compensate the disturbances in the web force, the output of the neural network is fed into the speed control of the winder to change the motor speed of the winder in this way that the web velocity is nearly constant. This reduces the oscillations of the web force in a big range. But the requirement is a fast speed control of the winder. A conventional PI–controller is not able to fulfill that conditions. Therefore an adaptive state space control of the motor speed was designed.

The advantage of this method is, that no additional mechanical equipment is necessary. The identification of the unknown eccentricity of the roll and the compensation are done only in the digital control system.

NOMENCLATURE

A_0	Unstrained area of the web
$\underline{A}(\varphi)$	Activation vector of the neural network
B	Unstrained width of the web
E	Modulus of elasticity of the web
E_a, E_f	Errors of the neural network
F_{12}, F_{12gl}	Unsmoothed and smoothed forces
$G(s)$	Transferfunction
i_W, i_2	Ratio of the winder and roller gear
M_N	Nominal value of the motor torque
$N_W, \Delta N_W$	Winder speed and change of that speed
N_{Wm}	Mean value of the winder speed
R_0	Radius of the core
R_m	Mean value of the winder radius
$R_\varphi, \Delta R_\varphi$	Winder radius dependant on the angle and its change
T_{delay}	Delay time of the compensation
T_{ei}	Time constant of the current control
T_{en}	Time constant of the speed control
$T_{\Theta W}$	Time constant of the inertia of the winder
V_2	Velocity of the roller No. 2
V_W	Velocity of the winder
ε_{01}	Strain in the stored material
ε_{12}	Strain in the web between winder and roller No. 2
$\underline{\Phi}^T$	Network error
η	Adaption step size of the neural network
ϱ	Density of the web
$\underline{\Theta}^T$	Neural network parameter
Index ref	Reference value

INTRODUCTION

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. In many plants of the steel–, paper–, printing–, plastic– or textile industry the first section is an unwinder. But during storage and transport of the rolls, they are often non–circular. If such a roll is unwinded, the radius is variable around the circumference of the roll. If the unwinding speed is constant, a changing web velocity is caused depending on the variable radius and big oscillations of the web forces are the consequence. A mechanical solution to keep the web forces constant is to use a dancing roller [1]. But the dancing roller is a mechanical component like a spring–mass system and generates new oscillations.

To solve the problem, it is necessary to use new methods to compensate the disturbances without additional mechanical systems. To do this, there are to solve two fundamental problems:

- getting the unknown, nonlinear variable radius of the non–circular running winder and
- the design of a fast speed control of the winder which is able to compensate the changes of the radius.

The first problem can be solved in two ways. The first method is to use a mechanical sensor to measure the radius of the roll. But during running and because of the variable radius we get additional oscillations in the measured output, especially if the speed is high.

Therefore a neural network is used to identify online the unknown, nonlinear radius with respect to the angle position continuously during running. The advantage of neural networks is that they do not need any information about the nonlinearities, they are able to handle unknown nonlinearities. So the neural network is like a "learning" observer. The inputs are well measurable quantities like current, speed and web force, the output is the variable radius of the winder.

To compensate the disturbances in the web force, the output of the neural network is fed into the speed control of the winder. The principle of the compensation is shown in Fig. 2. As we get from the neural network the changing radius dependent on the angle position, we can change the motor speed of the winder that the web velocity is nearly constant. This diminishes the oscillations of the web forces in a big range. But the requirement is a fast speed control of the winder. A conventional PI–controller is not able to fulfill these conditions. Therefore an adaptive state space control of the motor speed was designed.

The advantage of this method is, that no additional mechanical equipment is necessary. The identification of the unknown eccentricity of the roll and the compensation are done only in the digital control system.

PRINCIPLE of COMPENSATION

Web Force

The behaviour of the web between two rollers can be described by the theory of fluid dynamics. In doing so, we get the following non–linear differential equation:

$$\frac{d}{dt}\left(\frac{L_{12}(t)}{1+\varepsilon_{12}(t)}\right) = \frac{V_W(t)}{1+\varepsilon_{01}(t)} - \frac{V_2(t)}{1+\varepsilon_{12}(t)} \tag{1}$$

If we are in a steady–state, equation 1 gives the result:

$$\frac{V_2}{V_W} = \frac{1+\varepsilon_{12}}{1+\varepsilon_{01}} \tag{2}$$

Equation 2 shows that the strain ε_{12} in the web between roller 1 and 2 is created by the relation of the output to input velocity $\frac{V_2}{V_W}$ of the rollers *and* the incoming web strain ε_{01} of the stored material in the winder.

The velocity of the winder is:

$$V_W = 2\pi \cdot N_W \cdot R_\varphi = 2\pi \cdot N_W \cdot (R_m + \Delta R_\varphi) \tag{3}$$

The radius R_m is the mean value and ΔR_φ is the change of the radius around the circumference. Equation 3 can be transformed:

$$V_W = 2\pi \cdot N_W \cdot R_m + 2\pi \cdot N_W \cdot \Delta R_\varphi = V_{Wm} + \Delta V_W \tag{4}$$

From equation 2 we get the strain ε_{12}:

$$\varepsilon_{12} = \frac{V_2}{(V_{Wm} + \Delta V_W)} \cdot (1 + \varepsilon_{01}) - 1 \tag{5}$$

If we assume that the velocity V_2 is constant, we get after some transformations:

$$\varepsilon_{12} = \frac{\varepsilon_{12m} - \frac{\Delta R_\varphi}{R_m}}{1 + \frac{\Delta R_\varphi}{R_m}} \tag{6}$$

If the stress – strain behaviour of the web is linear, we can use Hooke's law to get the force in the web:

$$F_{12} = \varepsilon_{12} \cdot E \cdot A_0 \tag{7}$$

Now we get the force as a function of the changing radius from equation 6:

$$F_{12} = \frac{F_{12m} - E \cdot A_0 \cdot \frac{\Delta R_\varphi}{R_m}}{1 + \frac{\Delta R_\varphi}{R_m}} \tag{8}$$

The force F_{12m} is the mean value.

