Journal of Mechanical Engineering and Automation 2013, 3(2): 29-37
DOI: 10.5923/j.jmea.20130302.02

Application of a Smith Predictor for Control of Fabric Weight during Weaving

Yves-Simon Gloy*, Robert Büllesfeld, Tobias Islam, Thomas Gries

Institut für Textiltechnik der RWTH Aachen University, Aachen, 52074, Germany

Abstract Fabric weight is an important product criterion of woven fabrics. An adequate sensor in order to monitor fabric weight during weaving is proposed in this paper. In addition, a closed control loop is designed in order to regulate fabric weight during weaving. After plant identification it is observable that the system includes a long dead time. Therefore a stable Smith predictor is designed. Stability and robustness of the Smith predictor is proven by simulation. In addition, experiments do show the necessary speed of the Smith predictor to control the fabric weight.

Keywords Smith-Predictor, X-Ray, Weaving, Fabric Weight

1. Introduction

Woven fabrics are described by rectangle crossing of so called warp and weft yarns. They are produced on looms. Modern looms uses transport mediums such as water or air to transport the weft yarn over the width of the machine. Typical weaving machine speed is around 1200 rpm, meaning also 1200 weft insertions per minute. Depending on the desired weft density (wefts per cm), typical production speed is around 0.8 m per minute. The principle of a weaving machine is shown in figure 1[1].

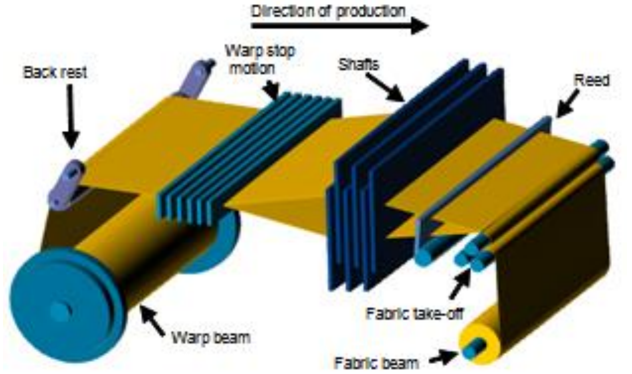

Figure 1. Principle of a weaving machine

Fabric weight per area is a major quality criterion for woven fabrics. It is important for example in composites for lightweight application. Setup of a loom regarding the fabric is done via the following formula

$$Fw = F_{Warp} \cdot D_{Warp} \cdot \left(1 + \frac{E_{Warp}\%}{100}\right) + F_{Weft} \cdot D_{Weft} \cdot \left(1 + \frac{E_{Weft}\%}{100}\right) \quad (1)$$

with Fw = mass of fabric[g/m^2], F = finesse of yarn[tex], D = yarn density[threads/cm] and E = Elongation of yarns[2]. After the setup of the loom and production of the first meters of fabrics, the operator cuts samples out to the check fabric weight by lab measurements. Afterwards adaption to the weaving machines settings are carried out until the desired fabric weight is reached. So far, there is no automation known for this process. Therefore, integration of an adequate sensor to measure the fabric weight and a control system to regulate fabric weight during weaving is presented in this paper.

2. Sensor to Monitor Fabric Weight during Weaving

In order to find an adequate sensor solution to monitor fabric weight online during weaving the so called 9-Step Method was used. The 9-Step Method was developed at the Institut für Textiltechnik der RWTH Aachen University (ITA) in order to find sufficient sensor solution for textile processes[3]. As results of the use of the method, radiation absorption was determined as best solution to monitor fabric weight.

A sensor using the radiation absorption is provided by the company BST ProControl GmbH, Freudenberg, Germany. The system consists of an X-ray emitter and a receiver. The X-ray emitter operates at an accelerating voltage of 5 kV and does not require permission in Germany. The sensor has a measurement range from 500 to 1000 g/m^2, a resolution of 0.1 g/m^2 and an accuracy of 0.3 g/m^2. The principle of this radiation absorption sensor, using X-Ray, is shown in figure 2.

* Corresponding author:
yves.gloy@ita.rwth-aachen.de (Yves-Simon Gloy)
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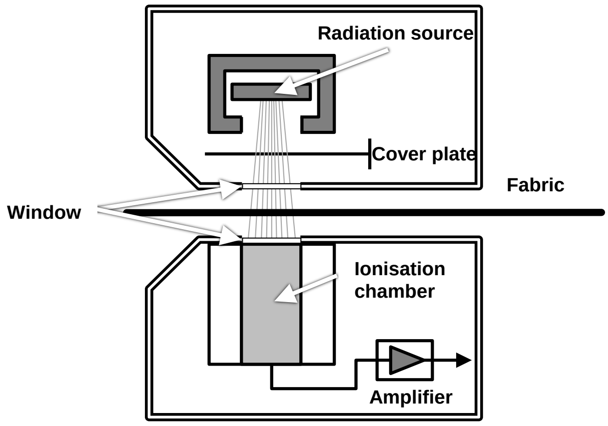

Figure 2. Principle of a X-Ray sensor system

Mounts were manufactured to integrate the sensor system in the weaving machine. Thus, the measuring system can be installed between fabric take-off and fabric beam. Figure 3 shows the exact measuring arrangement.