If we assume that the relatively change of the radius $\Delta R_\varphi / R_m$ is small compared to 1, we get the change of the force in the web due to the non–circularity of the winder as follows:

$$\Delta F_{12} = -E \cdot A_0 \cdot \frac{\Delta R_\varphi}{R_m} \tag{9}$$

As the coefficient $E \cdot A_0$ of the material is high, we get also high changes in the web force, if the winder runs non–circular.

Compensation

To compensate the changes of the force in the web, the velocity V_W of the winder must be kept constant. To do this, we have to change the speed of the winder. So it must be:

$$V_W = \text{const.} = 2\pi \cdot N_W \cdot R_m = 2\pi \cdot (N_{Wm} + \Delta N_W) \cdot (R_m + \Delta R_\varphi) \quad (10)$$

ΔN_W is the necessary change of the speed to keep constant the velocity V_W in spite of the change of the radius $\Delta R(\varphi)$.

From equation 10 we get the additive change of the winder speed:

$$\Delta N_W = -N_{Wm} \cdot \frac{\frac{\Delta R_\varphi}{R_m}}{1 + \frac{\Delta R_\varphi}{R_m}} \quad (11)$$

To compensate the non–circularity of the winder, we need the mean value N_{Wm} of the speed, the mean value R_m of the radius and the change of the angle–dependent radius ΔR_φ of the winder. That means that the compensation parameters are dependent on the operating point of the radius and the processing velocity of the plant. Hence the compensation algorithm must be designed adaptive to fulfill equation 11.

It is usual to calculate the mean radius of the winder from the velocity V_2 and the speed N_{Wm}:

$$R_m = \frac{V_2}{2\pi N_{Wm}} = \frac{i_W}{i_2} \cdot \frac{N_{M2}}{N_M} \quad (12)$$

As we can see from equation 11, we need the changing radius ΔR_φ as a function of the angle. That means we have to know the changing radius along the circumference of the roll. It is impossible to measure the changing radius in industrial plants with mechanical sensors. There would be problems with oscillations. As the non–circularity changes during winding and the change is unknown and nonlinear, we have to use different methods. We suggest to use a neural network to learn the non–circularity online during running the winder. A speed control with high dynamic is necessary to compensate the changes of the radius according to equation 11 with a change of the motor speed of the winder.

CONTROLLED SYSTEM

The controlled system exists of two parts. The first is the motor–winder system, called drive system and the second is the web system. The drive system was designed as a two–mass system because of the low stiffness of the shaft between motor and winder. This system principally is shown in Figure 3 [4].

The web system was designed with the web between winder and the next roller [2]. The signal flow graph of the winder is shown in Figure 4.

The moment of inertia of the winder is a function of the radius. Therefore the parameters of the speed control have to be adapted to the radius.

$$T_{\Theta W} \;=\; \frac{\pi \cdot \rho \cdot B \cdot ({R_W}^4 - {R_0}^4) \cdot \Omega_{0N}}{2 \cdot i^2 \cdot M_N} \tag{13}$$

SPEED CONTROL

PI–Controller.

The state of the art is a cascaded control structure with a current– and speed–control. The controller is designed using the Symmetrical Optimum (SO) [3].

This kind of control is not fast enough to compensate the non–circularity. Figure 6 shows the speed, if a non–circularity with a frequency of 1 Hz is acting. The speed N_M is not able to follow the reference speed N_{ref}. Therefore a new control is necessary.

State Space Control of the speed

The state space control of the speed was designed with the two–mass system shown in Figure 4. The requirement of the state space control is to feed back all states. As the speed N_W and the angle of rotation φ_{12} of the winder is not measurable, an observer was used. The state space controller was designed with the *damping optimization criteria.* This method is based on the pole placement. The advantage is that we get a defined equivalent time constant T_{en} of the speed control. Additionally, this controller shows a sufficient disturbance behaviour when the winder is coupled with the plant. Figure 5 shows the entire speed control and the observer. As shown in Figure 7, this speed control is able to compensate the non–circularity. Here the speed N_M follows the reference speed N_{ref} better than with the PI–controller.

FORCE CONTROL

The control of the web force can be done in three ways. The first is to design a cascade control with PI–controllers. But this control has poor dynamics. The second is a state space control. But in view to the compensation of the non–circularity according to equation 11 this kind of control is not practicable. So we made a mixture between a state space and cascade control as shown in Figure 8. The speed is state space controlled as explained above whereas the force control is cascaded to the speed control with a PI–controller. The PI–controller was designed to the rules of *Ziegler–Nichols.* The measured step response of the force F_{12} is shown in Figure 9. We get a fast step response. Now we have solved the control problem. The next is to get the nonlinear, unknown change of the radius of the winder.

IDENTIFICATION of the NON–CIRCULARITY

Neural Network

General discussion. Considering nonlinear control, identification of nonlinearities has become essential. Thus, a universal function approximator has to be found which is able to approximate an unknown nonlinear function. For this objective, various neural networks are offered. To use one of these methods for adaptive control, two requirements have to be met: First, a stable self–tuning algorithm has to be established and second, this method has to perform universal function approximation with required accuracy and convergence.