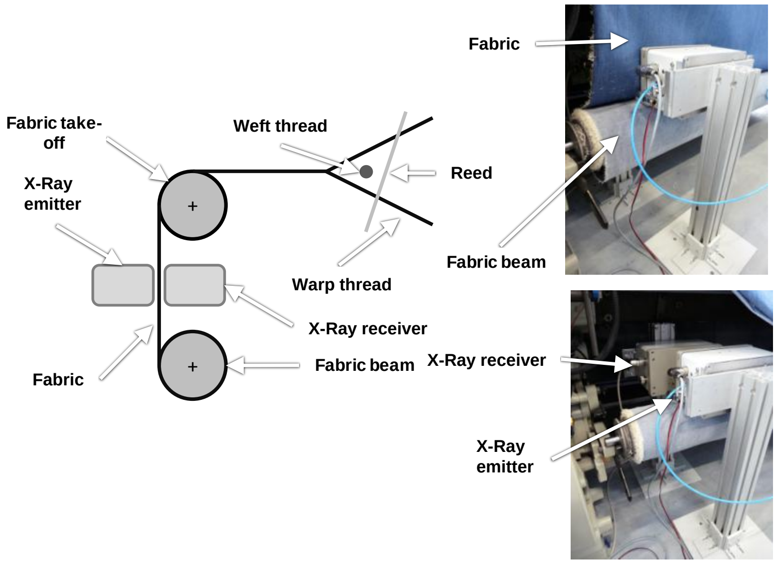

Figure 3. Installation of the X-ray system in the weaving machine

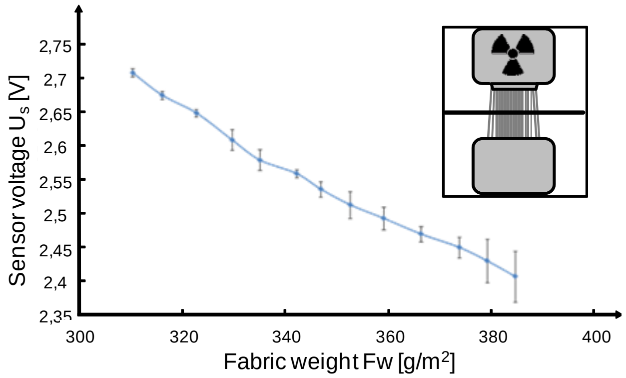

Figure 4. Correlation between sensor signal U_s and fabric weight Fw

The sensor system was tested on an OmniPlus 800 weaving machine, manufactured by Picanol NV, Ieper, Belgium in the technical centre of the Institut für Textiltechnik der RWTH Aachen University, Aachen, Germany. The weaving machine is equipped with polyester 730dtex f2 in weft and warp yarn. The warp density is 20 threads/cm. The operating speed is 700 rpm and a twill 3/1 fabric is woven. The sensor signal is recorded while running the machine on different weft densities. Afterwards the fabric weight for each variation of the weft density is measured according to DIN EN 128181[4]. A linear correlation between fabric weight and sensor signal was found after evaluating the test results, see figure 4. Therefore the sensor system is suitable to monitor fabric weight during weaving.

3. System Identification

System analysis and thus knowledge and of the relevant system behaviour is a essential requirement to design a functional control loop. The present system is composed of the weaving machine and the X-ray sensor there to installed. Since the sensor is placed between fabric take-off and fabric beam, the system contains a dead time. Figure 5 shows the functional diagram of the controlled system.

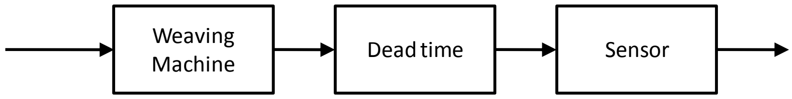

Figure 5. Action diagram of the controlled system

All following research was done on a weaving machine with following main parameters:

- Weave pattern: twill 3/1
- Weft and warp material: Polyester dtex 334/72x2
- Warp density: D_{Warp} = 20 threads/cm
- Warp tension: 2.5 kN

A set point A with a weaving speed of n_A = 600 rpm and weft density D_{Weft} = 16 threads/cm is defined. The operating range of the weft density is set from 12 up to 20 threads/cm.

3.1. Analysis of Weaving Machine

As shown in equation 1, fabric weight is depending on the yarn density and the elongation of the yarns. Since warp density and weft tension cannot be easily changed during weaving, the influence of warp tension and weft density was investigated in a first series of experiments.

Therefore, warp tension was varied in an range of 1,75 kN up to 4 kN. During the trial speed and weft density were kept constant. Figure 6 shows the measured correlation between fabric weight and warp tension. It is visible, that there is no linear correlation between these two factors.

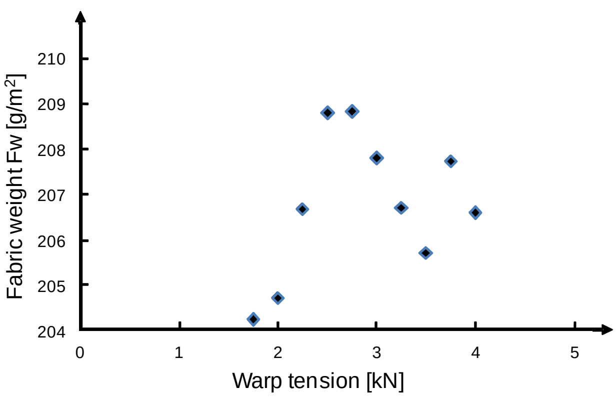

Figure 6. Correlation between warp tension and fabric weight Fw at constant speed and weft density D_{Weft}

Table 1. Correlation between weft density and fabric weight

Weft density D_{Weft}[threads/cm]	Fabric weight Fw[g/m^2]
12	263.23
13	271.47
14	281.15
15	288.94
16	298.99
17	308.52
18	317.47
19	324.68
20	333.46

The correlation between weft density and fabric weight is gained though a series of measurements. Therefore fabric weight was determined according to DIN EN 12127 for several weft densities. Results of the measurements are shown in table 1. As shown, there is a linear linear correlation between the two parameters weft density and fabric weight.

With the help of a linear curve fitting calculation, the coefficients of this linear equation

$$Fw = K_W \cdot D_{Weft} + Fw_0 \tag{2}$$

can be determined to K_W = 8.88 g cm/m^2 and Fw_0 = 156.6 g/m^2. It has to kept in mind, that these values will change depending on parameters like yarn material. The linear equation 2 describes the output behavior of the weaving machine. Equation 2 can be linearised under use of a taylor series in the set point A with D_{WeftA} and Fw_A as

$$fw = \left.\frac{\delta Fw}{\delta d_{Weft}}\right|_A \cdot d_{Weft} = K_W \cdot d_{Weft} \tag{3}$$

with the deviation values fw and d.

The linearisation is independent from the set point A and therefore valid for the whole operating range due to the linear correlation of equation 2. Hence, the output behavior of the weaving machine can be described by a P element:

$$G_W = K_W \tag{4}$$

3.2. Analysis of Sensor and Dead Time

Figure 7 shows the step response for a change of Fw = 334.2 g/m²(with D_{Weft} = 20 cm^{-1}) to Fw = 263.16 g/m²(with D_{Weft} = 12 cm-1). The output function is smoothed using an interpolation.

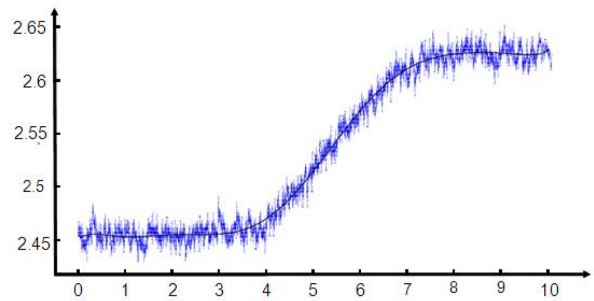

Figure 7. Step response of X-ray sensor

Furthermore, approximation is conducted according to Strejc[5]. With this approximation the output function is designed as PT_1T_t element:

$$G_S(s) = \frac{K_S}{1 + sT_S} \cdot e^{-sT_{tS}} \tag{5}$$

Constants T_S and dead time T_{tS} are calculated via:

$$T_{tS} = T_S \cdot \ln\left(1 - \frac{h_2}{\kappa}\right) + t_2 \tag{6}$$

$$T_S = \frac{t_2 - t_1}{\ln\left(\frac{\kappa - h_1}{\kappa - h_2}\right)} \tag{7}$$

Course of step response is nearly point-symmetrically at the turning point at t_W = 2.5 s. The analysis results the following values h_1 = 0.0452 V, h_2 = 0.1272 V and K = 0.1709 V, hence T_{tS} = 1.3129 s and T_S = 1.4197.