Various neural network approaches exist. For example the *Multilayer Perceptron* with the well known *Backpropagation algorithm*, the *Kohonen neural network*, the *Radial Basis Function (RBF) network* or the *General Regression neural network (GRNN)*. For the use in control systems, we prefer the GRNN. This has evolved from the RBF network to improve function approximation with a minimal number of weights. Given a finite number of samples of a continuous function, regression means the calculation of the most probable output for a specific input. The normalized activation function of the GRNN yields a bounded range of output values of the network, which will be limited by its minimum and maximum weights even if unlearned input vectors are present. This leads to improved interpolation and extrapolation performance compared to a standard RBF network, where the output at unlearned regions and between the centers of weights tends to zero. In contrast to that, extrapolation of a GRNN always maintains the value of the nearest weight as shown in Figure 10 [6, 7].

Approximation of non–circularity. Figure 11 shows the observer and neural network structure. The inputs to the whole system are the reference value of the motor torque M_{ref}, the velocity V_2 of the plant, the web force F_{12}, the meanvalue of the radius R_m and the strain ε_{01} of the stored web in the winder. It is assumed that the motor speed N_M, the web force F_{12} and the velocity V_2 or speed N_2 are measurable. The mean value of the radius R_m is calculated as described in equation 12. The inputs to the neural network are the speed $\hat{N}_W$, the angle position of the winder $\hat{\varphi}$ and the web force error E_f. This values are calculated by the observer of the drive system described above and a tension observer . This observer is described in [5]. The neural network is able to learn the non–circularity from the tension error

$$E_f = \hat{F}_{12} - F_{12} \qquad (14)$$

The unknown nonlinearity is the radius with respect to the angle position. It can be described by the following equation:

$$\mathcal{NL} = \underline{\Theta}^T \cdot \underline{\mathcal{A}}(\varphi) \cdot N_W \cdot 2\pi \qquad (15)$$

where $\underline{\Theta}^T$ are the network parameters and $\underline{A}(\varphi)$ is the activation vector of the GRNN. The output of the neural network is given by

$$\hat{\mathcal{NL}} = \hat{\underline{\Theta}}^T \cdot \underline{A}(\varphi) \cdot \hat{N}_W \cdot 2\pi \qquad (16)$$

The network error can be written as

$$\underline{\Phi}^T = \hat{\underline{\Theta}}^T - \underline{\Theta}^T \qquad (17)$$

This error is minimized by the following learning rule:

$$\dot{\underline{\Phi}} = \dot{\hat{\underline{\Theta}}} = -\eta \cdot E_a \cdot \underline{\zeta} \qquad (18)$$

with the main error

$$E_a = E_f + E_h \qquad (19)$$

the error of the network

$$E_h = \left(\hat{\underline{\Theta}}^T \cdot H(s) \cdot I - H(s) \cdot \hat{\underline{\Theta}}^T\right) \cdot \underline{A}(\varphi) \cdot \hat{N}_W \cdot 2\pi \qquad (20)$$

and the vector

$$\underline{\zeta} = H(s) \cdot I \cdot \underline{A}(\varphi) \cdot \hat{N}_W \cdot 2\pi \qquad (21)$$

$H(s)$ is the error transfer function of the observer and of second order. The adaption step size η of the neural network has to be positiv and as big as possible that the neural network is able to learn faster than the nonlinearity changes. The maximum value is limited by the discrete integration step size of the controller.

COMPENSATION of the NON–CIRCULARITY

The whole control concept is shown in Figure 11. Both, the control structure of the speed and force control and the observer with the neural network are shown. The output of the neural network is the change of the radius $\Delta\hat{R}$, which is after the learning time equivalent to the real value ΔR. This signal is fed into the compensation algorithm which is described in equation 11. The delay time T_{delay} is necessary to fed the compensation signal ΔN_W at the right time to the speed controller. There is a very small change of the non–circularity after one revolution of the winder if the thickness of the web is low. Therefore the signal $\Delta\hat{R}$ can be delayed for one revolution minus the time constant T_{en} of the speed control. In doing so, the speed reference value ΔN_{ref} is acting at the right time and the time constant T_{en} of the speed control is taken into account.

$$\Delta N_{ref} = \Delta N_W \cdot (t - T_{delay}) \qquad (22)$$

with

$$T_{delay} = \frac{1}{N_W} - T_{en} \qquad (23)$$

EXPERIMENTAL RESULTS

Plant Description

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. The speed and tension control as well as the drive observer are realized in the real time control system *SIMADYN D*. The neural network and the tension observer is written in the language C and realized in a PC with a Pentium Controller.

For the identification of winder eccentricities, arbitrarily chosen shapes were produced. The maximum thickness of the shape was about 6 mm.

Identification Results

To see how the identification works, first a comparison of the measured real radius R_φ and the identified radius $\hat{R}_\varphi$ was done. The real radius was measured mechanically before the machine was started. The picture above of Figure 13 shows that the identified values are corresponding with the real values. Remaining errors come from uncertainties like the elasticity and the unknown strain ε_{01} which describes the previous history of the web. The proposed method was also examined at different velocities.