Measurement is conducted a jump of fabric weight from von Fw = 334.2 g/m² to Fw = 263.16 g/m² and hence a difference of ΔFw = -71.04 g/m². According to the Strejc approximation K_s can be calculated as:

$$K_S = \frac{K}{\Delta Fw} = \frac{0.1709V}{-71.04\frac{g}{m^2}} = -0.0024057 \cdot V\frac{m^2}{g} \quad (8)$$

Further weaving speed v is investigated:

$$v = \frac{n}{D_{Weft}} = 0.625\frac{cm}{s} \quad (9)$$

Figure 7 shows, that a jump in fabric weight needs around t_{total} = 5.5 s until it totally passed the sensor. With the help of the speed v the length of sensor measurement range L_S can be calculated as:

$$L_S = t_{total} \cdot v = 5.5s \cdot 0.625\frac{cm}{s} = 3.4375cm \quad (10)$$

L_s kept constant during all setups, since the size of sensor does not change. Constants T_S und T_{tS} can be formatted to the characteristic length L_{TS} and L_{TtS} as:

$$L_{TS} = T_S \cdot v = 1.4197s \cdot 0.625\frac{cm}{s} = 0.88731 \cdot cm \quad (11)$$

$$L_{TtS} = T_{tS} \cdot v = 1.3139s \cdot 0.625\frac{cm}{s} = 0.82119 \cdot cm \quad (12)$$

hence for any v T_S and T_{tS} can be calculated as:

$$T_S = \frac{L_{TS}}{v} \quad (13)$$

$$T_{tS} = \frac{L_{TtS}}{v} \quad (14)$$

Table 2. Measured and approximated value for the sensor behaviour

Parameter	Value		
D_{Weft}[Threads/cm]	12	16	20
v[cm/s]	0.8333	0.625	0.5
T_s measured[s]	1.06479	1.4197	1.77464
T_s approximated[s]	1.06481	-	1.77462
T_{tS} measured[s]	0.98542	1.3139	1.642364
T_{tS} approximated[s]	0.98547	-	1.64238

Looking at the jump of fabric weight at different set points, T_S and T_{tS} are determined according to table 2.

As results, the output function of sensor is described accurate with the approximation.

Death time T_t depends on the length L_t between the location of fabric production and the place of the X-Ray sensor and furthermore weaving machine speed v, see figure 8.

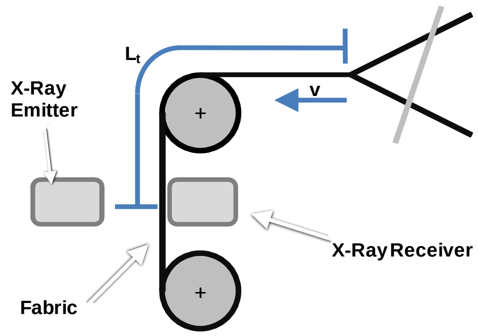

Figure 8. Dead time length L_t in the weaving process

Applying

$$T_t = \frac{L_t}{v} \quad (15)$$

with

$$D_{Weft} = \frac{n}{v} \quad (16)$$

leads to the linear correlation between dead time T_t and weft density D_{Weft}:

$$T_t = \frac{L_t}{n} \cdot D_{Weft} \quad (17)$$

Doing so, dead time distance L_t and speed n keep constant n. Length L_t was measured to 140.625 cm. As shown in equation 17 dead time depends on the parameters D and speed n. This has to be kept into account during the design of the control loop. The set point A is defined with n = 600 min^{-1} and D_{Weft} = 16 cm^{-1}. The length L_t counts 140,625 cm, hence dead time calculates to:

$$T_t = \frac{L_t}{n} \cdot D_{Weft} = \frac{140.625 \cdot cm}{600 \cdot min^{-1}} \cdot 16 \cdot cm^{-1} = 225s \quad (18)$$

The output function of the death time can be described as [Abe11]:

$$G_T = e^{-sT_t} \quad (19)$$

3.3. Summary of System Identification

The plant can be modelled as shown in figure 9.

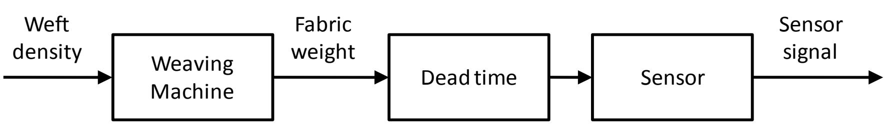

Figure 9. Plant model

Therefore the output function of the control path can bed described as:

$$G_W \cdot G_T \cdot G_S = K_W \cdot e^{-s \cdot T_r} \cdot \frac{K_S}{1+s \cdot T_S} \cdot e^{-s \cdot T_{tS}} = \frac{K_W \cdot K_S}{1+s \cdot T_S} \cdot e^{-s \cdot (T_t + T_{tS})} \tag{20}$$

4. Design of Control Loop

Due to the long dead time and the easy implementation a Smith predictor was chosen to design the control loop as shown in figure 10 with G_C as transfer element of controller [7].

The correlation between X-Ray sensor signal and fabric weight, as analyzed in section 2, was modelled using

$$G_F = K_S \cdot Fw + U_{S0} \tag{21}$$

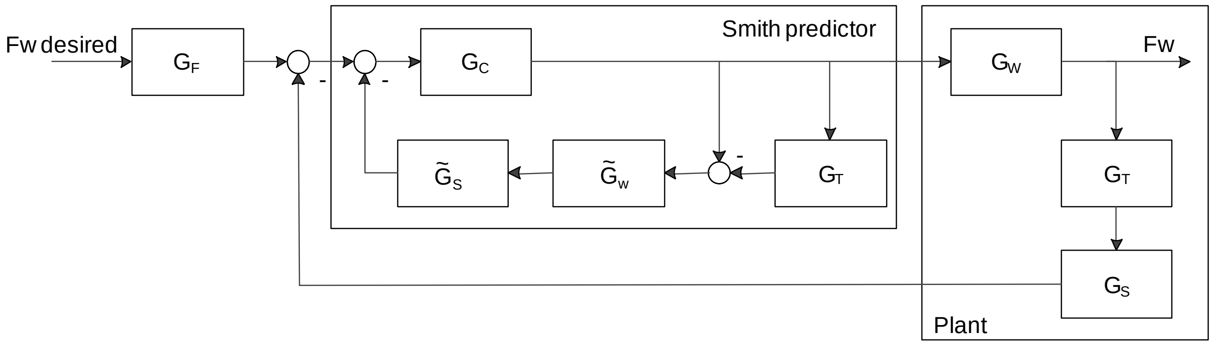

Figure 10. Closed control loop with Smith predictor

The output function of closed control loop is described as:

$$G_{closed} = \frac{G_F \cdot G_W \cdot G_{Smith}}{1+G_T \cdot G_S \cdot G_W \cdot G_{Smith}} \tag{22}$$

According to[8] it is possible to design the smith predictor based on the plant without dead time. Hence, output of the smith predictor is described as:

$$G_{Smith} = \frac{G_C}{1+(1-G_T)\cdot G_R \cdot \tilde{G}_W \cdot \tilde{G}_S} \tag{23}$$

Within the Smith predictor, the plant is modelled as precise as possible, therefore:

$$\tilde{G}_i = G_i \tag{24}$$

with $\tilde{G}_i$ as model of the plant. This is leading to the following equation of the output function of the closed control loop:

$$G_{total} = \frac{G_F \cdot G_C \cdot G_S}{1+G_R \cdot G_W \cdot G_S} \tag{25}$$

The closed control loop based on the smith predictor does not show a dead time. This simplified closed control loop is shown in figure 11.

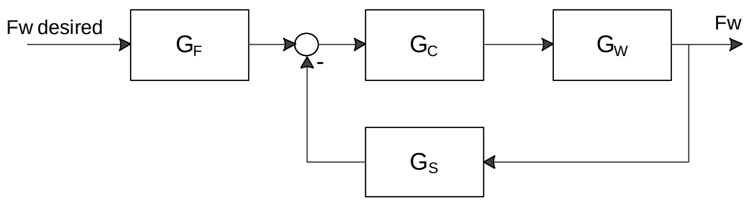

Figure 11. Simplified closed control loop

Due to expected instability of the Smith predictor, phase margin was set to 75°. A PI element was chosen for the controller. For the design of the controller, function PIDTUNE is used in MATLAB. The parameters of the closed control are calculated as:

$$K_R = -21 \cdot \frac{1}{V \cdot cm} \text{ and } T_R = 1.97 \cdot s^{-1}$$

Simulated output function of closed control loop with Smith predictor in comparison with a conventional PI controller is shown in figure 12. The conventional controller needs 1400 s, the Smith predictor need 20 sec to regulate the process.

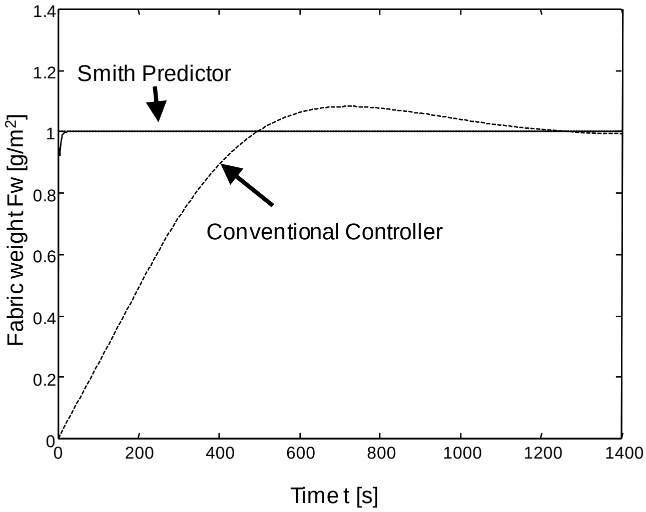

Figure 12. Comparison step response of a simulated conventional controller and a simulated Smith predictor

4.1. Stability of Smith Predictor

Within the set point the Smith predictor was designed for the following parameter of the transfer function according to section 3:

$$G_W = 8.88\frac{g\cdot cm}{m^2} \text{ and } G_S = -\frac{0.002598\frac{V\cdot m^2}{g}}{1+1.4197\sec\cdot s}\cdot e^{-1.3139\sec\cdot s}$$

Dead time and delay constant of the senor are independent of the used yarn material. In contrast the static amplification factors K_W and K_S are depending on the used yarn material They do effect the phase margin.