The picture below of Figure 13 shows the results of an identification and compensation of the non–circularity. The mean value of the tension was about 310 N. On the left side of the figure, the compensation is not working. Big changes of about 60 N occur. If the compensation is switched on, the changes of the force are reduced to about 10 N. It must be noted, that identification and compensation do not disturb each other and the compensation can already start at the beginning of the learning procedure. The parameter are convergent even if compensation is still working.

CONCLUSION

In this report a neural network based application in continuous web systems are shown. Many winders get non–circular during storage and transport. If such a roll is unwinded, the variable radius causes big changes of the web force. To solve the problem without additional mechanical equipment, new methods are used. The speed control of the non–circular running winder is fed by an additional change of speed in this way that the velocity of the winder is constant.

But there are two requirements to apply this method. First we have to identify the nonlinear, unknown change of the radius. This is done by an observer and a neural network. The neural network is "learning" from the web force error. It is designed with the method of identification of isolated nonlinearities so that stability for the procedure is guaranteed.

To compensate the non–circularity we need a fast speed control of the winder. The state of the art cascaded PI-control cannot fulfill these condition.

Therefore a new state space control, based on the two mass system was designed.

Better control results could be obtained using the described methods. Experimental results show good correspondence with the theory. The force oscillations could be reduced in a big range. The advantage of the described method is that no additional mechanical equipment is necessary. The identification of the unknown eccentricity of the roll and the compensation are done only in the digital control system.

References

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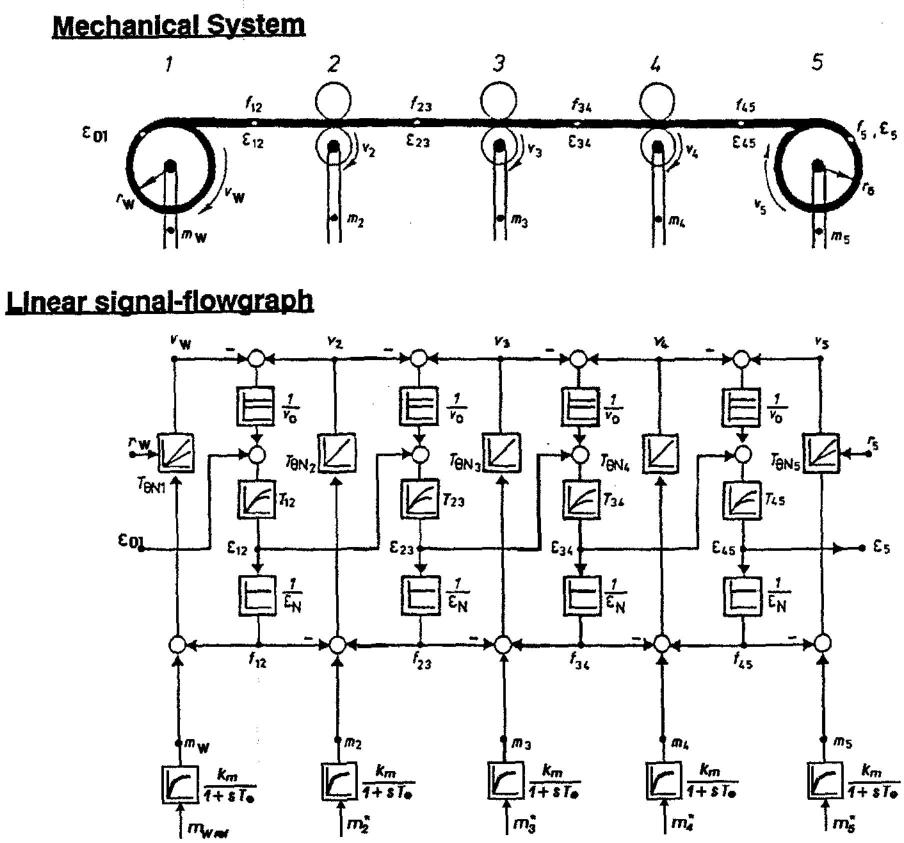


Fig. 1: Linear signal–flow graph of the mechanical system

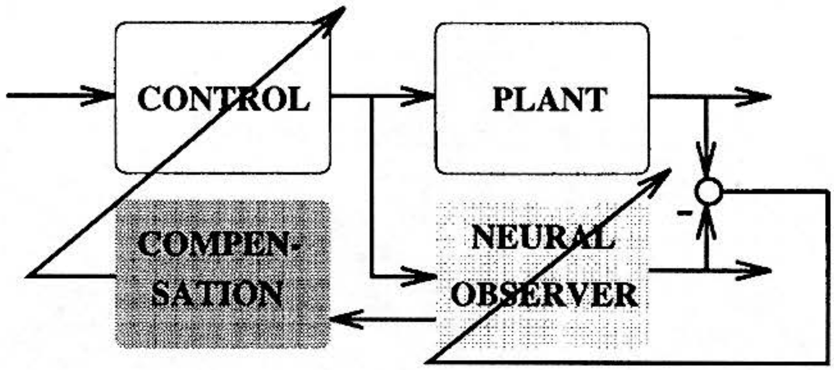


Fig. 2: Principle of compensation

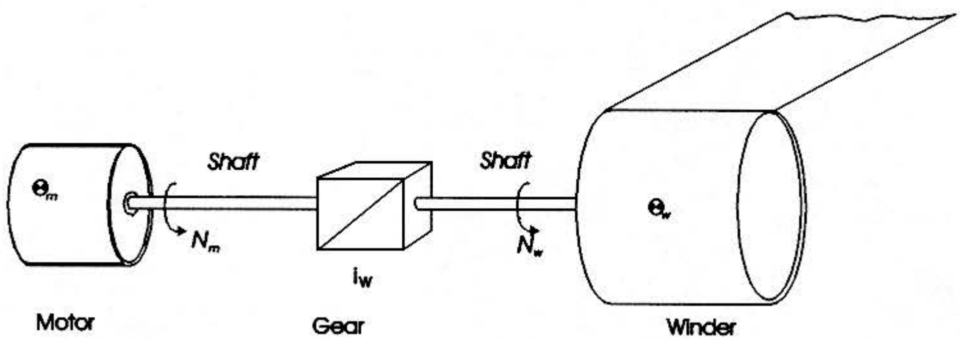


Fig. 3: Mechanical system of motor and winder

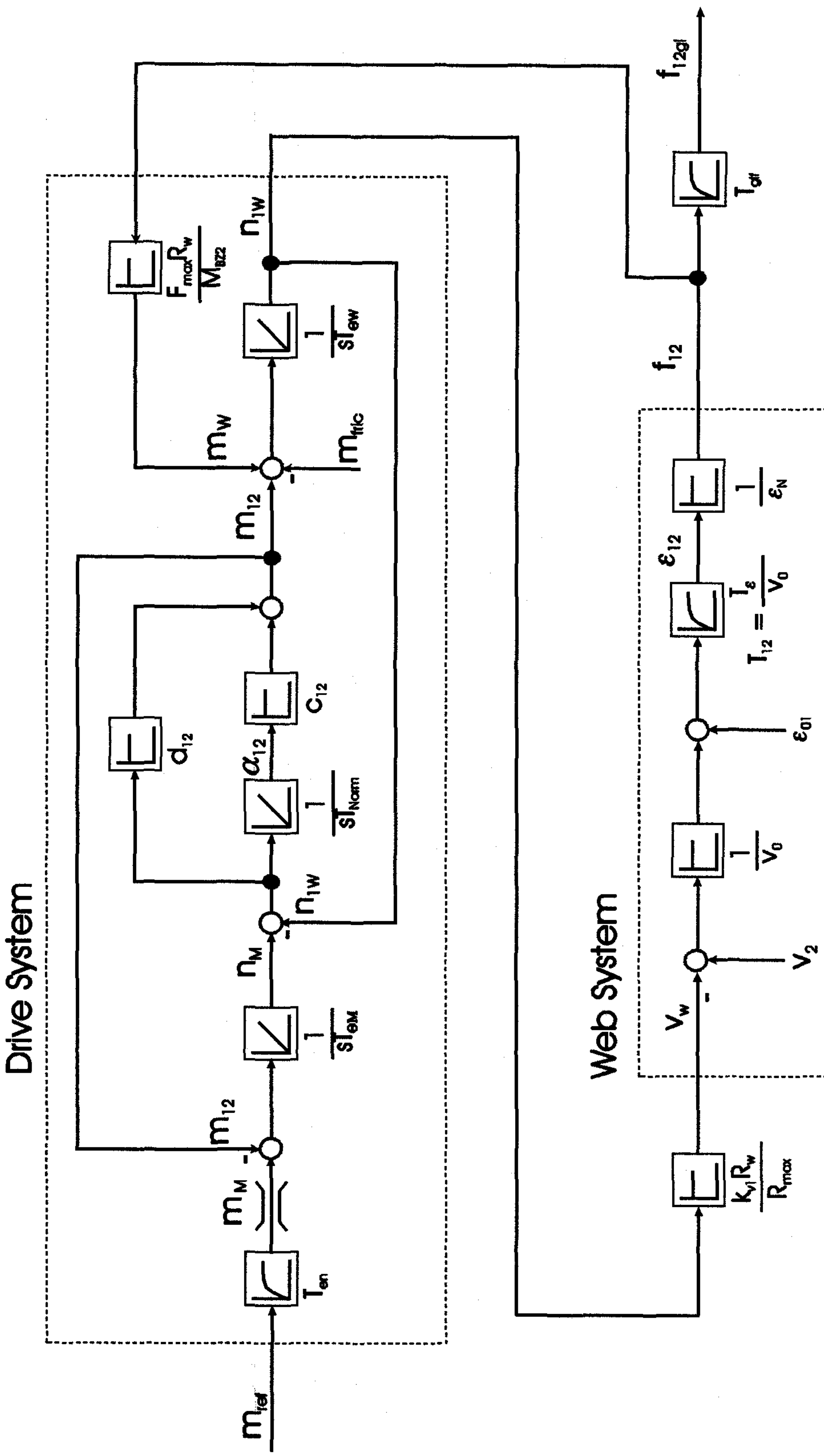


Fig. 4: Signal flow graph of the winder

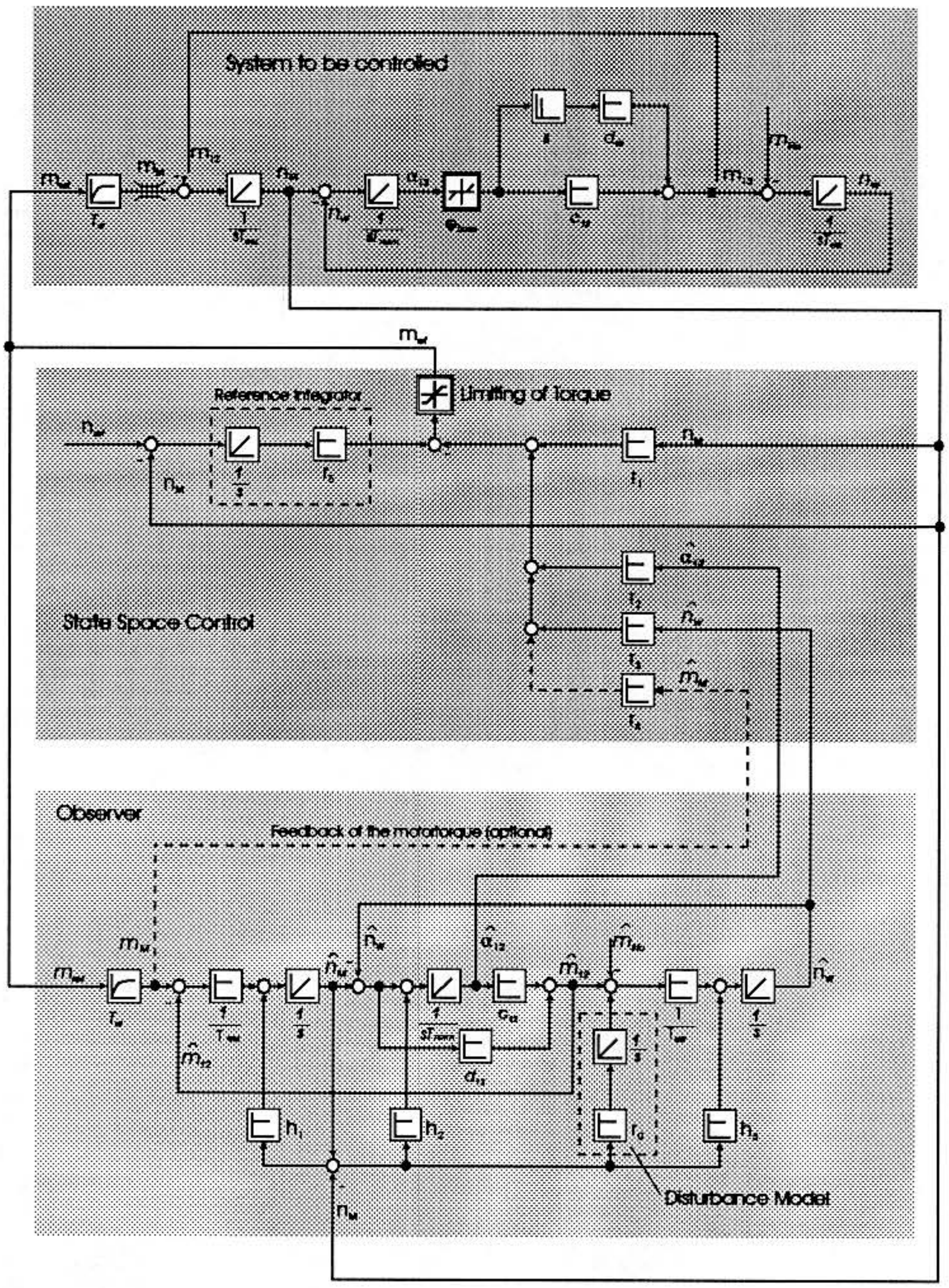


Fig. 5: Signal flow graph of speed control and observer

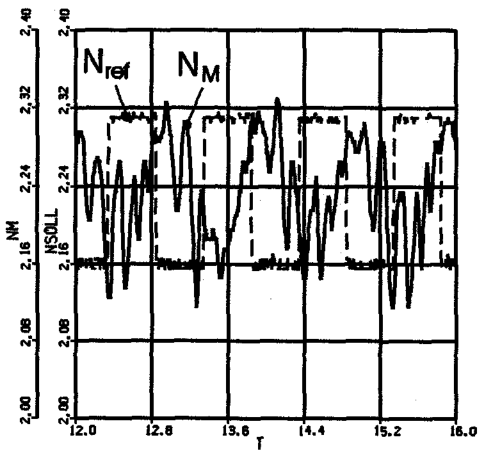


Fig. 6: *Speed control with PI*

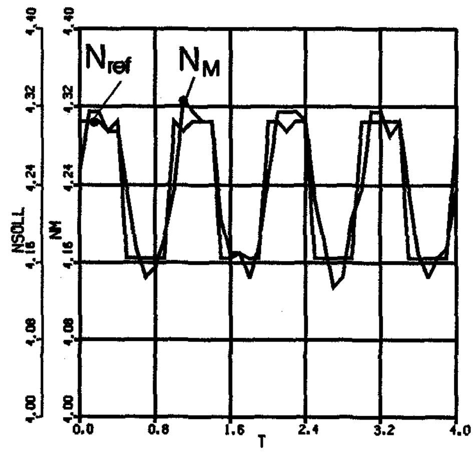


Fig. 7: *State space control*

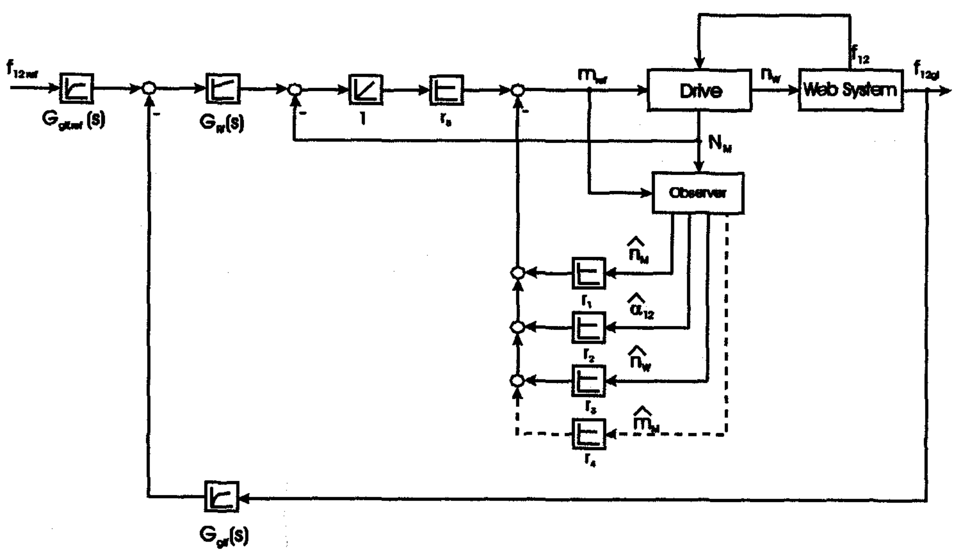


Fig. 8: Principle of the force control