The transfer elements G_W and G_S can be merged in such a way, that the control plant contains only a static amplification factor:

$$K_1 = 8.88\frac{g\cdot cm}{m^2}\cdot(-0.002598\frac{V\cdot m^2}{g}) = -0.02307V\cdot cm$$

The border of stability can be found in the point where the phase margin becomes zero. In order to obtain this point, the bisection method according to[9] is used.

Since the closed control loop gets unstable when the static amplification factor is raised, the second starting point for the bisection method was chosen to

$$K_2 = -500V\cdot cm\cdot m$$

In this case phase margin results in

$$\alpha_R = 103°$$

The closed control loop is not stable for K_2. Hence, this point will be the second starting value for the bisection method. Bisection method was implemented in MATLAB with an abortion accuracy of 10^{-10}. In this case the iteration stops after 50 cycles and delivers:

$$K_{stabilityborder} = -131.2137V\cdot cm$$

The product of K_S and K_W must not be smaller than $K_{stabilityborder}$. Since

$$K_1 \geq K_{stabilityborder}$$

it can be assumed that the control loop is stable.

4.2. Attenuation of Noise

In order to analyse the attenuation of noise, disturbance in the X-ray signal z_s and disturbance in the fabric weight z_W are intruded into the closed control loop, see figure 13.

The control loop is redesigned in order to have weft density D_{Weft} as input and fabric weight as output signal. The disturbance signal is simulated using random values within the dimension of real noise if of the sensor signal. The noise of the sensor output results in a deviation of ±6 g/m^2 of the fabric weight. According to the lowest fabric weight that can be produced on the weaving machine (263 g/m^2) this noise refers to relative deviation of ±2.3%. This deviation will be during the implementation of the control loop using a moving average. Noise z_W affects the fabric weight in a direct way, so it cannot be damped. It is assumed to be negligible

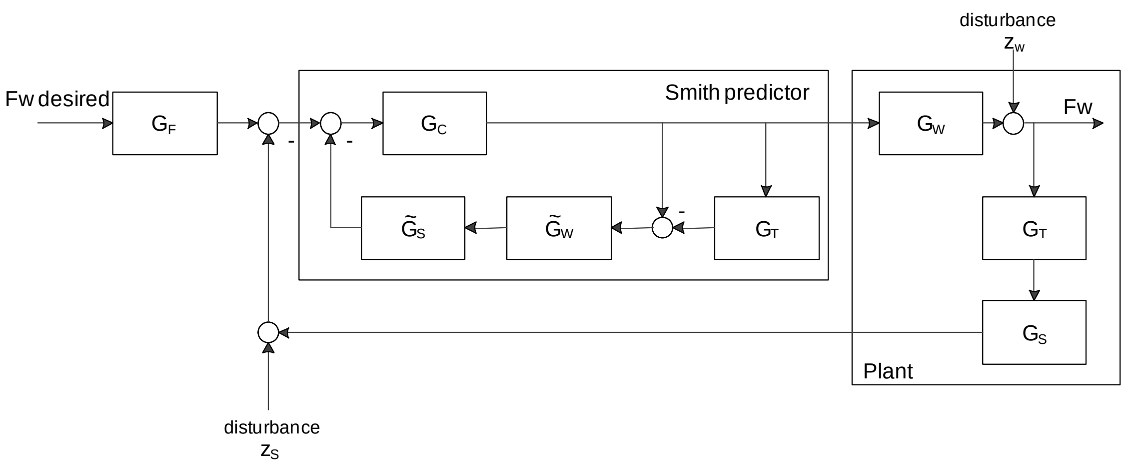

Figure 13. Closed control loop with Smith predictor and disturbance feedforward control

4.3. Robustness Analysis

First, robustness of the closed control loop within the static amplification factor K_W is analyzed. The measurement accuracy of the static amplification factor of the weaving machine is in the dimension of 10%. This deviation will be simulated as error with in MATLAB using a second transfer function within the model of the weaving machine. Step response of Smith predictor controller with defective transfer element of the weaving machine is shown in figure 14.

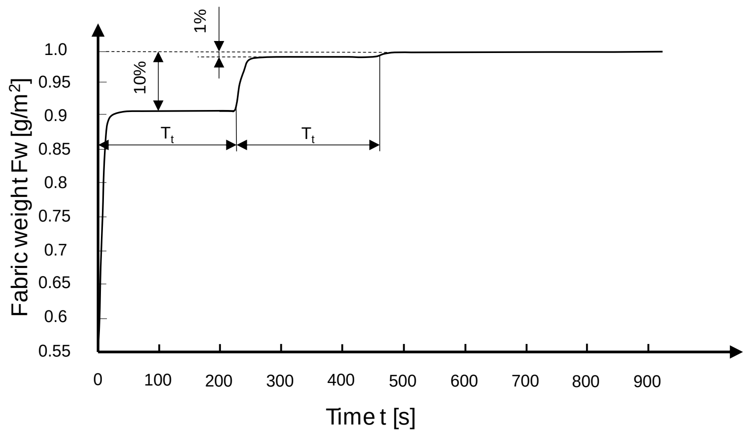

Figure 14. Step response of Smith predictor controller with defective transfer element of the weaving machine

The actuating variable D_{Weft} is controlled wrong within the Smith predictor due to the inserted error. Only after the dead time passed, the control deviation is further reduced. Never less the control loop keeps stable.

In the next step, similar as above, an error within the static amplification factor K_S is analyzed. Step response of this redesign closed control loop is shown in figure 15.

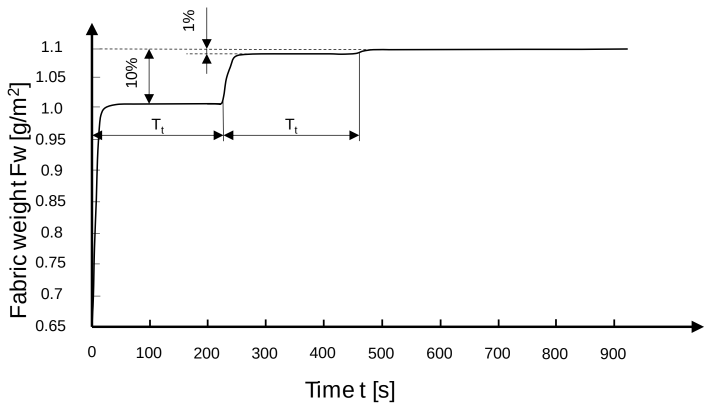

Figure 15. Step response of Smith predictor controller with defective transfer element of the sensor

The error within the static amplification factor of the sensor results in remaining control deviation. This deviation cannot be balanced. However the closed control loop keeps stable.

In a last step, the robustness according to error within the time constants is analyzed. Also in this case, an error with maximal 10 % deviation is simulated. Step response of the closed control loop with dead time errors is shown in figure 16.

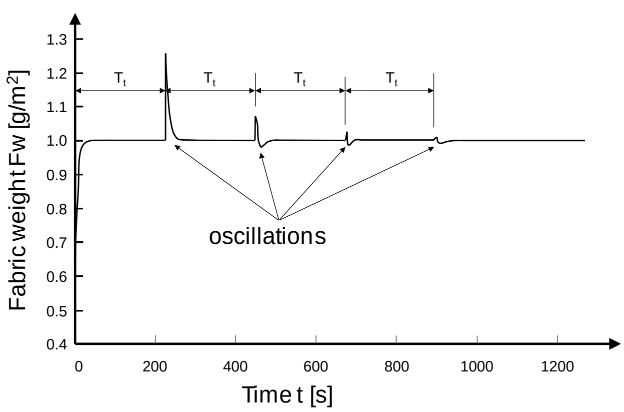

Figure 16. Step response of Smith predictor controller with defective transfer element of the dead time

Closed control loop keeps stable for a phase margin of 75 ° even if there a error within the time constants of 10 %. Never less decaying oscillations can be observed. These oscillations do have amplitude of around 25 % within the first oscillation. Period of the oscillations is equal to the dead time duration. Still, the balancing time of the Smith predictor is with 1000 s still 29 % faster than conventional closed control loop.

Summarising, the Smith predictor is stable for the parameters

$$K_R = -21 \cdot \frac{1}{V \cdot cm} \text{ and } T_R = 1.97 \cdot s^{-1}.$$

5. Validation of Control Loop

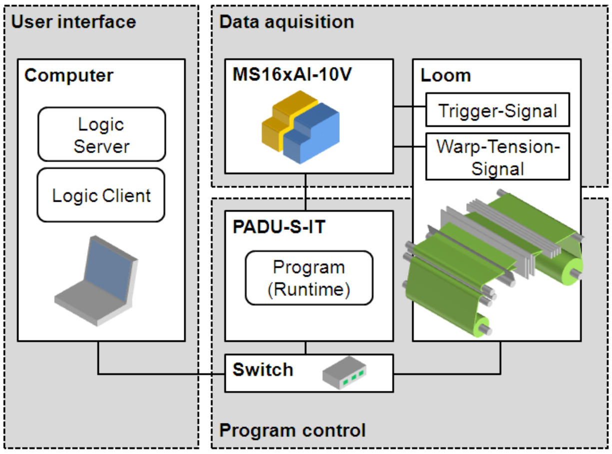

Figure 17. System architecture for implementation of control for fabric weight into a the weaving machine