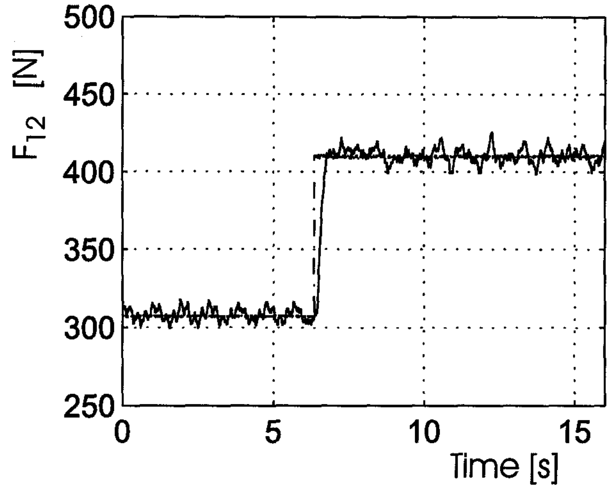


Fig. 9: Step response of the force

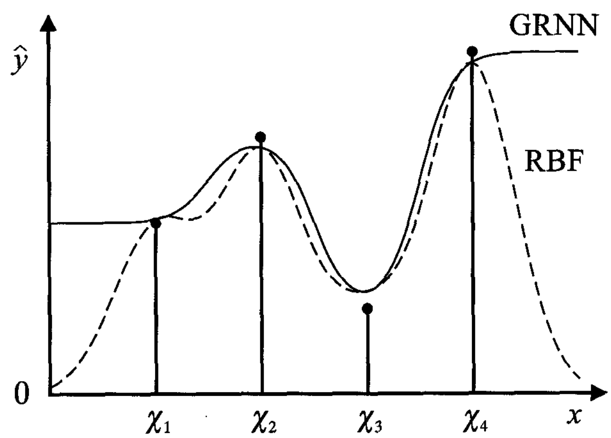


Fig. 10: Interpolation of the GRNN compared to the RBF network

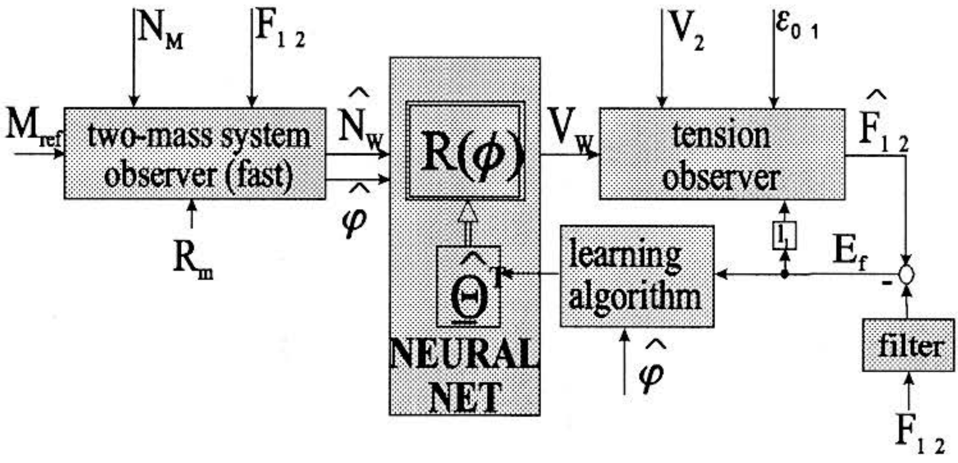


Fig. 11: Observer and neural network concept

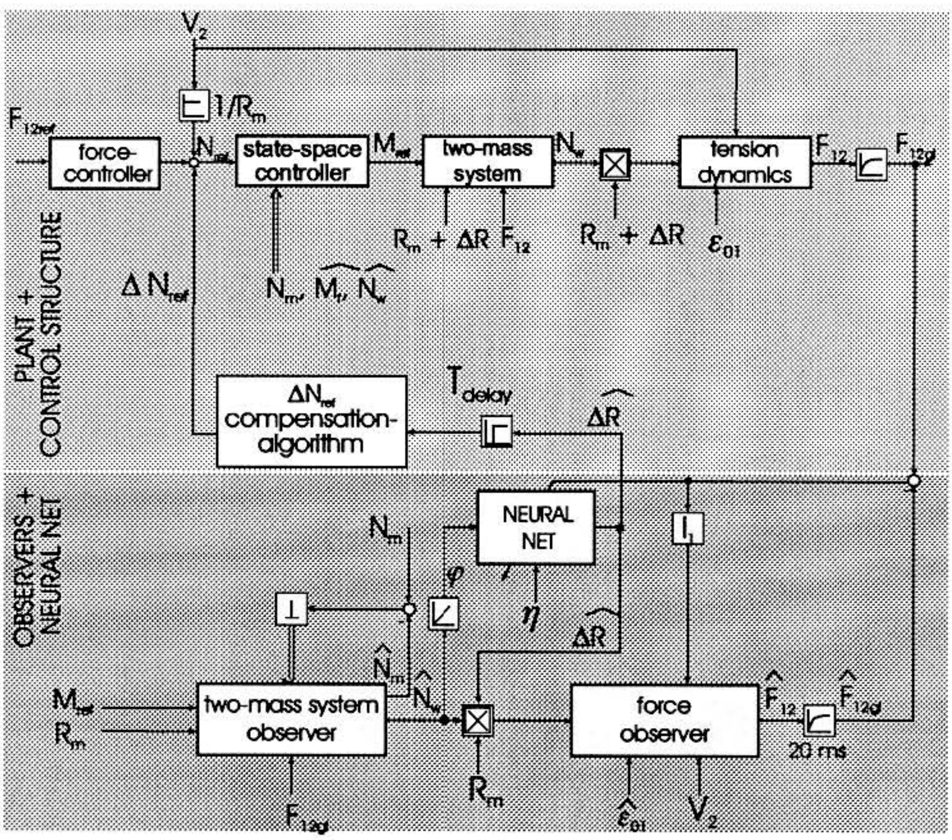
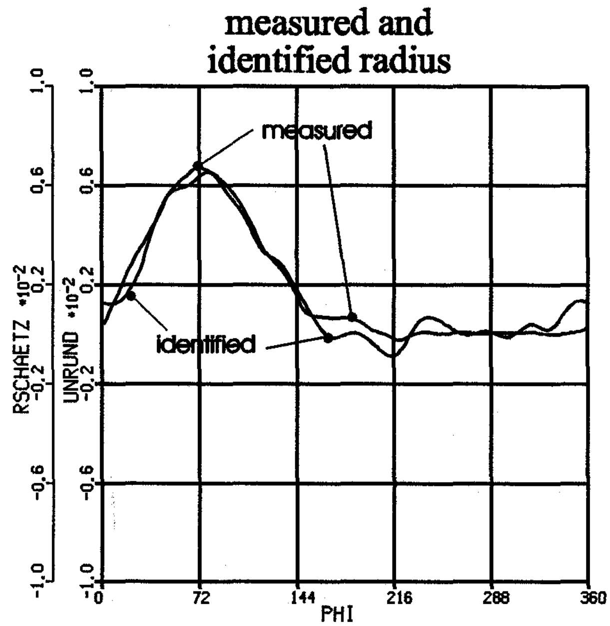


Fig. 12: Control concept



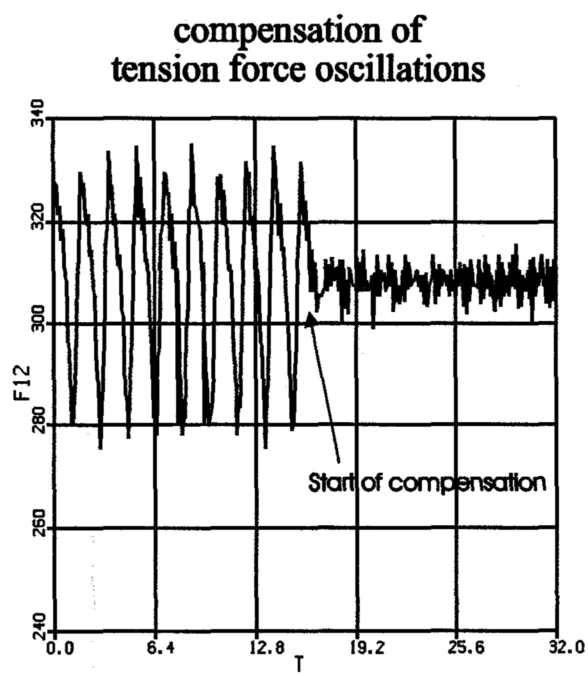


Fig. 13: Learning result and compensation of the non–circularity

W. Wolfermann

Compensation of Disturbances in the Web Force Caused by a Non-Circular Running Winder

6/7/99 Session 1 1:50 – 2:15 p.m.

Question – Mark Southman, Procter & Gamble
Are the observers for the force and the neural network used to find the non-circulating independent of each other, is that correct?

Answer – Wolfermann, Technical University of Munich
Well there is only one observer of the force to get the error. This force error is used to train the neural network. If there is now knowledge about the non-circularity, the neural network and the force observer have estimated a wrong force. This error is minimized during learning. A load cell measures the force for the force control. There are not interactions between this control and the force observer.

Question – Pete Werner, Rockwell Corporation
What degree of degradation of the roll did you experience by applying the torque to accelerate and decelerate the roll? Did you damage the roll in the center?

Answer – Wolfermann, Technical University of Munich
No, we didn't damage the roll in the center. During compensation there is not necessarily a high change of the speed. The amplitude is very small from equation (2) we can see that a change of only 0.5% of the velocity will cause the strain or force to double. What you need is a fast speed control. If the frequency of the non-circularity is not too high, the acceleration and deceleration will not be high. In our equipment, we have a limitation of the motor torque.