Validation of the control loop was conducted within the Institut für Textiltechnik der RWTH Aachen University using components from company iba AG, Fürth, Germany. The X-Ray sensor is connected to ibaMS16xAI-10V, an A/D converter. In addition, the control loop was programmed using software ibaLogic-V4 and implemented on the run-time system ibaPADU-S-IT. The run-time systems use an iX86-CPU with 1600 MHz and Microsoft Windows CE as operating system with an ibaLogic-V4 Runtime engine.

The communication with the weaving machine is realized using TCP/IP. Figure 17 shows the system architecture for implementation of control for fabric weight into a weaving machine.

The controller is tested on an air-jet OmniPlus 800 weaving machine, manufactured by Picanol NV, Ieper, Belgium with following setup:

- Weave pattern: twill 3/1
- Yarn material: Polyester dtex 334/72x2
- Warp density: D_{Warp} = 20 cm-1
- Warp tension: 2,5 kN

First of all, the values of the plant model parameters are calculated as shown in table 3.

Table 3. Calculated value of the plant

Parameter	Value
K_W	8.88 g cm/m^2
K_S	-0.002598 V m^2/g
Fw_0	156.6 g/m^2
U_{S0}	156.6 g/m^2
L_t	140.625 cm

In order to calibrate the output function G_F fabric weight was determined at two setting points as shown in

Table 4. Calculated value of the plant

Weft density D[threads/cm]	Fabric weight Fw[g/m^2]
12	262
20	333

After this calibration the desired fabric weight is set to 300 g/m^2 and the controller is started. The result is shown in figure 18.

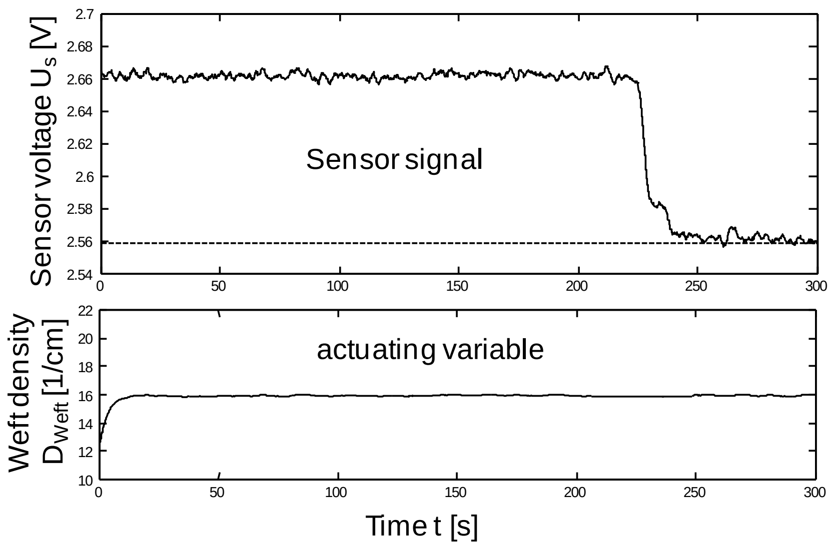

Figure 18. Behaviour of sensor voltage and weft density during control mode

The control loop needs around 20 s in order to regulate the fabric weight. In addition, fabric weight of the woven fabrics was determined according to DIN EN 12127 to

$$Fw_{measured} = 302.8\frac{g}{m^2}$$

representing a deviation of 0.93 % of the desired set value. This deviation is sufficient for industrial applications in weaving mills.

6. Conclusions

An X-Ray sensor is usable to monitor fabric weight during weaving. In addition the plant identification of the weaving machine including the sensor do show a long dead time in the system. Therefore a Smith predictor is proposed for the control of the fabric weight during weaving. The designed Smith predictor does show the necessary stability and robustness in simulations. In addition, the controller was integrated in a weaving machine and tested. The results of the experiment do show that the controller can regulate fabric weight with a necessary accuracy for industrial applications.

ACKNOWLEDGEMENTS

The authors would like to give thanks to German Research Foundation DFG for the support of the depicted research within the framework of the Cluster of Excellence “Integrative Production Technology for High-Wage Countries”. Furthermore the authors would like to give thanks to the companies

- BST ProControl GmbH, Freudenberg, Germany
- Picanol Nv, Ieper, Belgium
- iba AG, Fürth, Germany

for their support of this work.

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